EASR

Engineering and Applied Science Research

https://www.tci-thaijo.org/index.php/easr/index

Published by the Faculty of Engineering, Khon Kaen University, Thailand

Development of a computational model for the estimation of biogas production from putrescible wastes

Ogundola A.C.*[1, 2]), Orhadahwe T.A.[1, 3]), Ojetoye A.O.[4]), Emmanuel C.O.[2]) and Ogundola O.C.[5])

[1])Department of Mechanical Engineering, University of Ibadan, Nigeria
[2])Advanced Aerospace Engines Laboratory, Oka-Akoko, Nigeria
[3])Department of Mechanical Engineering, Ajayi Crowther University, Oyo, Nigeria
[4])Department of Mechanical Engineering, Adeleke University Ede, Nigeria
[5])Department of Chemistry, University of Ibadan, Nigeria

Received 23 September 2023
Revised 23 November 2023
Accepted 6 December 2023

Abstract

The use of putrescible wastes as a feed source for biogas production has been a research subject. The study aims to develop a simple computer model for estimating the volume of biogas produced from putrescible wastes. The predictive model was developed to predict the volume of biogas produced based on three parameters, the mass of waste used, the anaerobic processing time, and the percentage of residue accumulation in the reactor. The biogas estimator application was developed using the 2017 edition of Microsoft's Visual Studio .Net software developer's kit (SDK). The simple model does not require rigorous mathematical computations as the process parameters can readily be imputed in the simple data fields created. The model can operate in both batch and continuous modes. The result from both the batch and continuous biodegradation processes of 1.0 kg of putrescible waste per day in a biodigester using the Biogas Estimator model provided certain significant outputs. In the case of the batch process, a 1.0 kg mass of biodegradable putrescible waste yielded an average biogas production volume of about 0.236 m^3 per day, while the resulting volume from the continuous process, 1.0 kg mass of biodegradable putrescible waste produced on average an estimated biogas volume of about 0.164 m^3 per day. The values obtained are comparable to those of similar studies thereby validating the efficacy of the model. The model has been validated and is considered suitable for the estimation of biogas production from putrescible wastes.

Keywords: Renewable energy, Biodigester, Biogas estimator, Putrescible waste

1. Introduction

Biogas plants have a huge potential to produce clean fuel from unhygienic, wet organic waste [1]. These plants can be used in rural and peri-urban areas where access to clean, and affordable energy are limited. There is also a huge potential for biogas plants in towns and cities, where waste disposal and sanitation are becoming increasingly challenging due to persistent urban migration. Interest is also growing in the use of larger biogas plants as alternative sources for electricity generation and cooking gas supply [2, 3]. Biogas development brings about social benefits in many respects. The increase in organic manure can result in using less chemical fertilizer, improving soil, and increasing agricultural production. Environmental improvement in the rural area reduces illness and improves people's health. Besides, in regions where biogas is used to generate electricity, cultural, recreation, and spare time study conditions can also be improved [4, 5]. Furthermore, the need for alternative sources of fuel energy has become obvious, especially because of the soaring prices of petrol and the other grades of commercial energy from non-renewable resources, such as petroleum, coal, and natural gas, and the accompanying environmental implications of mining such products [6, 7]. Currently, about 88% of world energy demand is met by apparently economically-beneficial fossil fuels while the environmental cost associated with their widespread applications is mostly ignored [8, 9]. Biogas production involves anaerobic digestion; a biological process that converts organic material to methane and carbon dioxide by the activities of microorganisms in the absence of oxygen [4, 10]. Setting up a biogas plant is capital-intensive. Optimizing the process parameters during the design stage is one measure to reduce the cost of biogas production and ensure the high performance of the biogas plant. To this end, several researchers have developed various mathematical and computer models to predict biogas yield. Dahunsi [11] developed single and multiple regression models to predict methane yield for pretreated lignocellulose biogas production systems. Dandikas et al. [12] developed a model to predict biogas production from energy crops in a grassland. There are also numerous studies on the use of machine learning models and other computer-based techniques in predicting methane yield from biogas plants [13-15]. During biogas production, not all of the substrates are converted to methane. There is usually an accumulation of undigested solid matter in the digester which may impact the volume of gas produced. The amount of mass accumulation depends on the quality of the feedstock (substrate) used [16]. Putrescible wastes are one of those substrates with a high amount of non-biodegradable matter that accumulates in the digester [17]. In this study, a simple computational model was developed to predict the volume of gas produced from putrescible wastes at different levels of mass accumulation.

*Corresponding author.
Email address: ogundolacyril@gmail.com
doi: 10.14456/easr.2024.11

2. Materials and methods

2.1 Process reevaluation

The material focus of the study is putrescible waste which contains a high volume of volatile matter [18]. Biodegradation of the feedstock occurs in two reaction stages or processes: liquefaction and gasification as shown in Figure 1 [19].

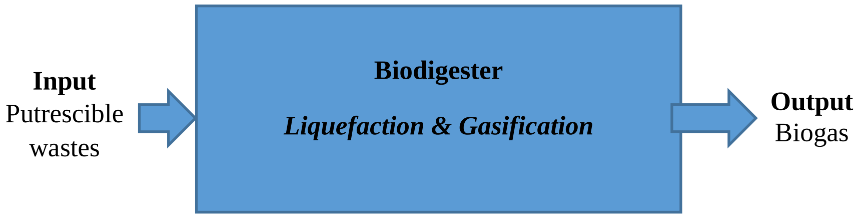

Figure 1 Process representation

Liquefaction is the first stage of organic waste digestion by acid-producing *(acetogenic)* bacteria into simple compounds of low molecular weight through the process of hyd*rolysis. Gasification* is the second stage in which methane-forming bacteria (called *methanogens)* use volatile acids produced in the first stage to form about 55-65% methane (the vital constituent of biogas) [19]. The overall methane (CH_4) production process for organics in the volatile solid portion can be represented with the chemical equation in Equation (1) [20]:

$$C_aH_bO_cN_d + nH_2O \rightarrow xCH_4 + yCO_2 + wNH_3 + zC_5H_7O_2N + energy \tag{1}$$

The reaction kinetics of this process as regards the change in mass concentration of organic components in the different phases of this reaction mechanism was accounted for by Zacharof and Butler [21] as shown in Equations (2 -5).

$$Solid\ mass: \frac{dm_{i(s)}}{dt} = -k_h m_{i(s)} \tag{2}$$

$$Methanogenic\ mass: \frac{dm_{i(me)}}{dt} = A_m t e^{[-k_m t]} \tag{3}$$

$$Acetogenic\ mass: \frac{dm_{i(ac)}}{dt} = A_a t e^{[-k_a t]} \tag{4}$$

$$Hygrolyzed\ mass: \frac{dm_{i(aq)}}{dt} = k_h m_{i(s)} - A_a t e^{[-k_a t]} \tag{5}$$

Where m_i is the mass of component *if*, and the subscripts *s, aq, ac* and Me denote solid, aqueous (hydrolyzed), acetogenic and methanogenic mass respectively. In the rate equations subscripts *h, a* and *m* denote the rate constant for hydrolysis, acetogenesis and methanogenesis respectively. In order words, the total mass concentration C of organic substrate (or putrescible waste) at the start of the process is given in Equation (6)

$$|C| = \left|\begin{matrix} Solid \\ mass \end{matrix}\right| + \left|\begin{matrix} Methanogenic \\ mass \end{matrix}\right| + \left|\begin{matrix} Acetogenic \\ mass \end{matrix}\right| + \left|\begin{matrix} Hydrolyzed \\ mass \end{matrix}\right| \tag{6}$$

Thus the change in mass concentration becomes

$$\frac{dc}{dt} = \frac{dm_{i(s)}}{dt} + \frac{dm_{i(Me)}}{dt} + \frac{dm_{i(ac)}}{dt} + \frac{dm_{i(aq)}}{dt} \tag{7}$$

This, according to Zacharof and Butler [21], can be simplified further by integrating the growth decay rate function in order to obtain the mass balance for the process of biochemical transformation

2.2 Parameters identification

The following parameters have been considerably accepted to influence the rate of production of biogas from biological organic waste fractions in a biodigester [22]:

(1) Mass balance for each biochemical transformation
(2) Overall mass (solid, methanogenic, acetogenic, and hydrolyzed of the biodigester's content
(3) Physical/environmental factors such as temperature, moisture pressure, pH/ alkalinity, and nutrient availability
(4) Substrate concentration or amount of volatile solids (biodegradable organics)
(5) Rate of reactions with respect to biodegradation, enzyme catalysis, and microorganism growth/decay, and for a model to successfully represent the overall process concept of this gas production, a significant consideration needs to be accorded to these factors or parameters since they inevitably contribute to the overall rate for biogas production.

Key model parameters such as moisture content, total solids and volatile solids were obtained for putrescible wastes collected from Ibadan city in Nigeria using standard methods reported in Safar et al. [23].

2.3 Mathematical model formulation

Empirically, for the biodegradation process, which is synonymous to a biochemical reaction in a closed system at equilibrium, with all conditions being equal, the amount of waste digested is proportional to the volume of gas generated [24]. Therefore, under steady-state conditions, this can be represented mathematically as:

$V_G \ \alpha \ M_W$ for the entire process time

Thus,

$$V_G = -R^* M_W \quad (8)$$

Where;
V_G = Volume of the gas generated [m^3 /day or litre/day
R = Rate coefficient for biogas production [per Kg Day]
M_w = Mass of waste digested [Kg]

Since this process occurs over a period of time, it follows that a change in the mass of waste digested would be proportionate to a significant change in the volume of gas produced. Thus,

$$\frac{dV_G}{dt} = -R\frac{dM_w}{dt} \quad (9)$$

Integrating this process changes over a start time t_0 and end time t_e we have

$$\int_0^e \frac{dV_G}{dt} = -R\int_0^e \frac{dM_W}{dt} \quad (10)$$

$$V_{te} - V_{t0} = -R(Mw_{te} - Mw_{t0}) \quad (11)$$

But at the start of the process, no significant amount of gas can be attributed. Thus,

$$V_{t0} = 0m^3 \quad (12)$$

And $V_{te} = -R(Mw_{te} - Mw_{t0})$ or $V_G = -R\Delta M_w$ (13)

It has been estimated that 1.0 m^3 of methane is approximately 480 litres of methane at standard temperature and pressure (s.t.p) in SI units [20]. So based on this conversion factor, the volume of gas generated during the biodegradation of putrescible waste can be represented as in Equation (14) with its unit in cubic meters per day (m^3/ day).

$$V_G = -\Delta M_w e^{-at} \quad (14)$$

The negative sign indicates the reverse process of change between the volumes of gas generated and the mass of putrescible waste digested during the process. Also, the microbial growth/death processes are assumed to *occur* naturally.

2.4 Software model development

To simplify the application of the biogas estimate model developed in this research, especially for the non-mathematically inclined user, a Windows-based computer program was developed. The biogas estimator application (Figure 2) was developed using the 2017 edition of Microsoft's Visual Studio .Net software developer's kit (SDK). The Windows-based application has a flexible interactive user interface. It is suitable for personal computers (PC) with any version of Microsoft Windows.

2.4.1 Working process

The operation of the program is relatively simple. First, with respect to the users' interface, the user is required to select the preferred biodegradation process (Batch or Continuous). Next, the user is required to input numeric values onto each highlighted parameter space before clicking the estimate button, which will then utilize the generated mathematical model to estimate the approximately expected biogas volume in litres per day. It requires only minimal data entry for its estimates. As shown in Figure 2, the user is provided with two process options: Batch and Continuous. There are also dropdown boxes for selecting the Process time and Percentage accumulation in the biodigester.

The user is also required to input the startup mass of the respective putrescible waste into a text input box before clicking on the Estimate button to process the model-based estimates. A typical example is shown in Figure 3 for the following parameters:

- *Process type* = Batch
- *Process time* = 10 days
- *Mass of startup waste* = 5 Kg
- *Mass accumulation* = 15% residue

For this example, the gas volume estimated is 11.125m^3/day. To further validate the application, the volume of gas produced was estimated at 1%, 5%, and 10% mass accumulation at various processing times and starting masses for the batch process, while for the continuous process, the starting mass was fixed at 1 kg while the mass accumulation was varied between 0 and 50%. The volume of biogas produced was estimated based on the proximate analysis of putrescible wastes obtained from Ibadan city as shown in Table 1 [25, 26].

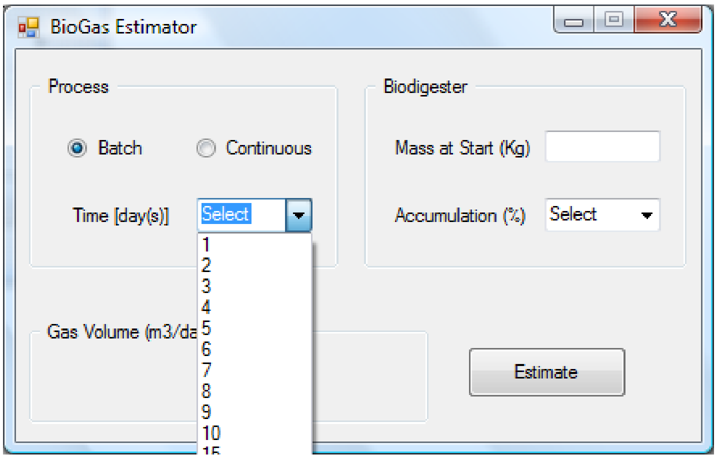

Figure 2 Flexible users' interface showing drop down functionality

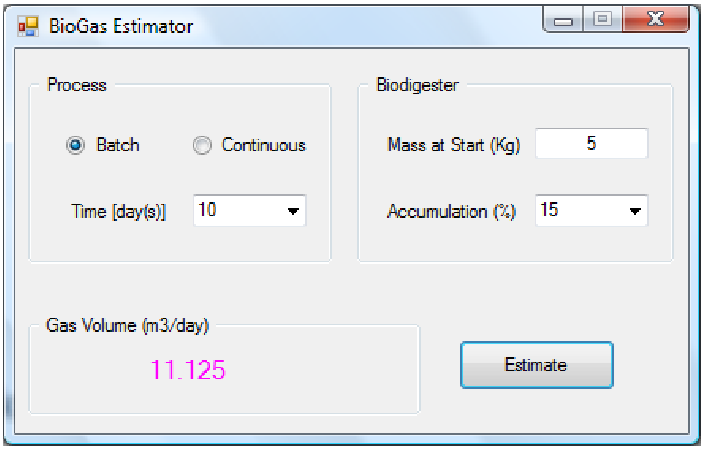

Figure 3 Sample estimate

2.4.2 Key assumptions

The following assumptions were made for optimal operation of the model

1. The moisture content of the putrescible wastes is within 75.1±10%
2. The digester operates at mesophilic temperature range of 35-40°C
3. The pH value of the putrescible wastes is within 6.5 – 7.3
4. Sulfides and other toxic substances are present in negligible amounts and do not affect the system output.

3. Results and discussion

3.1 Characteristics of model putrescible waste

The characteristics of the putrescible waste which formed the baseline for the development of the model is presented in Table 1. Table 1 also showed the comparison of the values obtained for the study's putrescible wastes and those obtained in other studies. It is observed that the values obtained are similar to those obtained by Safar et al. [23], and Safar et al. [27]. Furthermore, the moisture content of the putrescible waste is comparable to the average moisture content obtained in the study by Nwoke et al. [28]. This further validates the assumptions of this study.

Table 1 Characteristic of real-world putrescible wastes

Parameters	This study	Safar et al. [23]	Safar et al. [27]
Moisture content (%)	75.15	71.09	75.02
Total solids (TS)	24.86	28.91	24.98
Volatile solids (VS) (% of TS)	86.05	88.83	82.43
Carbon (C) (% of TS)	39.27	45.72	35.56
Hydrogen (% of TS)	7.09	7.83	6.43
Sulfide (% of TS)	0.26	0.3	0.18
Oxygen (% of TS)	41.22	31.96	48.49
Nitrogen (% of TS)	0.85	1.37	
C/N (% of TS)	26.75	33.44	23.24
Lignin content (% of VS)	8.15	10.83	6.18
pH	7.20		7.30

3.2 Batch process

The results generated using the biogas application are presented as follows for residue or accumulation of 1, 5 and 10 percent at various process times for different startup masses of waste respectively. Figure 4 shows the results for 1% mass accumulation. At a processing time of 1 day, and 1 kg of putrescible waste, 0.247 m^3/day of biogas was produced. The volume of biogas produced increased with the increase in startup mass of putrescible waste with 20kg initial startup mass yielding 4.95 m^3/day. A similar trend is observed with other processing times. However, for the same startup mass, the volume of biogas production increased with process time. Taking the 1kg startup mass, the volume of biogas increased from 0.247 m^3/day (t = 1 day) to 6.187 m^3/day (t = 25 days).

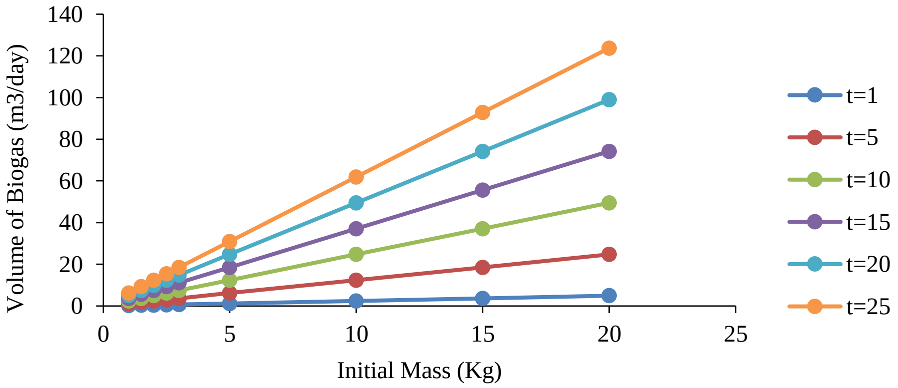

Figure 4 Biogas production at 1% mass accumulation

Similarly, Figure 5 shows the volume of biogas production at 5% residue accumulation. The volume of biogas production increased from 0.247 m^3/day at 1kg startup mass and 1 day processing time to 118.75 m^3/day at 20kg initial mass and 25 days processing time. The volume of gas produced increased with an increase in processing time and starting mass of putrescible waste.

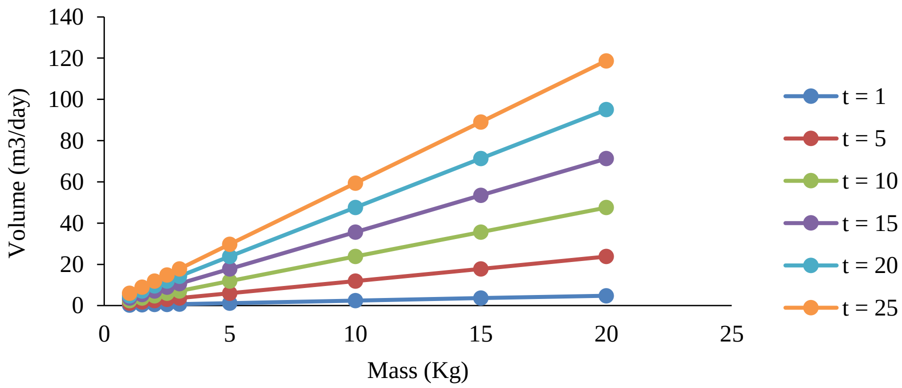

Figure 5 Biogas production at 5% mass accumulation

Figure 6 shows the volume of biogas produced at different processing times and starting masses when there is 10% mass accumulation in the digester. The volume of gas produced varied from 0.247 m^3/day (t=1 day, starting mass of 1 kg) to 112.5 m^3/day (t=25 days, starting mass of 20 kg). The results also depicted that the volume of biogas produced is directly proportional to the amount of substrate and processing time [29, 30].

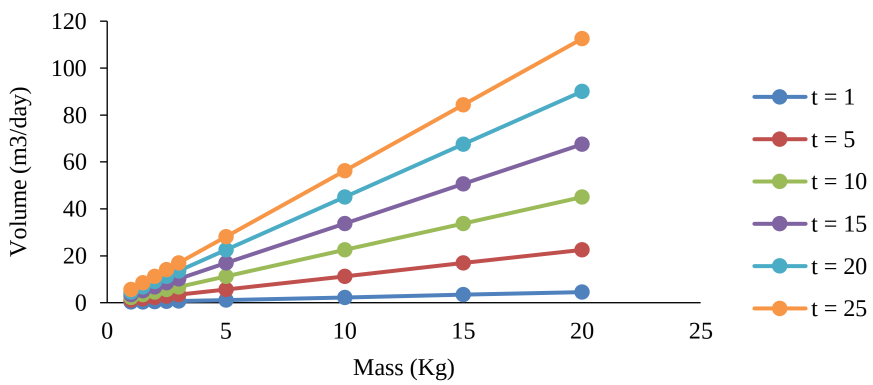

Figure 6 Biogas production at 10% mass accumulation

The results from the batch process shows that for 1.0 Kg mass of biodegradable putrescible waste gave yields of 0.247, 0.237, and 0.225 m3 of biogas per day at the 1, 5, and 10 percent accumulation rates respectively. Thus, in other words, an average biogas production volume of about 0.236 m^3/ day was estimated. Figure 7 establishes the effect of the volume of residue on biogas production by comparing the outputs at 1%, 5%, and 10% mass accumulation in the digester.

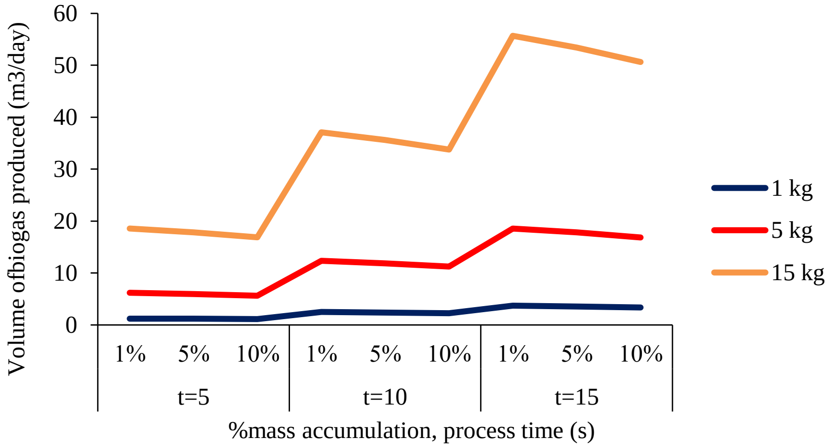

Figure 7 Effect of % mass accumulation on biogas production

3.3 Continuous process

To validate the continuous process of the mathematical model, a simulation approach was adopted in which the start mass of the process was kept constant at 1.0 kg while the accumulation (or end mass in this case) was varied using a random number generated between 0 and 50% of the start mass, that is $0 \leq M_e \leq 0.5M_0$. The result presented in Figure 8 reveals that the minimum daily production of biogas was recorded at the processing time of 1 day (t = 1), while the maximum values of daily gas production were recorded at 25 days of process time (t = 25). This shows that the volume of biogas produced varies directly with the processing time (duration of anaerobic digestion). Unlike the batch process, the volume of biogas produced in the continuous process fluctuates with an increase in mass accumulation. For a processing time of 25 days for instance, the value increased from 0 m^3/day at 0 kg mass accumulation to 6.14 m^3/day at 0.05 kg mass accumulation. It then decreased to 3.217 m^3/day at 0.096 kg mass accumulation and further increased to 5.651 m^3/day at 0.212 kg. This trend continued up to the set limit of 0.5 kg mass accumulation. However, the maximum volume of biogas production was 6.25 m^3/day at 0.5 kg mass accumulation. Similar trends were observed at lower processing times.

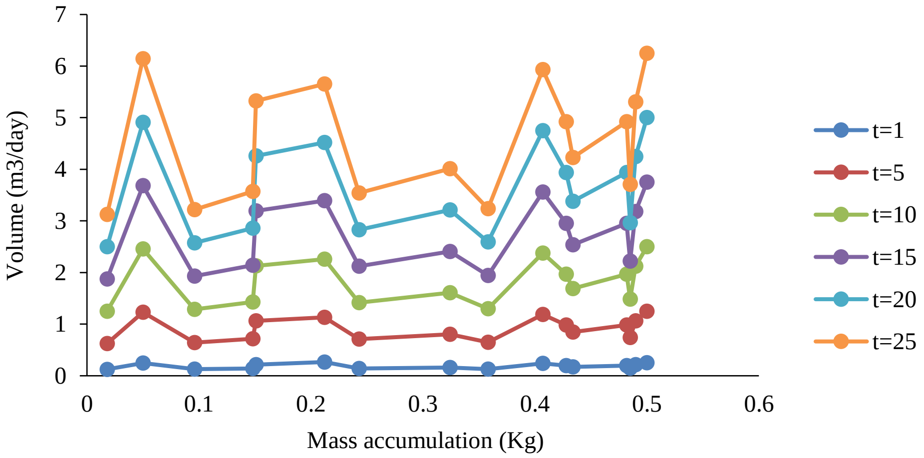

Figure 8 Biogas production for the continuous process

4. Discussion

The findings of the study showed the volume of biogas produced per day decreases with an increase in mass accumulation irrespective of the starting mass. This result is in line with the findings of Feng et al. [31] who posited that the accumulation of volatile fatty acids lowers biogas yield. The percentage mass accumulation is a result of several processing parameters such as environmental factor (pH, temperature), moisture content of feedstock, digester design, and choice of inoculum. This has necessitated researchers to develop several methods such as the pretreatment of substrates and special design of digesters to maximize biogas yields [32, 33].

The results of the continuous process indicate that 0.05 kg mass accumulation is sufficient to produce a considerable amount of biogas. This is preferred, as it will reduce the maintenance cost of the reactor [34]. The volume of gas produced is similar to those of other studies on putrescible wastes [35-37]. This shows that the model is suitable for the prediction of biogas production from municipal/putrescible wastes.

5. Conclusion

A computer-based model for the estimation of biogas produced from putrescible waste was developed based on three basic process parameters, namely, the gas volume, mass of waste used and its residue, and the process timing giving a simplified model of time-dependent anaerobic waste degradation. Therefore, certain specific assumptions were made for the successful testing and validation of the model while using the program. These assumptions were necessary for the values utilized for the testing process. By this approach no rigorous computations are required in achieving the process results from end-users. Hence, the model structure is not only simplified, but also targeted towards improved end-user functionality.

6. Reference

[1] Alayi R, Shamel A, Kasaeian A, Harasii H, Topchlar MA. The role of biogas in sustainable development aspects of environmental, security, and economic. J Chem Pharm Res. 2016;8(4):112-8.

[2] Hafeez S, Al-Salem SM, Manos G, Constantinou A. Fuel production using membrane reactors: a review. Environ Chem Lett. 2020;18:1477-90.

[3] Wang B, Mi Z, Nistor I, Yuan XC. How does hydrogen-based renewable energy change with economic development? Empirical evidence from 32 countries. Int J Hydrog Energy. 2018;43(25):11629-38.

[4] Fedailaine M, Moussi K, Khitous M, Abada S, Saber M, Tirichine N. Modeling of the anaerobic digestion of organic waste for biogas production. Procedia Comput Sci. 2015;52:730-7.

[5] Aghbashlo M, Tabatabaei M, Hosseini SS, Dashti BB, Soufiyan MM. Performance assessment of a wind power plant using standard exergy and extended exergy accounting (EEA) approaches. J Clean Prod. 2018;171:127-36.

[6] Anjum M, Khalid A, Mahmood T, Aziz I. Anaerobic co-digestion of catering waste with partially pretreated lignocellulosic crop residues. J Clean Prod. 2016;117:56-63.

[7] Guenther-Lübbers W, Bergmann H, Theuvsen L. Potential analysis of the biogas production–as measured by effects of added value and employment. J Clean Prod. 2016;129:556-64.

[8] Almasi F, Soltanian S, Hosseinpour S, Aghbashlo M, Tabatabaei M. Advanced soft computing techniques in biogas production technology. In: Tabatabaei M, Ghanavati H, editors. Biogas: Fundamentals, Process, and Operation, Vol 6. Cham: Springer; 2018. p. 387-417.

[9] Holechek JL, Geli HME, Sawalhah MN, Valdez R. A global assessment: can renewable energy replace fossil fuels by 2050?. Sustainability. 2022;14(8):4792.

[10] Fajobi MO, Lasode OA, Adeleke AA, Ikubanni PP, Balogun AO, Paramasivam P. Prediction of biogas yield from codigestion of lignocellulosic biomass using adaptive neuro-fuzzy inference system (ANFIS) Model. J Eng. 2023;2023:1-16.

[11] Dahunsi SO. Mechanical pretreatment of lignocelluloses for enhanced biogas production: Methane yield prediction from biomass structural components. Bioresour Technol. 2019;280:18-26.

[12] Dandikas V, Heuwinkel H, Lichti F, Drewes JE, Koch K. Correlation between biogas yield and chemical composition of grassland plant species. Energy Fuels. 2015;29(11):7221-9.

[13] Hansen BD, Tamouk J, Tidmarsh CA, Johansen R, Moeslund TB, Jensen DG. Prediction of the methane production in biogas plants using a combined gompertz and machine learning model. In: Gervasi O, Murgante B, Misra S, Garau C, Blečić I, Taniar D, et al., editors. Computational Science and Its Applications–ICCSA 2020; 2020 Jul 1-4; Cagliari, Italy. Cham: Springer 2020. p. 734-45.

[14] Appala VNSG, Pandhare NN, Bajpai S. Mathematical models for optimization of anaerobic digestion and biogas production. In: Nandabalan YK, Garg VK, Labhsetwar NK, Singh A, editors. Zero Waste Biorefinery. Singapore: Springer; 2022. p. 575-91.

[15] Olatunji KO, Madyira DM, Ahmed NA, Adeleke O, Ogunkunle O. Modeling the biogas and methane yield from anaerobic digestion of *Arachis hypogea* shells with combined pretreatment techniques using machine learning approaches. Waste Biomass Valor. 2023;14(4):1123-41.

[16] Ghosh P, Shah G, Sahota S, Singh L, Vijay VK. Chapter 7 - Biogas production from waste: technical overview, progress, and challenges. In: Singh L, Yousuf A, Mahapatra DM, editors. Bioreactors. Cambridge: Elsevier; 2020. p. 89-104.

[17] Moya D, Aldás C, Jaramillo D, Játiva E, Kaparaju P. Waste-To-Energy technologies: an opportunity of energy recovery from Municipal Solid Waste, using Quito-Ecuador as case study. Energy Procedia. 2017;134:327-36.

[18] Rasapoor M, Young B, Brar R, Sarmah A, Zhuang WQ, Baroutian S. Recognizing the challenges of anaerobic digestion: critical steps toward improving biogas generation. Fuel. 2020;261:116497.

[19] Honest A, Saria J. Performance of experimental bio-digestion for pathological and biodegradable waste management at Mwananyamala Regional Referral Hospital Tanzania. J Environ Prot. 2020;11(10):838-47.

[20] Qin W. Aspects of pretreated hospital waste biodegradation in landfills [dissertation]. Essen: University of Duisburg-Essen; 2004.

[21] Zacharof AI, Butler AP. Stochastic modelling of landfill leachate and biogas production incorporating waste heterogeneity. Model formulation and uncertainty analysis. Waste Manag. 2004;24(5):453-62.

[22] Saraswat M, Garg M, Bhardwaj M, Mehrotra M, Singhal R. Impact of variables affecting biogas production from biomass. IOP Conf Ser: Mater Sci Eng. 2019; 691:012043.

[23] Safar KM, Bux MR, Aslam UM. Waste to energy: power generation potential of putrescible wastes by anaerobic digestion process at Hyderabad, Pakistan. J Mater Cycles Waste Manag. 2018;20:1239-47.

[24] Yusuf MOL, Ify NL. The effect of waste paper on the kinetics of biogas yield from the co-digestion of cow dung and water hyacinth. Biomass Bioenergy. 2011;35(3):1345-51.

[25] Gidarakos E, Havas G, Ntzamilis P. Municipal solid waste composition determination supporting the integrated solid waste management system in the island of Crete. Waste Manag. 2006;26(6):668-79.

[26] Lawal IM, Ndagi A, Mohammed A, Saleh YY, Shuaibu A, Hassan I, et al. Proximate analysis of the waste-to-energy potential of municipal solid waste for sustainable renewable energy generation. Ain Shams Eng J. 2024;15(1):102357.

[27] Safar KM, Bux MR, Aslam UM, Shankar BA, Goel RK. The feasibility of putrescible components of municipal solid waste for biomethane production at Hyderabad, Pakistan. Waste Manag Res. 2018;36(2):169-82.

[28] Nwoke OA, Okonkwo WI, Echiegu EA, Okechukwu CH, Ugwuishiwu BO. Determination of the calorific value of municipal solid waste in Enugu, Nigeria and its potential for electricity generation. Agric Eng Int: CIGR J. 2020;22(2):86-97.
[29] Haider MR, Zeshan, Yousaf S, Malik RN, Visvanathan C. Effect of the mixing ratio of food waste and rice husk co-digestion and substrate to inoculum ratio on biogas production. Bioresour Technol. 2015;190:451-7.
[30] Çelik İ, Demirer GN. Biogas production from pistachio (*Pistacia vera* L.) processing waste. Biocatal Agric Biotechnol. 2015;4(4):767-72.
[31] Feng L, Li Y, Chen C, Liu X, Xiao X, Ma X, et al. Biochemical methane potential (BMP) of vinegar residue and the influence of feed to inoculum ratios on biogas production. BioRes; 2013;8(2):2487-98.
[32] Ferdeș M, Dincă MN, Moiceanu G, Zăbavă BȘ, Paraschiv G. Microorganisms and enzymes used in the biological pretreatment of the substrate to enhance biogas production: a review. Sustainability. 2020;12(17):7205.
[33] Obileke K, Onyeaka H, Nwokolo N. Materials for the design and construction of household biogas digesters for biogas production: a review. Int J Energy Res. 2021;45(3):3761-79.
[34] Obileke K, Mamphweli S, Meyer EL, Makaka G, Nwokolo N. Design and fabrication of a plastic biogas digester for the production of biogas from cow dung. J Eng. 2020;2020:1-11.
[35] Xu F, Li Y, Ge X, Yang L, Li Y. Anaerobic digestion of food waste–challenges and opportunities. Bioresour Technol. 2018;247:1047-58.
[36] Arabi M, Sbaa M, Vanclooster M, Darmous A. Impact of the municipal solid waste typology on leachate flow under semi-arid climate–a case study. J Ecol Eng. 2020;21(6):94-101.
[37] Gotmare M, Dhoble RM, Pittule AP. Biomethanation of dairy wastewater through UASB at mesophilic temperature range. Int J Adv Eng Sci Technol. 2011;8(1):1-9.