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DEVELOPMENT OF KINETIC MODELS FOR BIOGAS PRODUCTION FROM TOFU LIQUID WASTE

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Abstract: Biogas promises bioenergy to be developed as a renewable fuel to reduce the fossil energy crisis. Biogas raw material can be derived from tofu liquid waste. Biogas is processed by anaerobic digestion. This study aimed to develop a simulation of the kinetic model variations of biogas production from tofu liquid waste. The results showed that the ascending limb of the exponential equation had a greater coefficient ($R^2 = 1$) than the ascending limb of the linear equation ($R^2 = 0.9574$). The descending limb of the linear equation had a better coefficient ($R^2 = 0.9574$) than the descending limb of the exponential equation ($R^2 = 0.95$). The Gaussian model had the greatest R^2 of 0.9937. Logistic growth had the greatest coefficient ($R^2 = 0.9951$) compared to modified Gompertz ($R^2 = 0.9817$) and exponential rise to maximum ($R^2 = 0.9852$) in the simulation of cumulative biogas production. The fit model for kinetic biogas production from tofu liquid waste is Gaussian Model.
Keywords: anaerobic digestion, biogas, tofu liquid waste, kinetic model

Abstrak: Biogas merupakan salah satu bioenergi yang menjanjikan untuk dikembangkan dalam mengurangi krisis energi fosil. Bahan baku biogas dapat berasal dari limbah cair tahu yang diolah secara *anaerobic digestion*. Penelitian ini bertujuan untuk mengembangkan variasi model simulasi kinetika produksi biogas dari limbah cair tahu. Hasil penelitian menunjukkan bahwa persamaan eksponensial untuk grafik kenaikan memilki koefisien yang lebih besar ($R^2 = 1$) dibandingkan grafik kenaikan dengan persamaan linier ($R^2 = 0{,}9574$). Grafik penurunan pada persamaan linier memiliki nilai koefisien lebih besar ($R^2 = 0{,}9574$) dibandingkan grafik penurunan pada persamaan eksponensial ($R^2 = 0{,}95$). Model Gaussian menghasilkan nilai koefisien tertinggi $R^2 = 0{,}9937$. *Logistic growth* menghasilkan nilai R^2 terbesar (0,9951) dibandingkan modified Gompertz ($R^2 = 0{,}9817$) dan *exponential rise* to maximum ($R^2 = 0{,}9852$) pada simulasi produksi biogas kumulatif. Model yang paling cocok untuk kinetika produksi biogas dari limbah cair adalah model Gaussian.
Kata kunci: *anaerobic digestion*, biogas, limbah cair tahu, model kinetika

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Introduction

The use of fossil fuels can harm environmental conditions such as greenhouse gas emissions and carbon gas accumulation that cause the global energy crisis. Renewable energy has been developed to reduce fossil fuel consumption (Winquist et al., 2019). Every year, around 220 million tonnes of renewable biomass are produced in the world. It is equivalent to 4500 EJ of solar energy per year. Energy production from biomass will meet the bioenergy market demand of 270 EJ in a year. The bioenergy market potential is estimated to increase by 10-50% in 2050 (Kumar et al., 2018).

Biogas is bioenergy that gains attention increasingly as renewable and sustainable energy technology (Budzianowski, 2016). Biogas technology is cost-effective and potential in organic waste management (Yu et al., 2019). The biogas production process is carried out by anaerobic digestion, a process that breaks down organic materials into biogas (Shitophyta et al., 2020). Anaerobic digestion processes help to reduce greenhouse gas emissions, carbon dioxide, and eutrophication(Kainthola, Kalamdhad, & Goud, 2019b). The anaerobic digestion stage consists of four phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis ((Kovacs et al., 2018). The digestion is carried out by different microorganisms, such as acidogens and methanogens (Kainthola et al., 2019).

The main composition of biogas is methane (CH_4) and carbon dioxide (CO_2) with other impurities such as hydrogen sulfide (H_2S), ammonia (NH_3) and water vapor (Ge et al., 2016). The combustion of methane produces relatively environmentally friendly gases such as carbon dioxide and water vapor (Liu et al., 2019). Biogas raw materials can be obtained from various kinds of organic wastes, such as tofu waste. Tofu waste is generated from tofu manufacture, and soybeans wash. Tofu liquid waste contains organic compounds in the form of protein, carbohydrates, fats, and oils. If the amount of waste increased and buried for a long time, the waste substances will be difficult to be degraded by microbes. Tofu liquid waste also contains methane and carbon dioxide. The methane content in tofu liquid waste is suitable for the raw material of biogas production. (Shitophyta et al., 2019). Several studies on biogas production from tofu liquid waste have been done previously, but no study discusses the kinetics of biogas production from tofu liquid waste. Therefore, this study aimed to develop variations in the kinetics model of biogas production from tofu liquid waste.

Other researchers have offered the previous simulation models of biogas. Still, the models needed simultaneous solutions of mass balance equations for each substrate and microbial population, generating equations with copious unknown factors. Thus a simple model is required to express the anaerobic biogas digestion process (Das & Mondal, 2015). The main goal of this study focuses on the kinetic models of biogas using linear, exponential, and gaussian equations. Linear and exponential equations can illustrate the biogas production rate as the phase of microbial growth by an increasing and a decreasing curve (Kafle &

Chen, 2016). Cumulative biogas production was also simulated in this study using a logistic growth model, an exponential increase to maximum, and a modified Gompertz equation. These three models provide a better correlation coefficient to calculate the cumulative biogas. Besides, Logistic and Gompertz equations give the potential biogas production, maximum biogas production, and production delay time under various conditions based on the cumulative biogas production (Ali et al., 2018). Modified Gompertz also widely signifies the basis structure for biogas kinetic simulation (Oyejide et al., 2018).

Material and Methods

Material

Tofu liquid waste was obtained from a tofu industry in Banguntapan, Yogyakarta, Indonesia. Solution of NaOH 2 N was used to neutralize pH.

Methods

Biogas production was carried out using a batch digester 2 L. Tofu liquid waste (800 mL) was mixed and stirred with water (800 mL) (1: 1 ratio), then put into a digester. The initial pH in the digester was 7 by adding a solution of NaOH 2 N. The experiment was carried out at room temperature. The daily biogas volume was measured by the water-displacement method every 3 days. This measurement method has also been done by Dababat & Shaheen (2019). Biogas production was run until 45 days. The experimental setup of biogas production is presented in Figure 1.

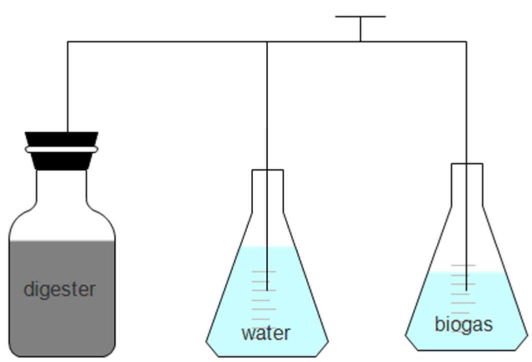

Figure 1. The scheme of biogas production from tofu liquid waste

Kinetic Models of Biogas Production

Linear equation

The kinetics of biogas production using a linear equation model was simulated with the biogas production rate increasing linearly with an increasing time, reaching the peak point and decreasing linearly to zero. The linear equation is stated as follows (Das & Mondal, 2015; Lukhi Mulia Shitophyta, 2020; Okewale et al., 2018)

$$y = a + b(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where y is biogas production rate (mL/g VS), t is hydraulic retention time (days), a and b are constants obtained from the intercept and slope (mL/g VS/day). In the ascending limb, "b" is positive, while the descending limb, "b" is negative.

Exponential equation

The exponential model was assumed by increasing the biogas production rate exponentially with an increase in time and achieving the peak value, then decreases exponentially until zero value. The exponential equation is expressed as follows (Shitophyta & Maryudi, 2018).

$$y = a + b\ exp(c.t) \dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

Where y is biogas production rate (mL/g VS), t is hydraulic retention time (days), a, b (mL/g VS/day), and c (day^{-1}) are constants. In the ascending limb, "c" is positive, while in the descending limb, "c" is negative.

Gaussian equation

The Gaussian model can be simulated both as ascending and descending plots. The Gaussian equation also has been used previously by Ahmed & Kazda, 2017; Choi, Ryu, & Lee, 2020; Lukhi Mulia Shitophyta 2020 to model biogas kinetic rate. Equation 3 represents the Gaussian equation.

$$y = a\ exp\left[-0{,}5\left(\frac{t - t_0}{b}\right)^2\right] \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3)$$

Where y is biogas production rate (mL/g VS), t is hydraulic retention time (days), a (mL/g VS/day), b (day) are constants, t_0 is the time when the maximum biogas production rate occurred.

$$y = \frac{a}{1 + be^{-kt}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4)$$

Where, y is cumulative biogas production (mL/g VS), k is rate constant (day^{-1}), a, b are constants, and t is hydraulic retention time (days) (Ugwu & Enweremadu, 2019)

$$y = A\ exp\left\{-exp\left[\frac{\mu_m e}{A}(\lambda - t) + 1\right]\right\} \dots\dots\dots\dots\dots\dots (5)$$

Where, y is cumulative biogas production (mL/g VS), A is potential biogas production (mL/g VS /day), μ_m is maximum biogas production rate (mL/g VS/day), λ is the minimum time required to produce biogas or lag phase (day) t is hydraulic retention time (days)

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$$y = A\left(1 - exp(-kT)\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$

Where, y is cumulative biogas production (mL/g VS), A is potential biogas production (mL/g VS/day), k is rate constant (day^{-1}), t is hydraulic retention time (days)

Results and Discussion

Biogas production was carried out for 45 days until no more biogas produced. The biogas production is presented as daily biogas yield in Figure 2.

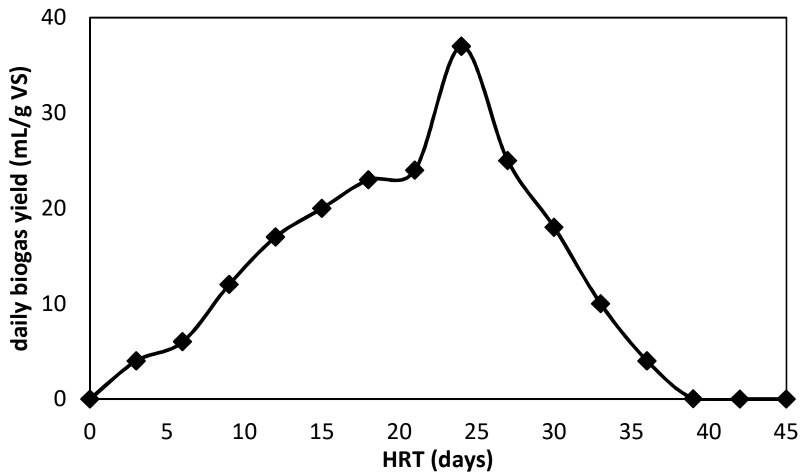
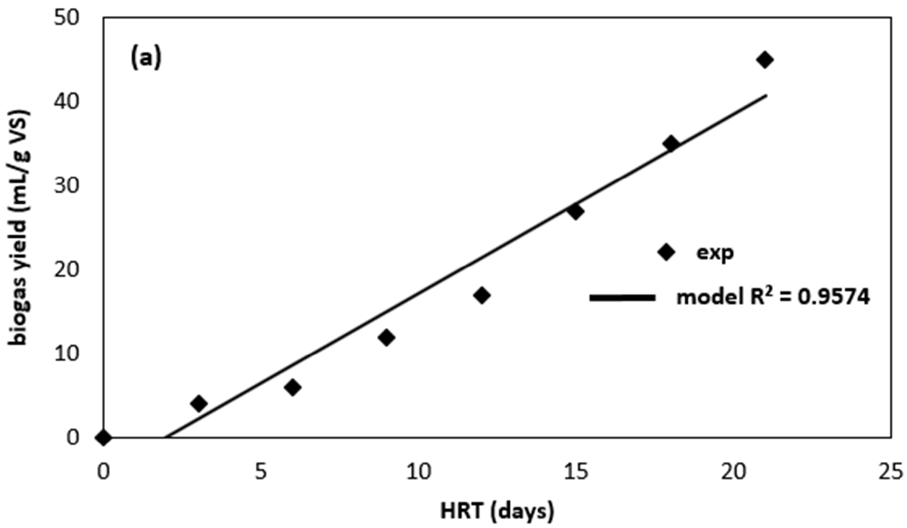
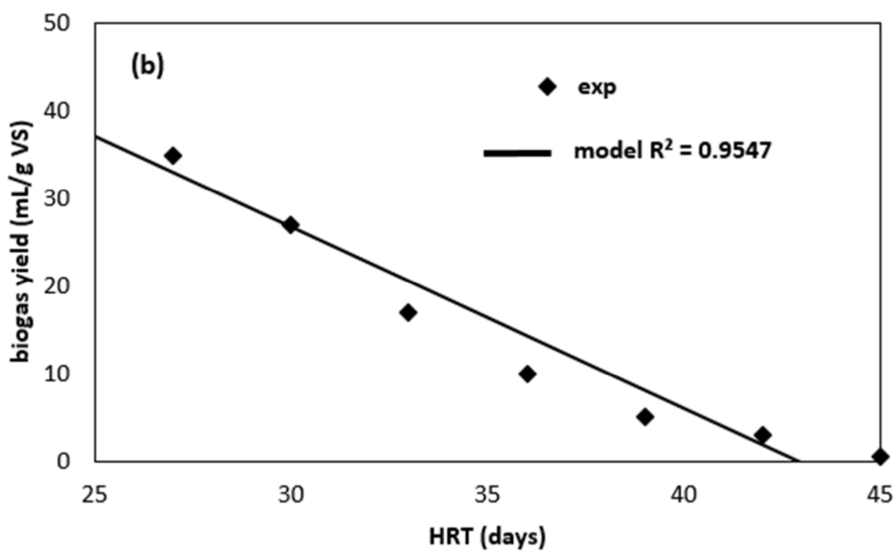


Figure 2. Daily biogas yield of biogas production from tofu liquid waste

Biogas production started on the second day with a biogas yield of 4 mL/g VS. Biogas production increased slowly until it reached the peak value on the 24^{th} day with a biogas yield of 37 mL/g VS. After attaining the peak point, the biogas production gradually decreased until it reached a constant value on the 42^{nd} to 45^{th} day. The kinetics model of biogas production with linear equations was simulated in ascending and descending plots, which can be seen in Figures 3(a) and 3(b), respectively.



(a)



(b)

Figure 3. Exponential plots of biogas production rate from tofu liquid waste (a) ascending limb; (b) descending limb

As seen in Figures 3(a) and 3(b), both ascending and descending limbs have the same value of regression coefficient (R^2 = 0.9547). The $R^2 > 0.9$ indicated that the linear equation could be modeled on the biogas production rate. Figures 4(a) and 4(b) show the exponential equation's ascending and descending limbs. The coefficient of R^2 for the ascending limb was 1, while the descending limb had the R^2 value of 0.95. This model denotes that the biogas production rate increased exponentially with time and achieved a peak value. It decreases linearly with time until it reached a very low or zero value (Das & Mondal, 2015). The result signifies that the exponential equation gives a better correlation for the ascending limb, while the linear equation is better for the descending limb. A similar study reported by (Ejimofor, et al., 2020) stated that the ascending limb of the exponential equation had more higher R2 than the ascending limb of the linear equation on kinetic biogas production from post coagulation sludge.

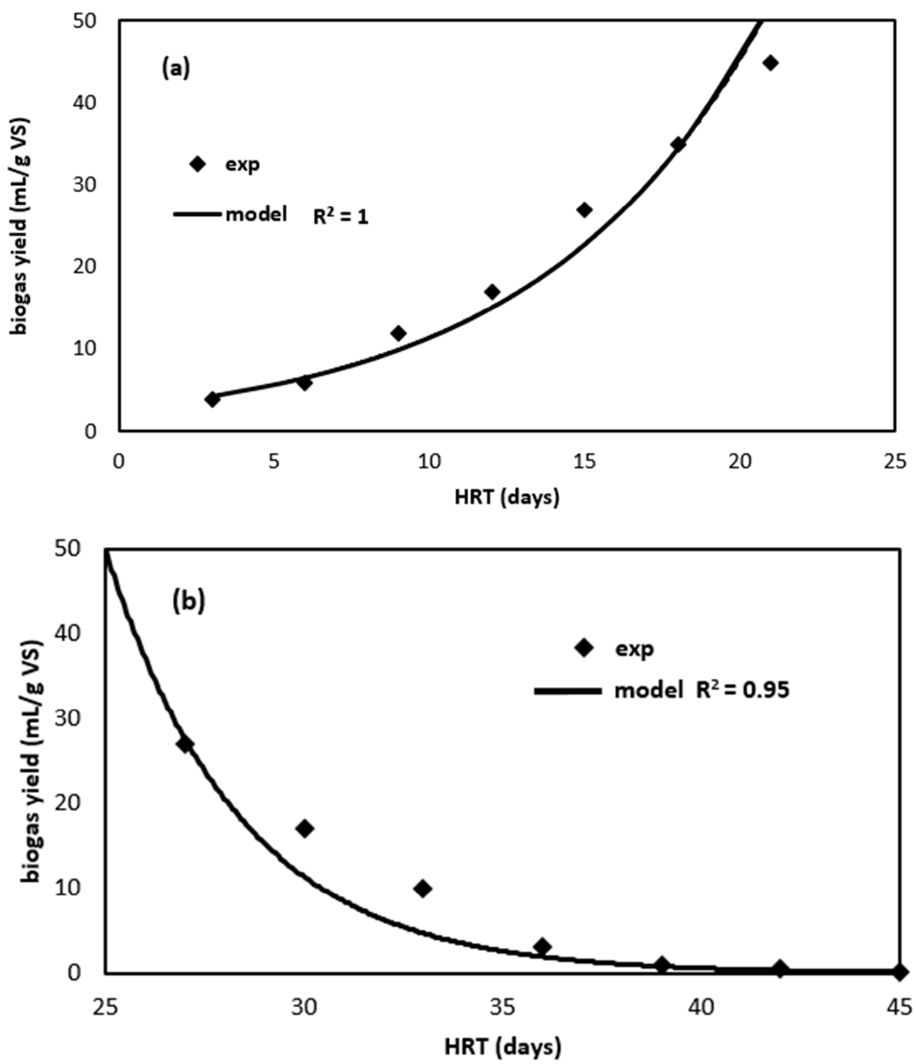


Figure 4. Exponential plots of biogas production from tofu liquid waste: (a) ascending limb; (b) descending limb

The kinetics model of biogas production with the Gaussian equation is shown in Figure 5. The coefficient of R^2 (0.95) in the Gaussian equation was greater than $R^2 > 0.9$. Compared to Figure (3) and Figure (4), the Gaussian equation was suitable to be applied both on the ascending and descending limb because it had the highest R^2 value compared to the linear and exponential

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equations, even though the ascending limb of the exponential equation had the highest R^2. However, the descending limbs on linear and exponential equations have a small R^2. The prior study, which was reported by Das et al. (2017), also stated that coefficient R^2 was higher for the Gaussian model (R^2 0.992) as compared to the linear (R^2 0.895-0.987) and the exponential models (R^2 0.945-0.961) on a kinetic model of biogas production from pretreated rice husk.

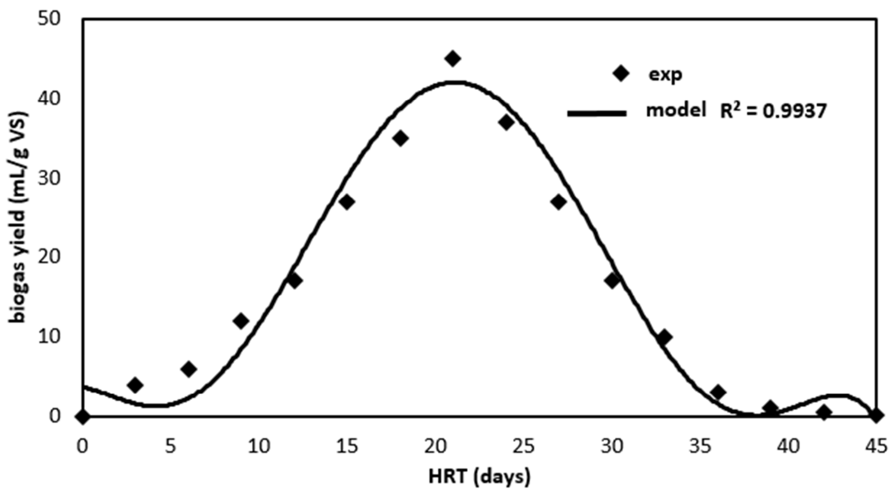
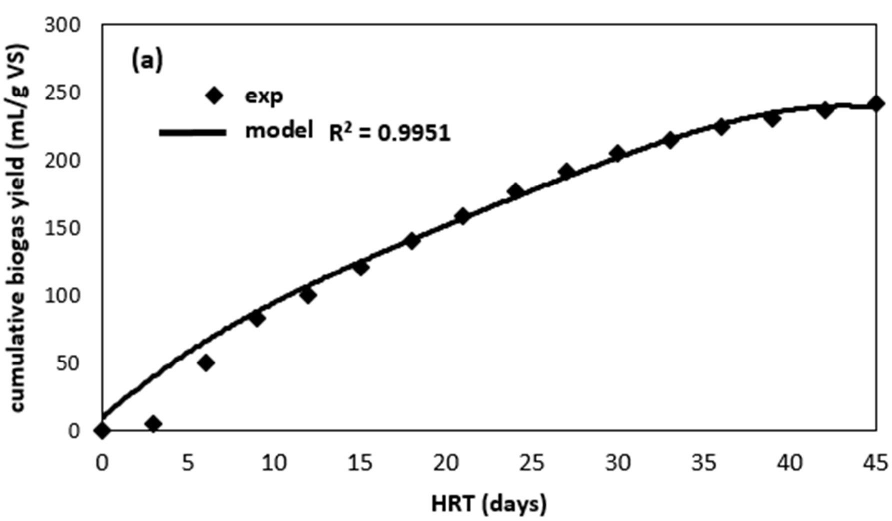


Figure 5. Gaussian plot for biogas production from tofu liquid waste

Cumulative biogas production was simulated using the logistic growth model, modified Gompertz, and exponential rise to maximum, which are shown in Figures 6(a), 6(b), and 6(c), respectively.



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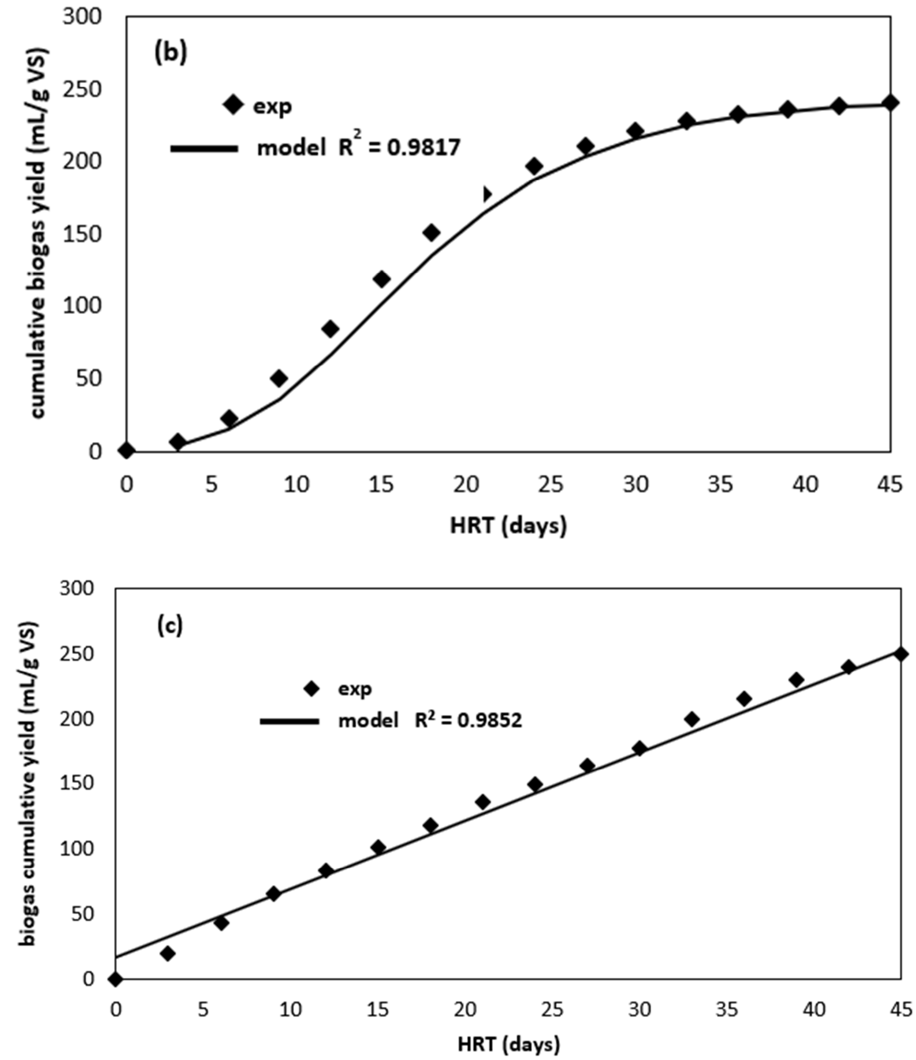

Figure 6. (a) logistic growth plot, (b) modified Gompertz plot, (c) exponential rise to a maximum of cumulative biogas production from tofu liquid waste

The coefficient of R^2 (0.9951) in logistic growth had the greatest value among the modified Gompertz (R^2 = 0.9817) and the exponential rise to maximum (R^2 = 0.9852). The logistic growth equation is ideal for the simulation of cumulative biogas production. The k value in logistic growth was 0.1 day^{-1}, while the k value in the exponential rise to maximum was 0.02 day^{-1}. In the modified Gompertz equation, the biogas production potential (A) was 243 mL/g. The biogas production rate (μ_m) and the lag phase period (λ) were 12 mL/g/day and 5 days, respectively.

This result is equivalent to the previous study, which was conducted by Ejimofor et al. (2020), who found that the regression coefficient of the logistic model (R^2 = 0.997) was higher than modified Gompertz (R^2 = 0.64) and exponential rise to maximum (R^2 = 0.966) on the biogas kinetic of biogas production from paint wastewater. Therefore, the logistic growth equation is a fit model to simulate cumulative biogas production.

Conclusion

The biogas production rate with the exponential model has a better correlation than the ascending limb of the linear equation. In comparison, the descending limb of the linear equation has a better correlation than the descending limb of the exponential equation. The Gaussian equation has a higher coefficient R^2 than the linear equation and the ascending limb of the exponential equation. Logistic growth has the highest correlation compared to modified Gompertz and exponential rise to maximum in the simulation of cumulative biogas production. Therefore, this study concludes that the Gaussian equation is a suitable model to predict the kinetic of biogas production from tofu liquid waste. In contrast, the logistic growth equation is a good alternative model to simulate the cumulative biogas production from tofu liquid waste.

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