IJSRA

International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(RESEARCH ARTICLE)

Kinetics simulations for thermophilic biogas production data from market wastes co-digested with rumen matter

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International Journal of Science and Research Archive, 2023, 09(02), 926–934

Publication history: Received on 04 July 2023; revised on 22 August 2023; accepted on 25 August 2023

Article DOI: https://doi.org/10.30574/ijsra.2023.9.2.0661

Abstract

This study reports simulation of cumulative biogas production data from thermophilic digester loaded with mixed fruit and vegetable wastes co-digested with slaughterhouse wastes at 55 °C and 6.8 -7.2 operation temperature and pH respectively. The experimental data was fitted to the linear, exponential, Gaussian, logistic and modified Gompertz kinetic models.

The results obtained showed that biogas generation rate was slow at the lag phase with exponential increment thereafter. The maximum generated biogas was 33100 mL on day 25 with the yield showing a decrease henceforth. The ascending limb data modeling fitted best in the modified Gompertz model with regression values of 0.998 compared to the 0.8909, 0.9025, 0.9899 and 0.9860 for linear, exponential, Gaussian and logistic models respectively.

Keywords: Anaerobic Digestions; Biogas; Kinetics; Gompertz model; Simulation

1. Introduction

With persistent increment in world population, food waste and accumulation are becoming big issues all over the world (Kunwar *et al.,* 2017). Food wastage is increasing at an exponential rate, posing serious challenges to our society such as pollution, health risks, and a lack of disposal space. The term food loss refers to the reduction of safe to eat food mass in the entire section of the supply chain resulting to scarcity of consumable food (Gustavsson *et al.,* 2011). Food waste (FW) refers to the removal of foodstuff from the supply chain resulting from spoilage or expiry caused by weak economic behavior (Beede *et al.,* 1995; FAO, 2012). Agricultural produce wastes originate during harvest, transport, storing, processing and marketing. FAO reports that almost 1.3b tons of food comprising of vegetables, meat, wheat, fruits, and milk products are wasted (FAO, 2012). Food wastage (FW) is projected to increase with technological and population increase. For instance, in Asian countries, the annual quantity of city FW might rise from 278 to 416 million tonnes from 2005 to 2025 (Melikoglu *et al.,* 2013). Approximately 1.4b hectares of fertile land (28% of the world's agricultural area) are utilized yearly in production of food that is wasted (Melikoglu *et al.,* 2013). Further, food waste contributes to greenhouse gas (GHG) pollution through an accumulation of about 3.3b tonnes of CO_2 into the atmosphere annually (FAO, 2014).

Food waste is largely managed by incineration and open air dumping which has always led to releases of dioxins due to excess moisture (Katami *et al.,* 2004) and destruction of waste nutrients and constituent elements in waste, thus reducing the economic fee of a substrate (Paritosh *et al.,* 2017; Kamau *et al.*, 2020).

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Anaerobic digestion (AD) is an attractive alternative to the world's renewable energy by utilizing food waste to generate biogas. Due to their high bio-digestibility and high-water levels (75–90%), watery fresh fruit and vegetable wastes would be a suitable feedstock for renewable energy recovery via the anaerobic digestion (Nasir *et al.,* 2012). Therefore, in the current study, the cumulative biogas yield data from thermophillic digester was fitted to different kinetic models to test the data fitness to the model.

2. Material and methods

2.1. Sampling

The market waste comprising of fruit and vegetable (FVMW) was obtained from Kangemi and Wakulima markets in Nairobi, Kenya. Rumen matter was obtained from freshly slaughtered cows from Dagoretti slaughterhouse. The samples were transported to the laboratory in sealed containers and used within 12 hours.

2.2. Biogas Production

The market wastes was made up of twenty different fruits and vegetable wastes as previously reported by Kamau *et al.,* (2020). About 5 L of specific fruits and vegetable wastes were blended and mixed thoroughly before loading into the reactor shown in figure 1. The inoculum was added to the wastes in a ratio of 1:1 to make a total working volume of 350 mL and biogas production initiated at thermophilic conditions by placing the setup in a water-bath and maintaining it at 55 °C. The initial operating pH was 6.8-7.2 at room temperature.

a b

Figure 1 A set-up of (a) biogas production at the thermophilic condition (b) Volumetric biogas measurement setup

The gas produced was monitored volumetrically using graduated polythene bags and recorded daily for a 30 days retention time. The simulation was done as previously described by Latinwo & Agarry, (2015); Munyuchi, (2018); Ali et al., (2018); Nwosu-Obieogu et al., (2020) and Mbugua et al., (2023b).

2.3. Biogas Production modeling

The study of the biogas production kinetics for the description and evaluation of methanogenesis was carried out by fitting the experimental data of biogas production to various kinetic equations Ghatak & Mahanta, (2014).Biogas production rates of market wastes co-digested with cattle rumen matter was simulated using linear, exponential and Gaussian plots. The linear equation of the biogas production rate in the ascending and descending limb can be expressed by the equation given below (Kumar *et. al*, 2004; Lo *et. al*, 2010). It is assumed that biogas production rate will increase linearly with increase in time and after reaching a maximum point after some time, it would decrease linearly to zero with increase in time.

$$y = a + bt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . (1)$$

Where, y =biogas production rate in ml/gm/day; T=time in day for digestion; a (ml/gm/day) and b (ml/gm/day2) are the constants obtained from the intercept and slope of the graph of y vs T.

The exponential plot for the ascending and descending limb can be presented by the equation (2) (De Gioannis *et al.,* 2009). Here it is assumed that biogas production rate will increase exponentially with increase in time and after reaching the high point it would decrease to zero exponentially with increase in time.

$$y = a + bexp(ct) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

Where, y=biogas production rate (ml/gm/day); T=time needed for digestion (days); a, b= constants (ml/gm/day); c= constant (1/day).

The Gaussian equation shown in equation 3 can be applied to simulate biogas production rates including both ascending and descending limb, assuming that biogas production rates would follow the normal distribution over the hydraulic retention time.

$$y = aexp\left[-0.5\left(\frac{t - t_0}{b}\right)^2\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(3)$$

Where, y=biogas production rate (ml/gm/day) at time *t*; *t*=time needed for digestion (days); a (ml/gm/day) and b (day) are the constants; t_0 = time where the maximum biogas production rate took place.

In addition, cumulative biogas production was simulated using logistic growth model, exponential rise to maximum and modified Gompertz equation. Logistic growth equation is shown in equation (4).

$$y = \frac{a}{1 + bexp(-kt)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4)$$

Where, y = Cumulative biogas production (ml/gm); k = kinetic rate constant (1/day); T=HRT (Days); a, b are the constants. Exponential rise to maximum is presented in Eq. (5) (De Gioannis et. al, 2009; Lo et. al, 2010).

Exponential rise to maximum is presented in Eq. (5) (De Gioannis *et. al,* 2009; Lo *et. al*, 2010).

$$y = A\big(1 - exp(-kt)\big) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(5)$$

The modified Gompertz model is a Statistical Regression Model which describes the cumulative biogas production in batch digestion. It assumes that methane production is a function of bacterial growth or that methane production is a composite function of substrate levels limit growth in a logarithmic relationship (Van et al., 2018; Zhang et al., 2021). Modified Gompertz equation is modified form of the Gompertz equation which is commonly used to simulate the cumulative biogas production (Lo et. al, 2010). The modified Gompertz equation is can be presented as follows:

$$Y = A.exp\left\{-exp\left[\frac{u.e}{\gamma_m}(\lambda - t) + 1\right]\right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(6)$$

Where, Y is the cumulative of the specific biogas production (ml/gm), A is the biogas production potential (ml/gm), U is the maximum biogas production rate (ml/gm/day), λ is the lag phase period or the minimum time required to produce biogas (day).

Analysis of the experimental data was performed in MS- excel using the solver feature by non-linear regression and QtiPlot.

3. Results

Biogas generation from wastes mixture at (55 °C) was initiated by co-digesting the waste mixture with rumen wastes in a ratio of 1:1 and maintaining the digester temperatures at (55 ^{0}C). The cumulative biogas yield obtained is shown in figure 2. The rate of production was slow at the initial phases (lag phase) with exponential increment from day 6 to 25 (exponential phase). The production slowed down hence forth as the organic matter is depleted and the microbes start dying (Stationary phase). The maximum production was recorded on day 25 at 33100 mL. Previously, Kamau *et al.* (2020), had obtained similar results from market wastes inoculated with slaughterhouse wastes at 35200 mL, 15800 mL and 700 mL for thermophilic, mesophilic and psychrophilic reactors fed with market wastes. Thermophilic temperatures favor a high rate of degradation of organic matter which implicitly increases biogas methane yield

(Angelidaki & Sanders, 2004). The rate of biogas formation from anaerobic digester is highly dependent on operation conditions, substrate properties and digestibility (Mbugua *et al.,* 2023a).

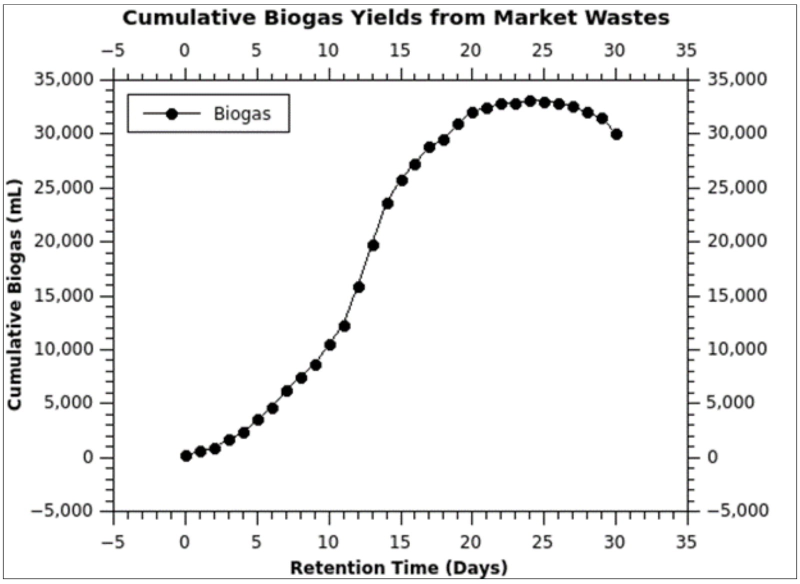

Figure 2 Cumulative biogas yield from market wastes

The results obtained are similar to what was obtained by Budiyono *et al,* (2010) who investigated the kinetics of biogas production while using cattle manure as substrate inoculated by rumen fluid to the anaerobic biodigester. They reported that rumen matter is a good inoculum in anaerobic digestion due to its high microbial community which had also been observed by Kamau *et al*., (2020).

The linear kinetic model for biogas production suggests that the cumulative amount of biogas produced increases linearly with increase in digestion time. The linear kinetic model was fitted on the experimental data and coefficient of determination of R^2 = 0.93 was found (figure 3), which showed it is a good model in explaining the rate of biogas generation.

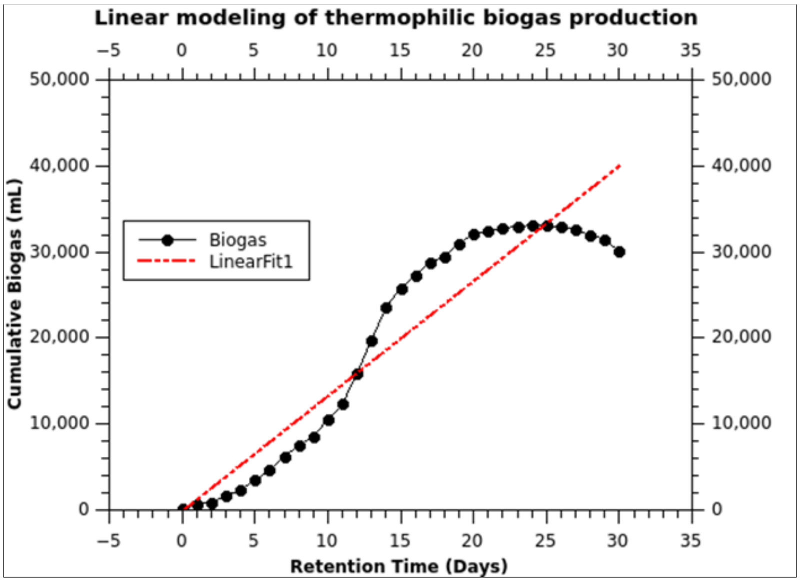

Figure 3 The simulated linear model plot with experimental data

As observed in this study, Manyuchi, (2018) and Manyuchi *et al.,* (2018) reported that the cumulative biogas produced increased with increase in the digestion time for municipal waste. Further, a comparison of two models showed the superiority of the linear model against the exponential model.

The exponential plot for the ascending and descending limb can be presented by the equation (2) (*De Gionnis et al.,* 2009). Here it is assumed that biogas production rate will increase exponentially with increase in time and after reaching the high point it would decrease to zero exponentially with increase in time. The resulting exponential fit is shown in figure 4.

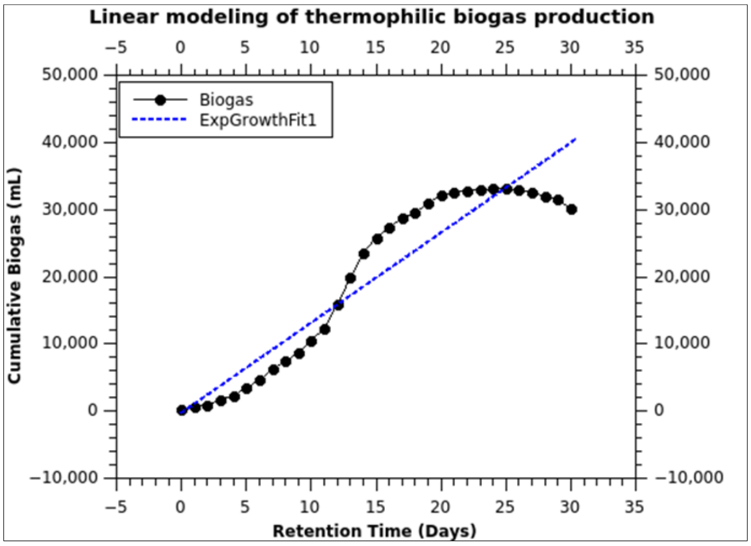

Figure 4 The simulated exponential plot with experimental data

The exponential model of the experimental data gave a regression value of 0.9025 compared to 0.8909 for the linear model. Similar findings had been reported by Shitophyta & Maryudi (2018) who showed that the exponential equation had a better correlation than the linear equation on the ascending graph of biogas production while using maize cobs.

The Gaussian and the Boltzman equations can be applied to simulate biogas production rates for both the ascending and descending limb, assuming that biogas production rates would follow the normal distribution over the hydraulic retention time, the resulting fits are shown in figure 5.

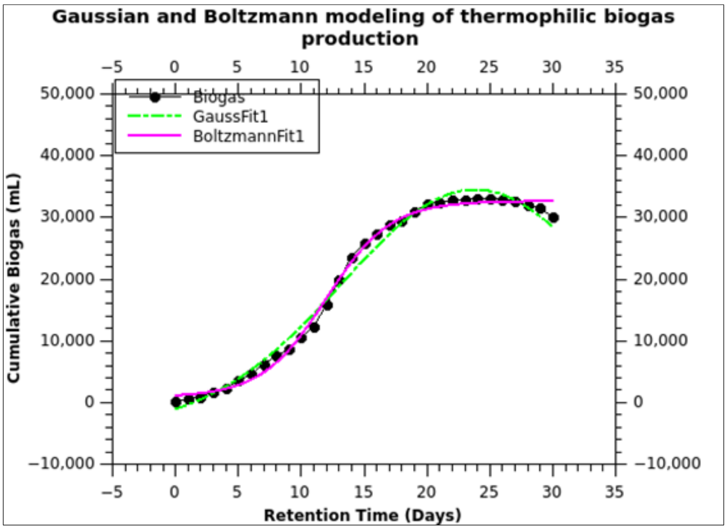

Figure 5 The simulated Gaussian and Boltzman plot with experimental data

Further, cumulative biogas production was simulated using logistic growth model, exponential rise to maximum and modified Gompertz equation. Logistic growth simulation plot is shown by figure 6.

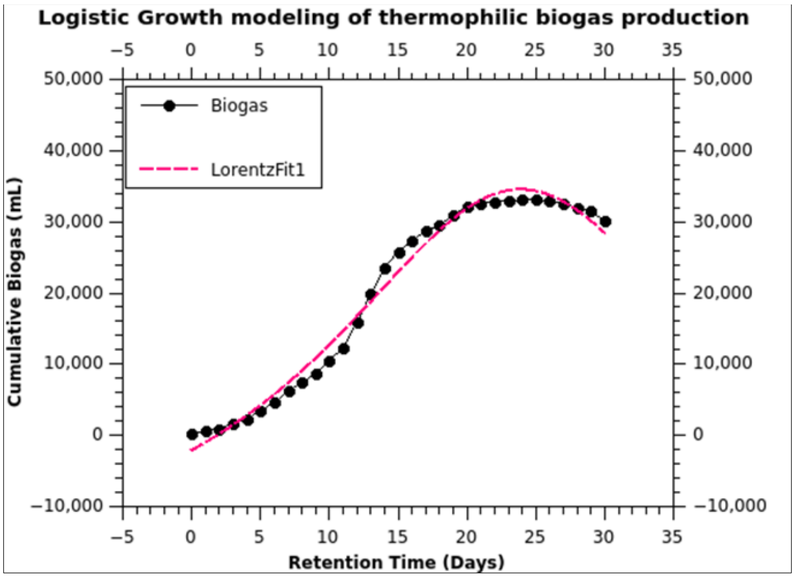

Figure 6 The simulated Logistic growth plot with experimental data

Modified Gompertz equation is modified form of the Gompertz equation which is commonly used to simulate the cumulative biogas production (Lo *et al.* 2010). The resultant plot is shown by figure 7.

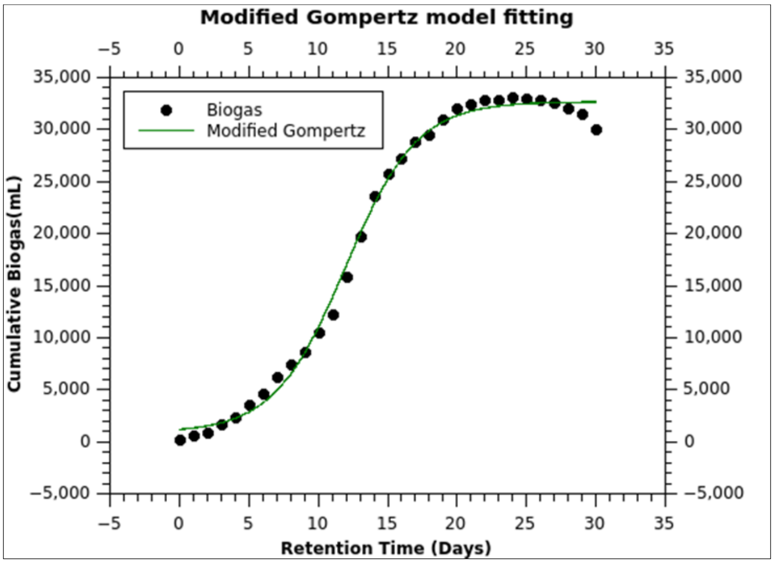

Figure 7 The simulated modified Gompertz plot with experimental data

In the simulation section, the coefficient of determination of FVMW inoculated with rumen was 0.96 and the plot is shown in figure 7. Biogas generation rate (μm) and lag phase period (λ) re found to be 3.34mL/gm/day and 0.86 days at 55 °C while the biogas generation (P) was estimated at 49.09 mL/gm. This is consistent with the results reported for cow dung waste at the thermophilic temperature at 39.10 mL/g biogas produced at a production rate of 1.40 mL/g/day and a lag phase 6.22 day (Ghatak and Mahanta, 2014).

4. Discussions

The kinetic parameters obtained from fitting the experimental data various models are shown in table 1. These parameter are ranges of constants extracted from the resulting plot equations.

Table 1: Kinetic Parameter of the Various Models

Model	**Parameters**	**R^2**	**Adjusted R^2**
Linear	A=1.340 b=-2.273	0.8909	0.8832
Exponential	A=1.837 b=-1.887 c=1.371	0.9025	0.8952
Gaussian	A1= 1.027 T1= 2.119 b1= 2.382	0.9899	0.9884
Logistic Model	A=3.076 b=-2.157 c=2.389 k=3.487	0.9860	0.9838
Modified Gompertz	A= 23-635 b= -0.9666 k= 3.987 A= 20.879 λ= 1.987 U = 3.879	0.9987	0.9979
Boltzmann (Sigmoidal)	A1=8.791 a2=3.268 b=2.556 c=1.197	0.9956	0.9949

The kinetics parameters are in correlation with other research works in biogas experimental data simulation. For example, Mbugua *et al.,* (2023b) reported that modified Gompertz model was fit in modeling biogas data from organic market wastes with a correlation factor of 0.9998.

In other research works, while co-digesting biodegradable organic waste with pig dung, Oyejide et al., (2018) reported that the coefficient of determination recorded was high for modified Gompertz kinetic model (0.9952), and the regression value R^2 for rate of biogas yield obtained from linear plot was 0.9268. Therefore, concluding that, both Modified Gompertz plot and linear plot had high correlation, and both can be used to simulate biogas yields from codigestion of organic wastes with cowdung. In another study involving codigestion of horse manure with cowdung, the modified Gompertz equation adequately described the cumulative biogas production as reported by Yusuf et al., (2011). Mbugua et al. (2023b) investigated kinetic modeling of cumulative biogas data from anaerobic digestion of twenty market wastes with rumen wastes. They observed that coefficient of determination (R^2) were in the ranges of 0.5478 – 0.9973 for linear model, 0.9099 – 0.9984 for the exponential model, Gaussian model at 0.879-0.9932, Logistic Growth model at 0.9602 – 0.9963 and Modified Gompertz model: 0.9987 – 0.9999 respectively.

5. Conclusion

In this research work, the experimental data from co-digestion of market wastes with abattoir matter was successfully fitted into various kinetic models. This study concluded that biogas production rate increased exponentially and reached a peak value on day 25 and thereafter decreased linearly to a very low significant value. Modified Gompertz and logistic growth model resulted in better correlation than exponential rise to maximum for cumulative biogas production with regression values greater than 0.989. This shows that modified Gompertz equation and the logistic mathematical modeled equation of biogas yield rate can be used to model and simulate biogas yields. The value of cumulative biogas yield was approximately 20.879 L/100g while biogas yield rate was obtained as 3.987 litre/day.

Compliance with ethical standards

Acknowledgments

The authors wish to express their sincere gratitude to the National Research Fund (NRF), grants no. **501-000-053** for funding this research work.

Disclosure of conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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