Production and Kinetic Studies of Biogas from Anaerobic Digestion of Banana and Cassava Wastes

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Abstract

Purpose: In the present study, anaerobic digestion of cassava (Manihot esculenta) and banana (Musa paradisiaca) wastes was investigated and the kinetic modelling of the conversion process was carried out.

Methods: The experiments were carried out in a batch reactor under mesophilic conditions.

Results: The total solids content of cassava and banana were 14.7% and 15.7% respectively, moisture content of cassava and banana were 85.3 and 84.3% respectively while the volatile solids content of cassava and banana were 92.32% and 96.27% respectively. The cumulative biogas yield of cassava substrate reached 18.8 L/g VS after 30 days while that of banana reached 14.24 L/g VS in the same digestion time. The first- order kinetics showed that the cassava substrate had greater potential for biogas production due to its relatively higher k value (0.19) than the banana substrate (0.03). Modified Gompertz kinetic parameters showed a total biogas production of 30.54 L/gVS for cassava at a maximum production rate of 0.56 L/g/VS/day while banana had a total biogas production of 24.91 L/gVS at a maximum production rate of 0.44 L/g/VS/day. The short lag phase of the digestion process indicatedthat the microbes acclimatized quickly to the slurry environment. The modified Gompertz model was a better fit for the experimental and simulated data, based on the closeness of R2 values to 1.

Conclusion: Both cassava and banana substrates showed great potential for biogas production. Therefore, biogas generated from waste valorization can mitigate over-dependence on depleting fossil fuel/crude oil in Nigeria and Africa.

Keywords: anaerobic digestion; *Musa paradisiaca*; biogas; *Manihot esculenta*; kinetics

1. Introduction

A continuous explosion in population growth, globalization, and urbanization has led to a drastic increase in the energy demands for its sustainability. This is a problem that is associated with and more pronounced in underdeveloped and developing nations where their socio-economic conditions are very low [1, 2]. Shortage of infrastructure for generating, transmitting, and distributing energy, the dwindling nonrenewable energy sources such as fossil fuels, limited technology for conversion of energy from renewable energy sources such as biogas and shortage of funds for purchasing fossil fuels, acquire infrastructural and technological development in the energy sector have been identified for possible crisis points in the energy sector in most developing and underdeveloped countries [3-5]. Since renewable energy sources such as waste materials can also serve as sources of energy in developing and underdeveloped countries, the problem of poverty concerning the energy crisis can be drastically reduced.

Anaerobic digestion is a process through which bacteria break down organic matter such as animal manure, wastewater biosolids, and food wastes in the absence of oxygen. The technology is a biochemical conversion process of significantly high economic value [6]. Anaerobic digestion for biogas production takes place in a sealed vessel called reactor. Anaerobic digestion of organic waste materials which can be gotten from municipal solid waste, industrial waste, agricultural waste, and household waste can also provide enormous energy since it can serve as a renewable source of energy such as biogas [7]. Biogas is a cheap and relatively affordable form of renewable energy that can meet the energy demands of rural society to a reasonable extent and it is a flammable colourless gas that can be generated through anaerobic digestion of organic waste materials. It is more convenient and hygienic as a result of the fact that it does not generate any form of smoke [8]. Biogas contains a mixture of several gases, which include; methane (50-72 Vol. %), nitrogen (>2 Vol.%), carbon dioxide (25-45 Vol. %), hydrogen sulphide (>1 vol. %), water (2-7 Vol. %), oxygen (>2 Vol. %), and several other gases, produced by anaerobic digestion [9, 10]. The production of biogas occurs via three major biochemical processes which include; hydrolysis, acidogenesis/acetogenesis, and methanogenesis as shown below [11]:

$$(C_6H_{10}O_5)n + nH_2O \rightarrow n(C_6H_{12}O_6) \text{ - Hydrolysis} \quad (1)$$

$$n(C_6H_{12}O_6) \rightarrow nCH_3COOH \text{ - Acetogenesis/Acidogenesis} \quad (2)$$

$$nCH_3COOH \rightarrow nCH_4 + CO_2 \text{ - Methanogenesis} \quad (3)$$

The production of biogas occurs under the anaerobic digestion process in bio-digesters which transform organic substrate containing carbon into carbon dioxide and methane. Pathogenic organisms are inhibited in growth as a result of the anaerobic environment and prolonged digestion duration [12].

Crop residues and animal manures constitute a large portion of the agricultural wastes which are used in bioconversion for the production of biogas. As a result of the relatively high nitrogen present in cow dung which is animal manure, it possesses a high yield of biogas production. This was made possible because of the pre-fermentation stage the dung passed through in the stomach of the animals and the presence of micro-organisms which usually assist during the bio-digestion process, hence it serves as one of the most suitable substrates for biogas production [13].

Cassava and banana occupy a distinctive position in the food crops being grown in Nigeria [14]. The major economic activity every average Nigerian embarks upon is agriculture, with almost 70% making a living from it. Individuals grow cash crops as well as food crops for personal consumption. Nigeria is the world's largest producer of cassava, harvesting more than 46 million tons of cassava per year [15]. Each ton of fresh cassava root processed generates about 250 to 300 kg of cassava peels accounting for about 8-15 wt.% of the total dry matter of the root. These cassava peels consist of 20-31 wt.% hemicelluloses, 16-42 wt.% cellulose, and 6-8 wt.% lignin. They also contain about 81.9-93.9 wt.% organic matter and 4.1- 6.5 wt.% crude protein [16]. Banana, also being a major food crop in Nigeria generates large quantities of waste from its peels and thus becomes a problem to be reckoned with. Noxious gases such as hydrogen sulphide, ammonia, etc., could lead to dangerous environmental hazards emanating from improper disposal of these wastes.

Many recent studies have focused on biogas production from the anaerobic digestion of banana and cassava wastes across the world [17-23]. Many of these studies have modelled the biogas production process using different kinetic models such as first order model, cone model, and Gompertz model. Nevertheless, the present study was designed to deepen existing knowledge of the efficiency of the biogas production from cassava and banana wastes whilst also determining the scale-up potential of the biogas production process.

2. Experimental

2.1 Feedstock and set-up

The cassava and banana wastes were obtained from a local market in Ibadan, Oyo State, Nigeria. This present study was carried out for 30 consecutive days in an anaerobic digester made from 25

L plastic kegs. Rubber plug and valve were incorporated in the plastic keg for measurement of biogas produced. The digesters were operated at room temperature in a batch system. The produced biogas was measured using the water displacement method earlier reported in previous studies [24, 25]. The solid to liquid ratio maintained in the reactor was 5 kg of solid wastes to 10 L of water. Banana and cassava wastes have been reported to be rich in microorganisms (methane forming archaea) which are useful in the anaerobic conversion process [26, 27]. The study relied on the naturally occurring bacteria in the substrates. Hence, no external inoculum was used in the present study, in consonance with a previous study [28]. The physicochemical parameters (pH, temperature, moisture content, %TS (total solids), and %VS (volatile solids)) of undigested slurry were determined before the digester was sealed completely. pH, temperature, and volume of gas produced were monitored daily for 30 days. Jenway 3510 pH meter was used to measure the daily pH while a thermometer was used to measure the ambient and slurry temperatures. The water displacement method was used to determine the daily biogas volume and the experimental set-up is shown in Figure 1.

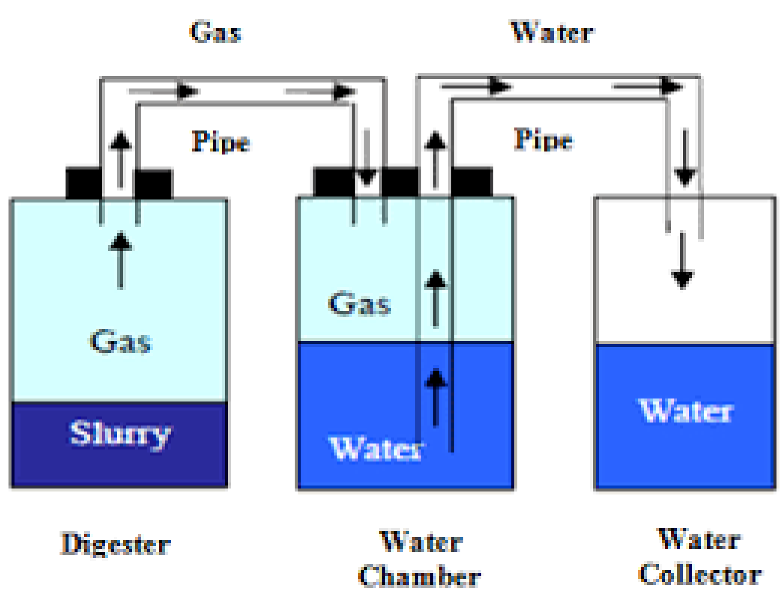

Figure 1. Schematic set-up of water displacement method

The measurement of the total solids was carried out according to the standard method for the examination of water and wastewater described by APHA [29]. 50 g of each of the biomass with pre-weighed porcelain boxes were taken using a weighing balance. The samples were pre-heated at 60°C for 6 h and then at 105°C for 3 h using a hot oven. The final weights or dried sample weights were recorded. The percentage total solids content of the samples was then calculated using the formula:

$$TS\ (\%) = \frac{M_3 - M_1}{M_2 - M_1} \times 100 \qquad (4)$$

Where:

TS = Total solids in percentage (%)

M_1 = Mass in grams of the empty dish

M_2 = Mass in grams of sample plus the empty dish before drying

M_3 = Mass in grams of sample plus empty dish after drying

The moisture content was also determined using the method described by APHA [29], samples were weighed in a dish pre-heated and then dried in an oven at 105°C for about 3 h. The weight of the dried sample plus dish was noted and the percentage moisture content was calculated by Eq. 5:

$$Moisture\ content\ (\%) = \frac{(M_2 - M_1) - (M_3 - M_1)}{M_2 - M_1} \times 100 \qquad (5)$$

Where:

M_1 = Mass in grams of the empty dish

M_2 = Mass in grams of the sample plus empty dish before drying

M_3 = Mass in grams of the sample plus empty dish after drying

The volatile solids content of feed materials was determined according to the standard method which was also stated by APHA [29]. After determining the total solids and moisture content, the oven-dried samples were further dried at 550±50°C temperature for 1 h in a muffle furnace and allowed to ignite completely. The dishes were then transferred to desiccators for final cooling. The weights of the cooled porcelain dishes with ash were taken. The volatile solids content of the samples was calculated using Eq. 6:

$$VS\ (\%) = \frac{(M_3 - M_1) - (M_4 - M_1)}{M_3 - M_1} \times 100 \qquad (6)$$

Where:

VS = The volatile solids in the dry sample (%)

M_4 = The mass of dry ash plus empty dish

(M_3-M_1) = The mass of oven-dried sample in grams

(M_4-M_1) = The mass of dry ash left after igniting the sample in a muffle furnace

2.2 Kinetic modelling of cumulative biogas production

The kinetic modelling of cumulative biogas production was carried out using the Polymath software. The first order and modified Gompertz kinetic models were used to determine the relevant biogas production kinetics useful for scaling up to large scale production [30, 31]. The choice of these models emanated from several reports in the literature that considered them the most suitable models for biogas production [32, 33]. The first order kinetics is shown below:

$$y(t) = A(1 - \exp(-k \times t)) \qquad (7)$$

The modified Gompertz kinetics is shown below:

$$y(t) = A\exp(-\exp[\frac{R.e}{A}(\lambda - \mathrm{t}) + 1]) \quad (8)$$

Where y(t) = The cumulative biogas yield (L/g VS)

A = The biogas production potential (L/g VS)

R = maximum biogas production rate (L/g VS/day)

λ = lag phase (days)

t = cumulative time for biogas production (days)

k = The biogas rate constant (day^{-1})

e = Mathematical constant (2.718282)

3. Results and Discussion

3.1 Feedstock Characterization and Daily Biogas Production

The substrates used in the present study were characterized in terms of moisture content, total solids, volatile solids, and pH. Table 1 shows the details of the preliminary characterization of the substrates used in this present study while Figure 2 shows the daily biogas production for each substrate. The cassava substrate has a moisture content of 85.3%, a total solid of 14.7%, a volatile solid of 92.32%, and a pH of 7. On the other hand, the banana substrate has a moisture content of 84.3%, a total solid of 15.7%, a volatile solid of 96.27%, and a pH of 6.9. The total solids content of cassava substrate in the present study is lower than those reported by Nkodi et al [34] but greater than those reported by Opurum et al [35]. The moisture content of the banana substrate is close to the 83.5% moisture content observed in banana peels used in another study [36]. It is expected that cassava would produce a higher yield of biogas due to their relatively lower total solids content. This is probably because methanogenic bioconversion to biogas is higher at high water content and a corresponding lower total solids content [37, 38]. The volatile solids content exhibited by both cassava and banana substrates were relatively higher than those obtained for poultry waste in a previous study by Opurum et al [35]. The yield and quality of biogas produced are predicated upon the proximate composition of the feedstock [39]. This can be improved by adopting co-digestion of substrates in biogas production [40]. pH is a suitable indicator of the stability of anaerobic digestion systems. At increased pH values higher than 7, there is an upsurge in the ratio of free ammonia to ammonium ion by 5%. The free form of ammonia is relatively more detrimental to methanogens than ammonium ions [41]. The pH value of the cassava and banana substrates is an indication that the substrates are suitable for biogas production under mesophilic conditions [42, 43].

Table 1. Feedstock Characterization

Composition	Cassava waste	Banana waste
Moisture content (%)	85.3	84.3
Total Solid (%)	14.7	15.7
Volatile Solids (%)	92.32	96.27
pH	7	6.9

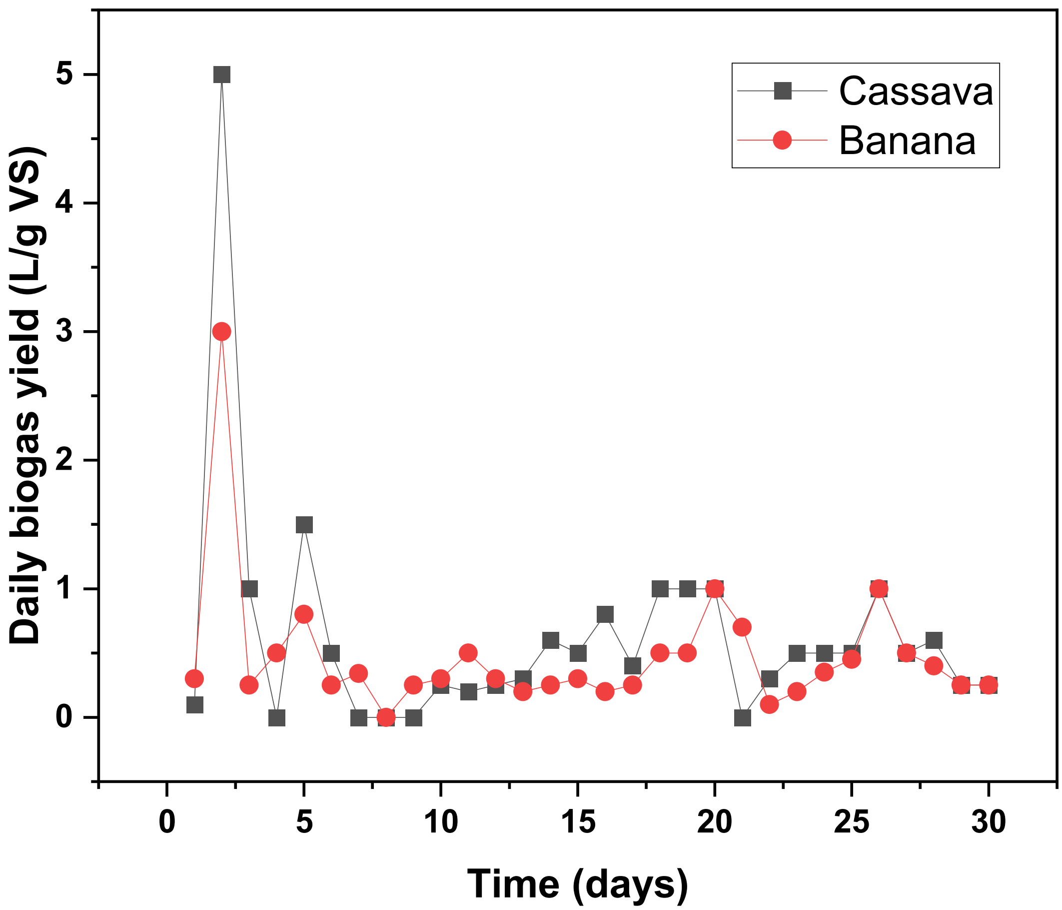

Figure 2. Daily biogas production for the period of 30 days

0.1 L of biogas was observed from the production of biogas from cassava waste on the first day. The low volume of biogas produced on the first day of anaerobic digestion could be ascribed to the low digestibility of plant residues owing to slow hydrolysis rate of lignocellulosic constituents and complex polysaccharides. The slow hydrolysis rate exhibited by the lignin component of plant residues is due to the created protective barrier which prevents the plant materials from degradation [44]. This significantly increased to 5 L on the second day and took a steady decline to 0 L on day

9. It further started to increase on the 10th day up till 1 L on the 20th day. This later declined to 0.25 L on the last day. The rate of biogas production in the batch condition is directly proportional to the specific growth rate of methanogenic bacteria in the bio-digester [13]. After the 9th day, there was a steady significant increase in biogas production because of the high level of microorganisms' growth in the digester. An unsteady declination in the volume of biogas produced from the 20th day to the 30th day (which is the last day for this present study) with a sudden increase of 1 L of biogas was observed at day 26. The fluctuations in biogas production rate during the anaerobic digestion can be attributed to the varying activity of microorganisms [18]. This is uncertain but not uncommon since biogas production studies closer to and beyond 30 days have shown trends of rising and falling in the daily yield of the biogas but it should be noted that sudden rises do not exceed that of the peak production [45]. The yield of biogas observed from that of banana waste took a similar trend to that which was observed in cassava waste, with 0.3 L on the first day and a sudden increase to 3 L on day two (2), which was the highest volume observed during the study for banana wastes.

3.2 Effect of pH on Biogas Production

pH has a direct influence on the digestion process and consequently the biogas production [46]. As shown in Figure 3**,** it can be observed that the pH of the digester containing cassava waste ranged from 5.2-7 while that of banana ranged from 6.4-6.9. The observed pH values were found in the optimal range for anaerobic digestion as reported by several authors [47-49]. Although sensitive to pH fluctuations, the development of methanogenic bacteria is aided within the observed pH range due to volatile acids which are generated during the digestion process [46, 50]. At the initial fermentation time, acid-forming bacteria will produce acids quickly which in turn causes the pH to decline [43]. The decrease in pH after the first few days of digestion is due to the consumption of available organic matter [51]. Budiyono et al [52] posited that the observed increase in pH immediately after the corresponding sharp decrease could be related to the production of NH_4^+ during protein degradation as carbon dioxide and water combine with ammonia which is a base resulting in the formation of ammonium bicarbonate (a natural pH buffer).

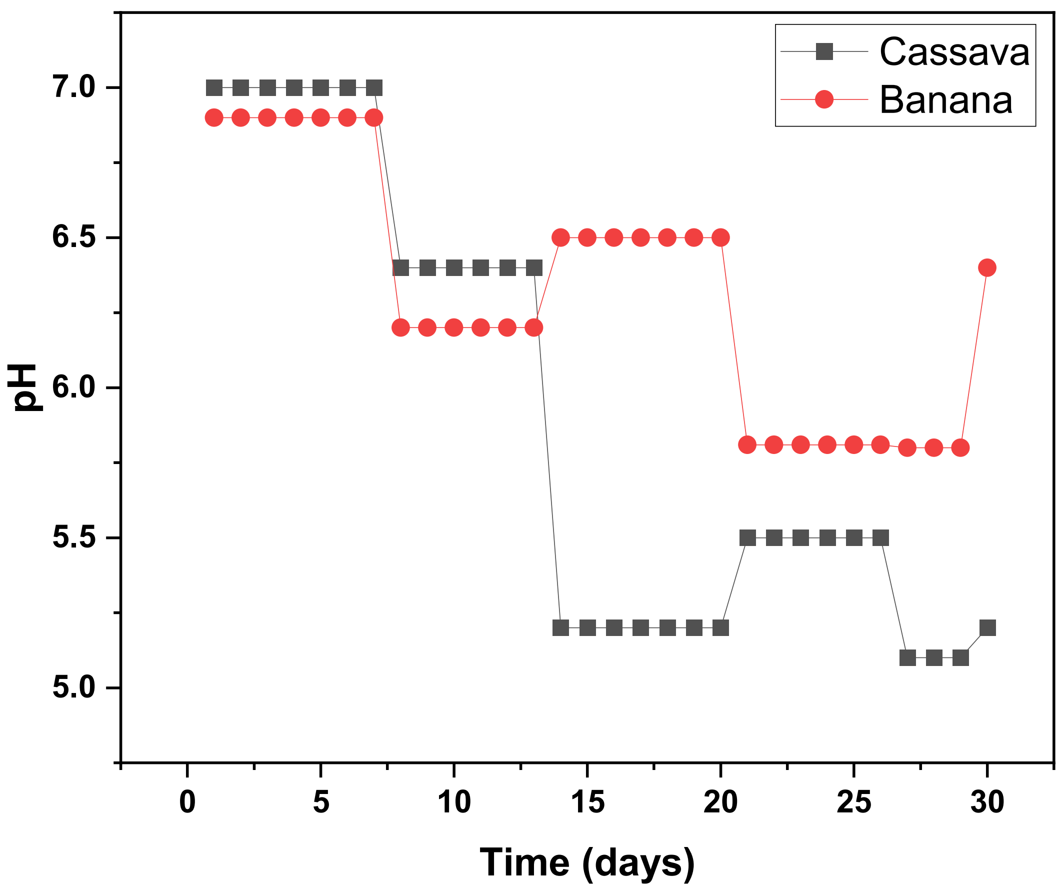

Figure 3. pH variation for the period of 30 days

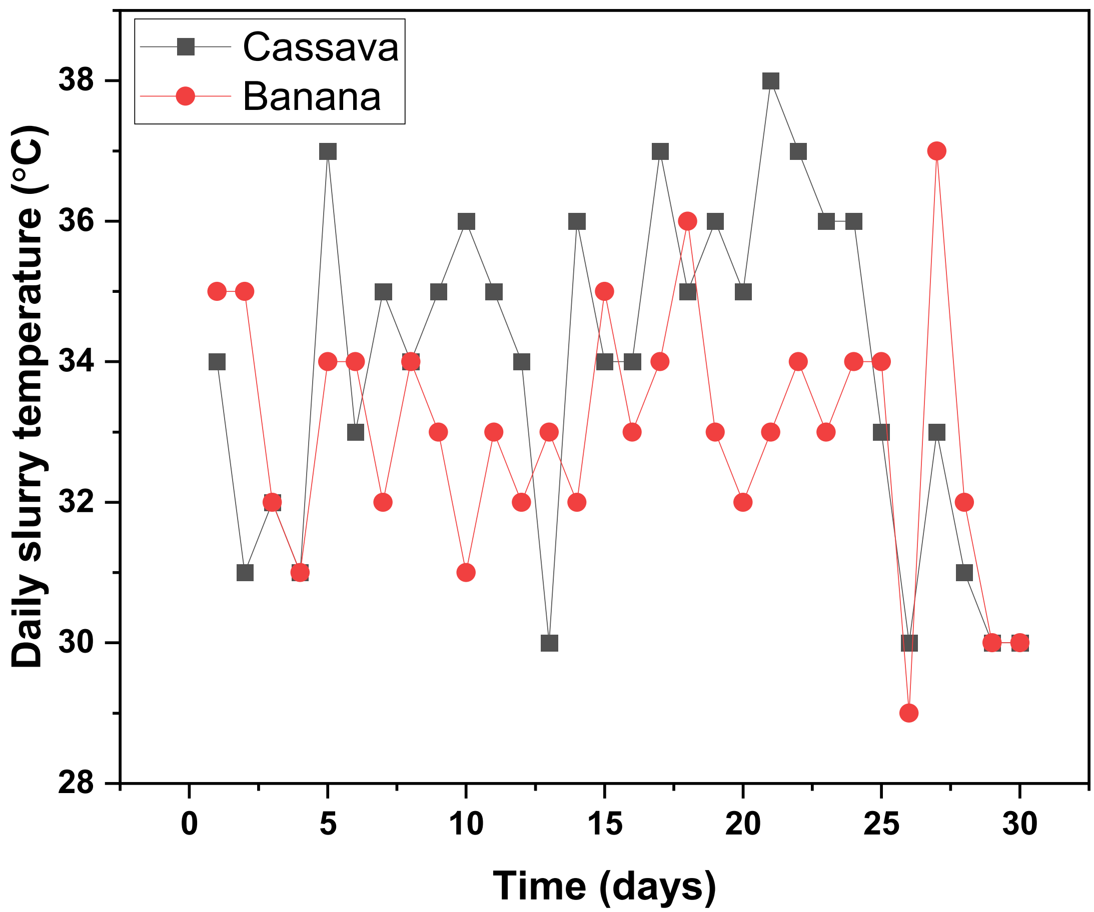

Figure 4. Variation of daily slurry temperature with time of digestion

3.3 Effect of Temperature Variation on Biogas Production

The temperature of the slurries in relation to the volume of biogas obtained is shown in Figure 4. The slurry temperature values were closely monitored in determining the rate of digestion since it is a relevant parameter in the production of biogas using anaerobic digestion. It is important to monitor the slurry temperatures because the external part of the digester surface is directly in contact with the atmosphere which may tend to significantly alter the temperature of the slurries. The average slurry temperatures within the digester observed during this study were 33.93°C for the digestion of cassava wastes and 33ºC for the digestion of banana wastes. It should be noted that the temperature of the slurry of each substrate was within the mesophilic range (24-37ºC) which encourages optimal biogas production [44].

3.4 Kinetic Studies

The kinetic modelling of biogas production from cassava and banana substrates is presented in Table 2. The first-order kinetic model and the modified Gompertz model were used in the kinetic study. The modelling plots of the cumulative biogas production from cassava and banana substrates are shown in Figures 5 and 6 respectively. The first-order kinetic model contains the kinetic constant k, which is a measure of biogas production rate with time. A fast rate of biogas production has been attributed to a more positive value of k [30]. In the present study, cassava has a k value of 0.19 while banana has a k value of 0.03. This is an indication that cassava substrate is more likely to produce biogas faster than the banana substrate.

Table 2. Parameters obtained from the kinetic modelling of biogas production

Kinetic models	Kinetic constants	Cassava	Banana
First order	A (L/gVS)	11.09	21.19
	k	0.19	0.03
	R^2	0.42	0.95
Modified Gompertz	A (L/gVS)	30.54	24.91
	R (L/g/VS/day)	0.56	0.44
	λ (days)	-4.51	-2.73
	R^2	0.94	0.96

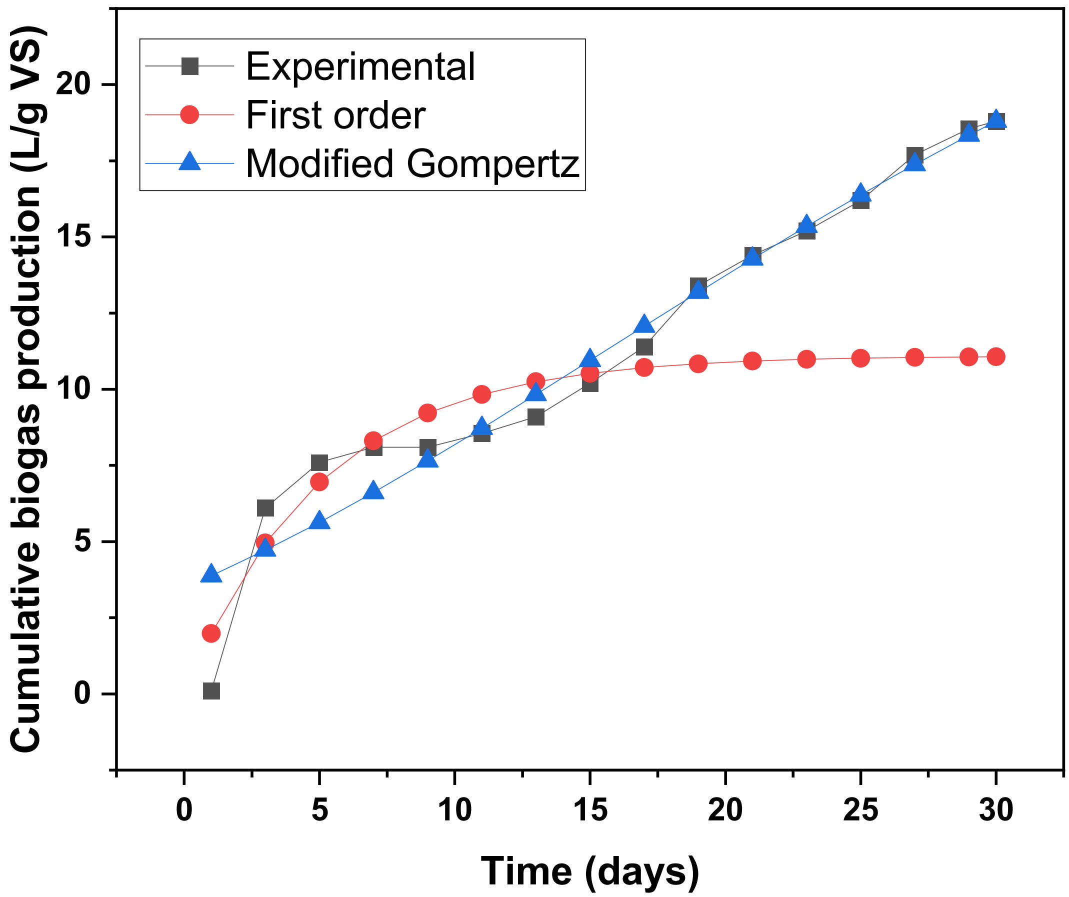

Figure 5. Kinetic model fitting of biogas production from cassava substrate

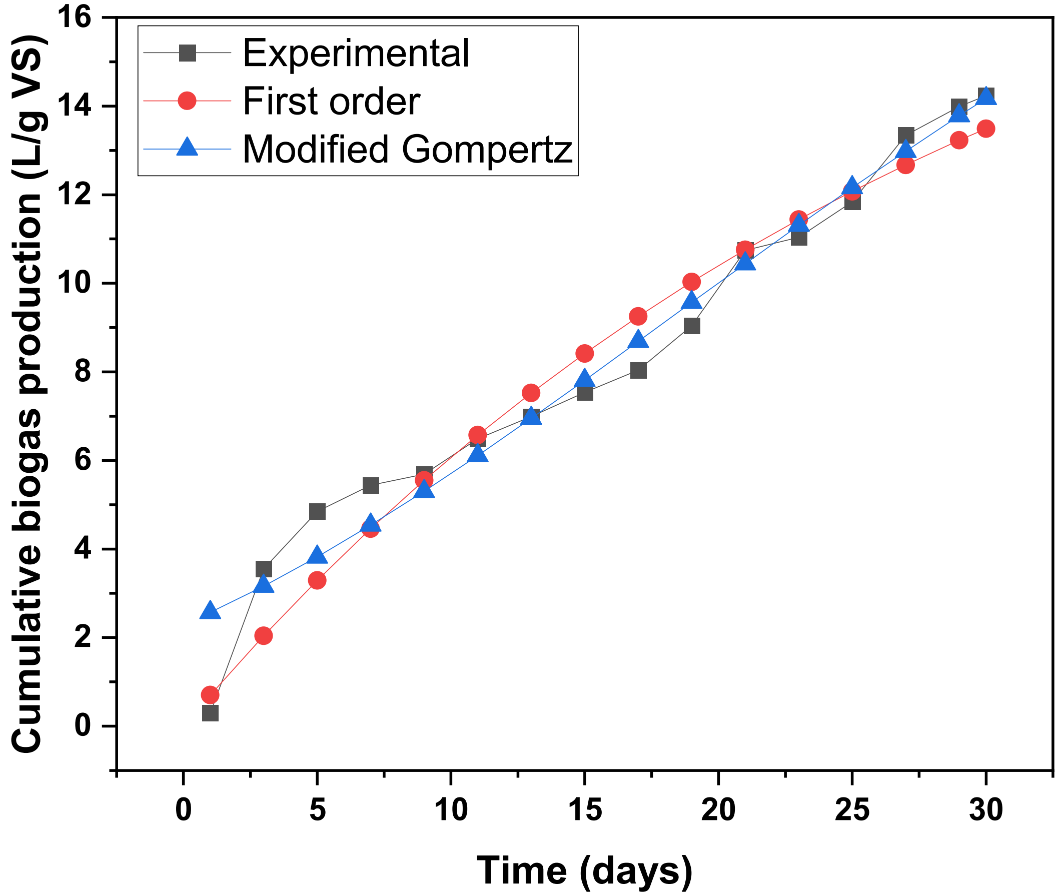

Figure 6. Kinetic model fitting of biogas production from banana substrate

The modified Gompertz kinetic model showed that cassava had the highest cumulative biogas production while that of banana was relatively lower. The kinetic parameters in Table 2 showed that cassava had the highest total biogas production of 30.54 L/gVS at a maximum production rate of 0.56 L/g/VS/day. On the other hand, banana had a total biogas production of 24.91 L/gVS at a maximum production rate of 0.44 L/g/VS/day. Increased maximum production rate of biogas has been reported to result in increased total biogas production [52]. This phenomenon was observed in the kinetic constants of the present study. The relatively lower total biogas production from banana might be an indication of its relative susceptibility to acidification, as opposed to cassava [31]. Similarly, cassava exhibited a shorter lag phase (-4.51 day) compared to banana's lag phase (-2.73). The lag phase is the minimum time required for bacteria to adapt in a bid to produce biogas [25]. Both substrates exhibited a very short and negative lag phase. The negative lag phase signified that the biogas production began from the first day representing suitable conditions for the growth of microorganisms [53, 54]. A negative lag phase has no influence on the fit of the experimental data with the simulated data, rather, it implies that the biogas production potential in day zero is not equal to the initial biogas production potential [33]. However, the relative upsurge in the banana's lag phase might be reflective of the slow acclimatization of microbes to the slurry environment [31]. The observed negative lag phase of the substrates used in the present study is consistent with the reports of previous studies [33, 55-58].

Generally, the modified Gompertz model had R^2 values close to 1, thus indicating a good fit between the experimental data and simulated data. In addition, the root mean square deviation and variance exhibited by the modified Gompertz model were relatively lower than the first-order model, indicating the precision of the former in predicting biogas production. This showed that the modified Gompertz model is a better kinetic model in modelling cumulative biogas production than the first-order kinetic model. This is consistent with the reports of previous findings [25, 59, 60].

4. Conclusion

The present study showed that the anaerobic digestion of cassava and banana substrates is a viable source of biogas production. The results of the study showed that biogas yield varied significantly with pH and slurry temperature. The pH values of the substrates indicated their suitability for biogas production. Nevertheless, cassava substrate exhibited a greater potential for maximum biogas production. The short lag phase of the digestion process indicated that the microbial population adapted swiftly to the slurry environment. The kinetic modelling showed that the modified Gompertz model is a better fit for biogas production compared to the first-order kinetic model. It is recommended that further studies on co-digestion of plant and animal wastes should be carried out to obtain a greater yield of biogas. Further reduction of feedstock size should also be carried out to improve the quality of biogas produced.

Data availability statement

The dataset used in the study will be made available by the corresponding author upon reasonable request

Declarations

Conflict of Interest

The authors declare that there is no conflict of interest

Ethical approval

Not applicable

Consent to participate

Not applicable

Consent for publication

The authors confirm that all authors mutually agree for submitting the manuscript and that the manuscript is the original work of all the authors

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References

[1] Achinas, S., Achinas, V., & Euverink, G. J. W. (2017). A technological overview of biogas production from biowaste. *Engineering*, *3*(3), 299-307.

[2] Hönig, V., Prochazka, P., Obergruber, M., Smutka, L., & Kučerová, V. (2019). Economic and technological analysis of commercial LNG production in the EU. *Energies*, *12*(8), 1565.

[3] Aisien, F. A., Aguye, M. D., & Aisien, E. T. (2010). Blending of ethanol from cassava wastewater with gasoline as a source of automobile fuel. *Electronic Journal of Environmental, Agricultural and Food Chemistry,* 9(8), 445 – 450.

[4] Kwasi – Effah, C. C., Obanor, A. I., & Aisien, F. A. (2015). A Technical approach to balance the use of renewable and non-renewable energy sources. *American Journal of Renewable and Sustainable Energy*, 1(3), 156- 165.

[5] Fraga, L. G., Teixeira, C. F., & Ferreira, E. C. (2019). The potential of renewable energy in Timor-Leste: An assessment for biomass. *Energies*, *12*(8), 1441.

[6] Achinas, S., & Euverink, G. J. W. (2019). Elevated biogas production from the anaerobic co-digestion of farmhouse waste: Insight into the process performance and kinetics. *Waste Management & Research*, *37*(12), 1240-1249.

[7] Igbum, O. G., Eloka-Eboka, A.C., & Adoga, S. (2019). Feasibility study of biogas energy generation from refuse dump in a community – based distribution in Nigeria. *International Journal of Low – Carbon Technologies,* 14(2), 58 – 78.

[8] Buren, A. V. (1979). A Chinese biogas manual. *Intermediate technology publications Ltd,* 11-24.

[9] Mel, M., Ihsan, S. I., & Setyobudi, R. H. (2015). Process improvement of biogas production from anaerobic co-digestion of cow dung and corn husk. *Procedia Chemistry,* 14, 91 – 100.

[10] Bienert, K., Schumacher, B., Rojas Arboleda, M., Billig, E., Shakya, S., Rogstrand, G., ... & Dębowski, M. (2019). Multi-indicator assessment of innovative small-scale biomethane technologies in Europe. *Energies*, *12*(7), 1321.

[11] Igwe, N. J. (2014). Production of biogas from cassava and plantain peels blended with cow dung. *International Journal of Life Sciences Biotechnology and Pharma Research,* 3(4), 201-213.

[12] Eze, J. I., & Agbo K. E. (2010). Studies on the microbial spectrum in anaerobic biomethannization of cow dung in 10m3 fixed dome biogas digester. *International Journal of Physical Sciences,* 5(8), 1331-1337

[13] Ukpai, P. A., & Nnabuchi M. M. (2012). Comparative study of biogas production from cow dung, cow pea and cassava peeling using 45 litres biogas digester. *Advances in Applied Science Research,* 3, 1864-1869.

[14] Wambugu, F., Njuguna, M., Acharya, S. and Mackey, M. (2008). Socio-Economic impact of tissue culture banana (Musa Spp.) in Kenya through the whole value chain approach. International conference on banana and plantain in Africa: Harnessing International Partnerships to Increase impact, 879, 77-86.

[15] IITA. (2013). The IITA Bulletin 1 August 2013 (Special Issue).

[16] Kongkiattikajorn J., & Sornvorawea B. (2011). Comparative study of bioethanol production from cassava peels by monoculture and co-culture of yeast. *Kasetsart Journal (Natural. Science).* 45, 268-274.

[17] Achinas, S., Krooneman, J., & Euverink, G. J. W. (2019). Enhanced biogas production from the anaerobic batch treatment of banana peels. *Engineering*, *5*(5), 970-978.

[18] Soeprijanto, S., Prajitno, D. H., Setiawan, B., Maghfiro, W., & Rohmawati, R. (2021). Biogas production from co-digestion of water hyacinth, banana peel and water spinach wastes using a horizontal anaerobic digester. In *IOP Conference Series: Earth and Environmental Science* (Vol. 649, No. 1, p. 012022).

[19] Barua, V. B., Rathore, V., & Kalamdhad, A. S. (2019). Anaerobic co-digestion of water hyacinth and banana peels with and without thermal pretreatment. *Renewable Energy*, *134*, 103-112.

[20] Rahim, I. R., Lando, A. T., Sari, K., Asriyanti, E., & Ihsan, M. (2019). Feasibility Study of Biogas from Banana Peel Waste and Livestock Manure Mixture as Renewable Energy Source. In *IOP Conference Series: Materials Science and Engineering* (Vol. 676, No. 1, p. 012024).

[21] Peres, S., Monteiro, M. R., Ferreira, M. L., & do Nascimento Junior, A. F. (2019). Anaerobic digestion process for the production of biogas from cassava and sewage treatment plant sludge in Brazil. *BioEnergy Research*, *12*(1), 150-157.

[22] Jaro, R. H., Icalina, M. A. A., Talemporos, R. T., Napiňas, P. M., Manuel, L. G., Cubio, G. M., ... & Arazo, R. O. (2021). Biogas production from waste pulps of cassava (Manihot esculenta Crantz) via anaerobic digestion. *Energy, Ecology and Environment*, *6*(3), 204-212.

[23] Ismail, N., Fauzi, N. F., Salehabadi, A., Latif, S., Awiszus, S., & Müller, J. (2022). A study on biogas production from cassava peel and stem in anaerobic digestion reactor. *International Journal of Environmental Science and Technology*, *19*(3), 1695-1704.

[24] Yusuf, M. O., & Ify, N. L. (2011). The effect of waste paper on the kinetics of biogas yield from the co-digestion of cow dung and water hyacinth. *biomass and bioenergy*, *35*(3), 1345-1351.

[25] Budiyono, I. S., & Sumardiono, S. (2014). Kinetic model of biogas yield production from vinasse at various initial pH: comparison between modified Gompertz model and first order kinetic model. *Research Journal of Applied Sciences, Engineering and Technology*, *7*(13), 2798-2805.

[26] APHA (1995). Standard Methods for the Examination of Water and Wastewater. 19th Edition, American Public Health Association Inc., New York, USA.

[27] Kafle, G. K., Kim, S. H., & Sung, K. I. (2013). Ensiling of fish industry waste for biogas production: a lab scale evaluation of biochemical methane potential (BMP) and kinetics. *Bioresource technology*, *127*, 326-336.

[28] Alfa, M. I., Owamah, H. I., Onokwai, A. O., Gopikumar, S., Oyebisi, S. O., Kumar, S. S., ... & Ilabor, S. C. (2020). Evaluation of biogas yield and kinetics from the anaerobic co-digestion of cow dung and horse dung: a strategy for sustainable management of livestock manure. *Energy, Ecology and Environment*, 1-10.

[29] Tsapekos, P., Kougias, P. G., Vasileiou, S. A., Treu, L., Campanaro, S., Lyberatos, G., & Angelidaki, I. (2017). Bioaugmentation with hydrolytic microbes to improve the anaerobic biodegradability of lignocellulosic agricultural residues. *Bioresource technology*, *234*, 350-359.

[30] Özön, E., & Erdinçler, A. (2019). Effects of microwave, H2O2/MW and H2O2/heat pre-treatments on the methane production from wastewater sludges: experimental and modeling approach. *Environmental Science and Pollution Research*, *26*(35), 35411-35421.

[31] Nkodi, T. M., Taba, K. M., Kayembe, S., Mulaji, C., & Mihigo, S. (2016). Biogas production by co-digestion of cassava peels with urea. *International Journal of Scientific Engineering and Technology*, *5*(3), 139-141.

[32] Opurum, C. C., Nwachukwu, I. N., Christopher, E., & Nwaneri, C. B. (2021). Predicting the rate of biogas production from the anaerobic digestion of blends of cassava (Manihot esculenta) peels with poultry manure. *Issues in Biological Sciences and Pharmaceutical Research*. 9(2), 38-47

[33] Nathoa, C., Sirisukpoca, U., & Pisutpaisal, N. (2014). Production of hydrogen and methane from banana peel by two phase anaerobic fermentation. *Energy Procedia*, *50*, 702-710.

[34] Liotta, F., d'Antonio, G., Esposito, G., Fabbricino, M., Frunzo, L., van Hullebusch, E. D., ... & Pirozzi, F. (2014). Effect of moisture on disintegration kinetics during anaerobic digestion of complex organic substrates. *Waste Management & Research*, *32*(1), 40-48.

[35] Le Hyaric, R., Benbelkacem, H., Bollon, J., Bayard, R., Escudié, R., & Buffière, P. (2012). Influence of moisture content on the specific methanogenic activity of dry mesophilic municipal solid waste digestate. *Journal of Chemical Technology & Biotechnology*, *87*(7), 1032-1035.

[36] Nsair, A., Onen Cinar, S., Alassali, A., Abu Qdais, H., & Kuchta, K. (2020). Operational parameters of biogas plants: A review and evaluation study. *Energies*, *13*(15), 3761.

[37] Tetteh, E., Amano, K. O. A., Asante-Sackey, D., & Armah, E. (2018). Response surface optimisation of biogas potential in co-digestion of miscanthus fuscus and cow dung. *International Journal of Technology*, *9*(5), 944-954.

[38] Domingues, P. S., Pala, H., & Oliveira, N. S. (2021). Anaerobic Mesophilic Co-digestion of Swine Slurry and Hidrolyzate in Batch Reactors: A Case Study. *Frontiers in Environmental Science*, *9*, 203. https://doi.org/10.3389/fenvs.2021.684074

[39] Appels, L., Baeyens, J., Degrève, J., & Dewil, R. (2008). Principles and potential of the anaerobic digestion of waste-activated sludge. *Progress in energy and combustion science*, *34*(6), 755-781.

[40] Budiyono, Arindra D. P., Listi A., Hashfi H. A., & Siswo S. (2018). Study of Biogas Production from cassava industrial waste by anaerobic process. *MATEC Web of Conferences* 156, 03052.

[41] Latinwo, G. K., & Agarry, S. E. (2015). Modelling the kinetics of biogas production from mesophilic anaerobic co-digestion of cow dung with plantain peels. *International Journal of Renewable Energy Development*, *4*(1), 55.

[42] Salam, B., Biswas S., & Rabbi M. S. (2015). Biogas from mesophilic anaerobic digestion of cow dung using silica gel as catalyst. *Procedia Engineering.* 105, 652-657.

[43] Cremonez, P. A., Sampaio, S. C., Teleken, J. G., Meier, T. W., Frigo, E. P., de Rossi, E., ... & Rosa, D. M. (2020). Effect of substrate concentrations on methane and hydrogen biogas production by anaerobic digestion of a cassava starch-based polymer. *Industrial crops and products*, *151*, 112471.

[44] Syaichurrozi, I., Suhirman, S., & Hidayat, T. (2018). Effect of initial pH on anaerobic co-digestion of Salvinia molesta and rice straw for biogas production and kinetics. *Biocatalysis and agricultural biotechnology*, *16*, 594-603.

[45] Mao, C., Feng, Y., Wang, X., & Ren, G. (2015). Review on research achievements of biogas from anaerobic digestion. *Renewable and sustainable energy reviews*, *45*, 540-555.

[46] Zhai, N., Zhang, T., Yin, D., Yang, G., Wang, X., Ren, G., & Feng, Y. (2015). Effect of initial pH on anaerobic co-digestion of kitchen waste and cow manure. *Waste management*, *38*, 126-131.

[47] Zhou, J., Zhang, R., Liu, F., Yong, X., Wu, X., Zheng, T., ... & Jia, H. (2016). Biogas production and microbial community shift through neutral pH control during the anaerobic digestion of pig manure. *Bioresource technology*, *217*, 44-49.

[48] Cremonez, P. A., Sampaio, S. C., Teleken, J. G., Meier, T. W., Dieter, J., & Teleken, J. (2019). Influence of inoculum to substrate ratio on the anaerobic digestion of a cassava starch polymer. *Industrial Crops and Products*, *141*, 111709.

[49] Budiyono, I. N., Widiasa, J., & Johari, S. (2010). The kinetic of biogas production rate from cattle manure in batch mode. *International Journal of Chemical and Molecular Engineering*, *4*(1), 75-80.

[50] Feng, L., Li, Y., Chen, C., Liu, X., Xiao, X., Ma, X., ... & Liu, G. (2013). Biochemical methane potential (BMP) of vinegar residue and the influence of feed to inoculum ratios on biogas production. *Bioresources*, *8*(2), 2487-2498.

[51] Khadka, A., Parajuli, A., Dangol, S., Thapa, B., Sapkota, L., Carmona-Martínez, A. A., & Ghimire, A. (2022). Effect of the substrate to inoculum ratios on the kinetics of biogas production during the mesophilic anaerobic digestion of food waste. *Energies*, *15*(3), 834.

[52] Zhang, H., Ning, Z., Khalid, H., Zhang, R., Liu, G., & Chen, C. (2018). Enhancement of methane production from Cotton Stalk using different pretreatment techniques. *Scientific reports*, *8*(1), 1-9.

[53] Li, L., Chen, C., Zhang, R., He, Y., Wang, W., & Liu, G. (2015). Pretreatment of corn stover for methane production with the combination of potassium hydroxide and calcium hydroxide. *Energy & Fuels*, *29*(9), 5841-5846.

[54] Syaichurrozi, I., Villta, P. K., Nabilah, N., & Rusdi, R. (2019). Effect of sulfuric acid pretreatment on biogas production from Salvinia molesta. *Journal of Environmental Chemical Engineering*, *7*(1), 102857.

[55] Syaichurrozi, I., Basyir, M. F., Farraz, R. M., & Rusdi, R. (2020). A preliminary study: Effect of initial pH and Saccharomyces cerevisiae addition on biogas production from acid-pretreated Salvinia molesta and kinetics. *Energy*, *207*, 118226.

[56] Kumar, V., Singh, J., Pathak, V. V., Ahmad, S., & Kothari, R. (2017). Experimental and kinetics study for phytoremediation of sugar mill effluent using water lettuce (Pistia stratiotes L.) and its end use for biogas production. *3 Biotech*, *7*(5), 1-10.

[57] Kumar, V., Singh, J., Nadeem, M., Kumar, P., & Pathak, V. V. (2020). Experimental and kinetics studies for biogas production using water hyacinth (Eichhornia crassipes [Mart.] Solms) and sugar mill effluent. *Waste and Biomass Valorization*, *11*(1), 109-119.