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Kinetic Analysis of Biogas Production from Poultry Manure Waste using Gompertz, Transference, and Logistic Models

Achmad Faizal Ibrahim*, Elisa Restu Dian Najiyah, Mohamad Farrel Abigail, Muhamad Ariel Satria, Iqbal Syaichurrozi

Chemical Engineering Department, Faculty of Engineering, Universitas Sultan Ageng Tirtayasa, Jl. Jend Sudirman km.03 Cilegon Banten 42435, Indonesia

Corresponding Author Email: achmadfibrahim@gmail.com

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ABSTRACT

Biogas production through anaerobic fermentation is a promising renewable energy alternative that continues to gain attention. To improve the accuracy and efficiency of production predictions, kinetic modeling approaches that describe the underlying biological processes are essential. This study compares three kinetic models Gompertz, Logistic, and Transference in predicting biogas production under varying pH conditions, with the aim of identifying the model that best represents the experimental data. The models were evaluated based on parameters including maximum production capacity (Ym), maximum production rate (U), lag time (λ), and prediction errors quantified by the sum of squared errors (SSE), root mean square error (RMSE), and coefficient of determination (R^2). The results demonstrate that the Transference model consistently outperforms the other models. At neutral pH (pH 7), the Transference model predicted a maximum biogas production of 2127.11 cm^3, a maximum daily production rate of 158.23 cm^3/day, a short lag phase of 0.947 days, a low SSE value of 3223.45, and an R^2 value of 1.000, indicating an excellent fit to the experimental data. Compared to the Gompertz and Logistic models, the Transference model exhibited greater stability, accuracy, and realism in representing the biogas production process. These findings indicate that the Transference model is a reliable predictive tool for the design and optimization of biogas production systems, particularly under optimal pH conditions.

Keywords: *Biogas production, gompertz, kinetic analysis, logistic, transference*

1. INTRODUCTION

Currently, the world is facing challenges related to the availability of fossil fuels which are increasingly scarce. According to the latest report from the British Petroleum (BP) Statistical Review of World Energy 2023, global oil reserves are expected to run out in the next 53 years since 2023 (Petroleum, 2023). The use of fossil fuels in the long term can have a negative impact on nature, this is because the combustion process that occurs produces carbon dioxide (CO_2) emissions. The carbon dioxide gas produced is increasing and accumulates in the atmosphere causing the greenhouse effect (Shitophyta et al., 2023). Therefore, to reduce the negative impacts of the use of fossil fuels, it is necessary to use alternative sources that are more environmentally friendly such as the use of biogas as fuel. Global warming is a phenomenon caused by an increase in carbon dioxide emissions in the earth's atmosphere causing significant changes in temperature and ecosystems.

Indonesia is also very serious about developing the use of New and Renewable Energy (EBT). This is proven by Government Regulation No. 79 of 2014 concerning the National Energy Policy (KEN) and Presidential Regulation No. 22 of 2017 concerning the National Energy General Plan (RUEN) which have a target for the use of EBT in 2025 and 2050 of 23% and 31% of the total national energy needs, respectively (Presidential Regulation of the Republic of Indonesia, 2017). However, until 2020, the realization of the EBT share had only reached 11.31% (Ministry of Energy and Mineral Resources, 2021). It seems that the efforts made so far to increase the share of EBT still face serious challenges, one of which is because the price of EBT is not yet competitive with fossil energy.

This condition indicates that more intensive efforts are needed to achieve the set targets. Among the various types of renewable energy, biogas is one of the promising alternatives and has great potential in accelerating the transition to sustainable energy in Indonesia. Biogas is formed through the anaerobic digestion process of organic materials such as animal waste, agricultural waste, and organic waste (Scarlat et al., 2018). Biogas has a main content of methane (CH_4) around 50-70% and carbon dioxide (CO_2) around 30-50%, accompanied by other contents such as hydrogen sulfide (H_2S) and ammonia (NH_3). As a mixture of gases produced through the anaerobic digestion process of organic materials. The main composition of biogas is methane (CH_4) and carbon dioxide (CO_2), with a small amount of other gases such as hydrogen sulfide (H_2S) and ammonia (NH_3). This process involves the decomposition of organic matter by microorganisms in the absence of oxygen, producing gas that can be used as a renewable energy source (Pöschl et al., 2010). Organic waste has great potential as a raw material for biogas production through anaerobic digestion. Various types of waste such as livestock waste, food waste, tofu industry waste, and domestic waste contain easily decomposed organic matter that supports the methanogenic fermentation process (Nanang Apriandi et al., 2022). In addition, potential waste, namely chicken manure, is used as organic fertilizer because of its high nutrient content, especially nitrogen, phosphorus, and potassium. The use of chicken manure as fertilizer can increase soil fertility and agricultural yields (Henuk & Dingle, 2003).

This article is a new attempt to deepen the understanding of the biogas production process through a more comprehensive modeling approach. Unlike previous studies that generally only use one or two kinetic models, this study specifically compares three models at once, Gompertz, Logistic, and Transference, in describing the rate and pattern of biogas production at various pH conditions. These three models are applied to the same experimental data to see how each predicts the maximum production potential, daily production rate, and the initial time of gas formation (lag phase).

Kinetic analysis conducted using biogas production data in the article Investigation Of The Effects Of Starting Ph, Mass And Retention Time On Biogas Production Using Poultry Droppings As Feedstock studied by (Adebimpe et al., 2020). has an important role in understanding the biological mechanisms that occur in more depth and predicting biogas production results under various environmental conditions, such as variations in pH, temperature, or residence time. By modeling the digestion process using a mathematical approach, researchers can evaluate system performance without having to conduct direct experiments that require large amounts of time, money, and resources. Therefore, the purpose of writing this article is to determine the effect of feed pH on biogas production on poultry manure through kinetic analysis. In addition, this study also compares and evaluates three kinetic models commonly used in biogas production studies, namely the Gompertz, Logistic, and Transference models. These three models were chosen because each has its own characteristics and approaches in describing the growth rate of microorganisms and biogas accumulation during the anaerobic digestion process.

2. METHODS

2.1 Secondary data collection

Collected from the scientific article *'Investigation of the effects of starting pH, mass and retention time on biogas production using poultry droppings as feedstock'* (Adebimpe et al., 2020). The cumulative biogas data from the article (Adebimpe et al., 2020), obtained at a substrate mass of 200 grams, are presented in Table 1.

Table 1. Cumulative Biogas Data (cm^3)

Time (day)	pH of Feed				
	5	6	7	8	9
1	9	23	32	25	5
2	46	97	119	97	87
3	112	235	296	231	189
4	185	392	459	395	285
5	247	476	554	494	350
6	316	548	661	575	422
7	358	626	776	666	516
8	396	676	872	768	576
9	442	739	947	846	629
10	481	792	1046	921	696

Source : (Adebimpe et al., 2020)

2.2 Kinetic Model

The secondary data that has been collected will be analyzed using a kinetic model, in which three models are applied: the Gompertz model equation (1), the Logistic model equation (2), and the Transference model equation (3) (Alharbi & Alkathami, 2024).

1. *Modified Gompertz* Model

$$P_o = \mathbf{P.EXP}\left(-\mathbf{EXP}\left(\frac{\mathbf{R.e\,(L-t)}}{\mathbf{P}} + \mathbf{1}\right)\right) \ldots\ldots\ldots\ldots\ldots (1)$$

2. *Logistic* Model

$$P_o = \frac{\boldsymbol{P}}{\left(\mathbf{1+EXP}\left(\frac{\boldsymbol{4R\,(t-L)}}{\mathbf{p}}\mathbf{+2}\right)\right)} \ldots\ldots\ldots\ldots\ldots (2)$$

3. *Transference* Model

$$P_o = = \mathbf{P}\ \left(-\mathbf{EXP}\ \frac{\boldsymbol{R.e\,(t-L))}}{\mathbf{P}}\right) \ldots\ldots\ldots\ldots\ldots (3)$$

In kinetic analysis using modeling, the objective function is used to show the magnitude of the error between the actual data and the modeling data. In this modeling, the objective function used is the Sum of Squared Errors (SSE). Data processing with the above modeling uses Ms. Excel software.
SSE Formula is shown in equation (4) (Verma et al., 2024).

$$SSE = \sum_{i=1}^{n}(\mathbf{yi} - \tilde{y})^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

RMSE formula is in equation (5), and R^2 formula is in equation (6) (Ali et al., 2018).

$$RSME = \frac{\sqrt{\mathbf{yi - \tilde{y}i}}}{\frac{n}{\bar{y}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$R^2 = 1 - \frac{\sum(yi - \tilde{y}i)^2}{\sum(yi - \bar{y}i)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

3. RESULT AND DISCUSSION

The following are the results of biogas production modeling using the Gompertz, Transference and Logistic models.

3.1 Model graph

1. *Modified Gompertz* Model

The simulation results of the kinetic analysis of biogas production using the Modified Gompertz model are presented in Figure 1.

2. *Logistic* Model

The simulation results of the kinetic analysis of biogas production using the Logistic model are presented in Figure 2.

3. *Transference* Model

The simulation results of the kinetic analysis of biogas production using the Transference model are presented in Figure 3.

3.2 Modeling Result Data

The constants obtained from the simulation of the kinetic analysis of biogas production are presented in Table 2 . Figure 4 is a comparative graph of the constants produced from the three models used.

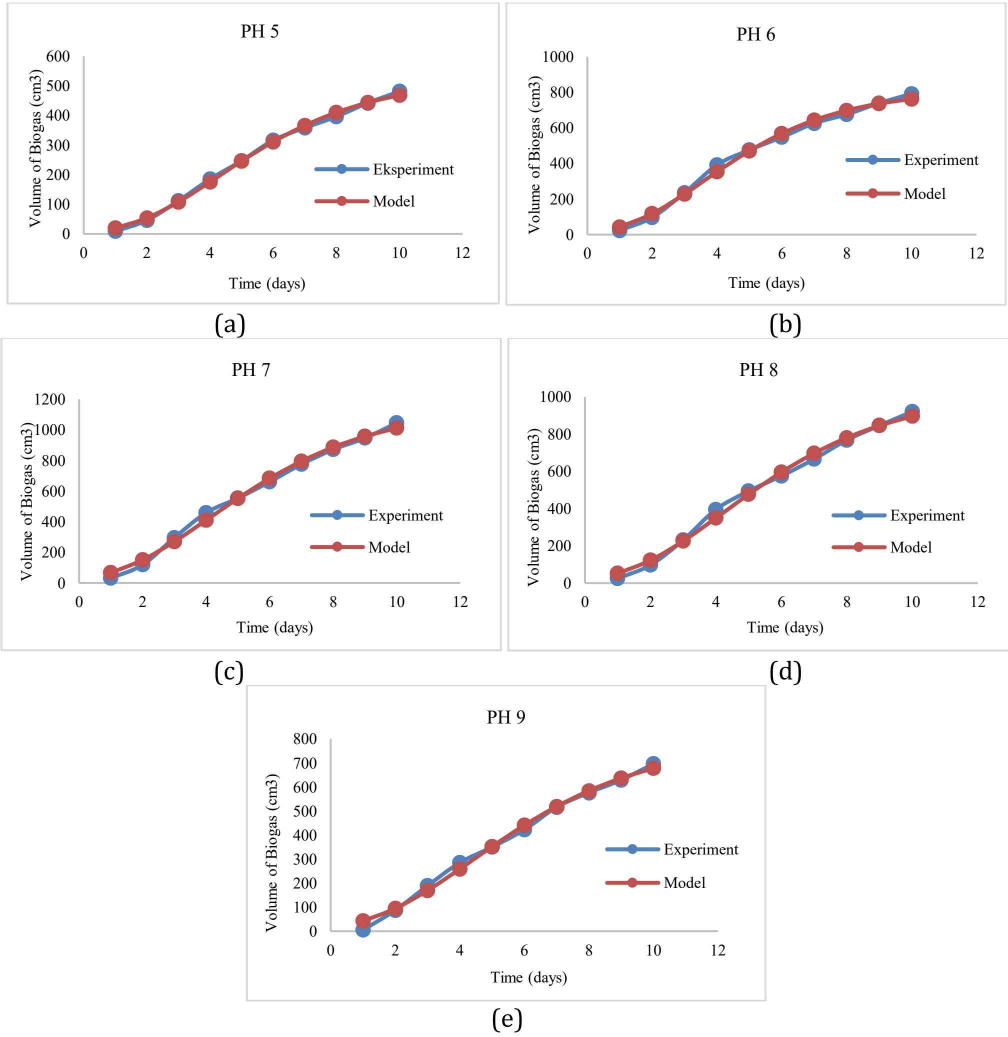

Fig. 1. Modified Gompertz model graph (a) pH 5 (b) pH 6 (c) pH 7 (d) pH 8 (e) pH 9

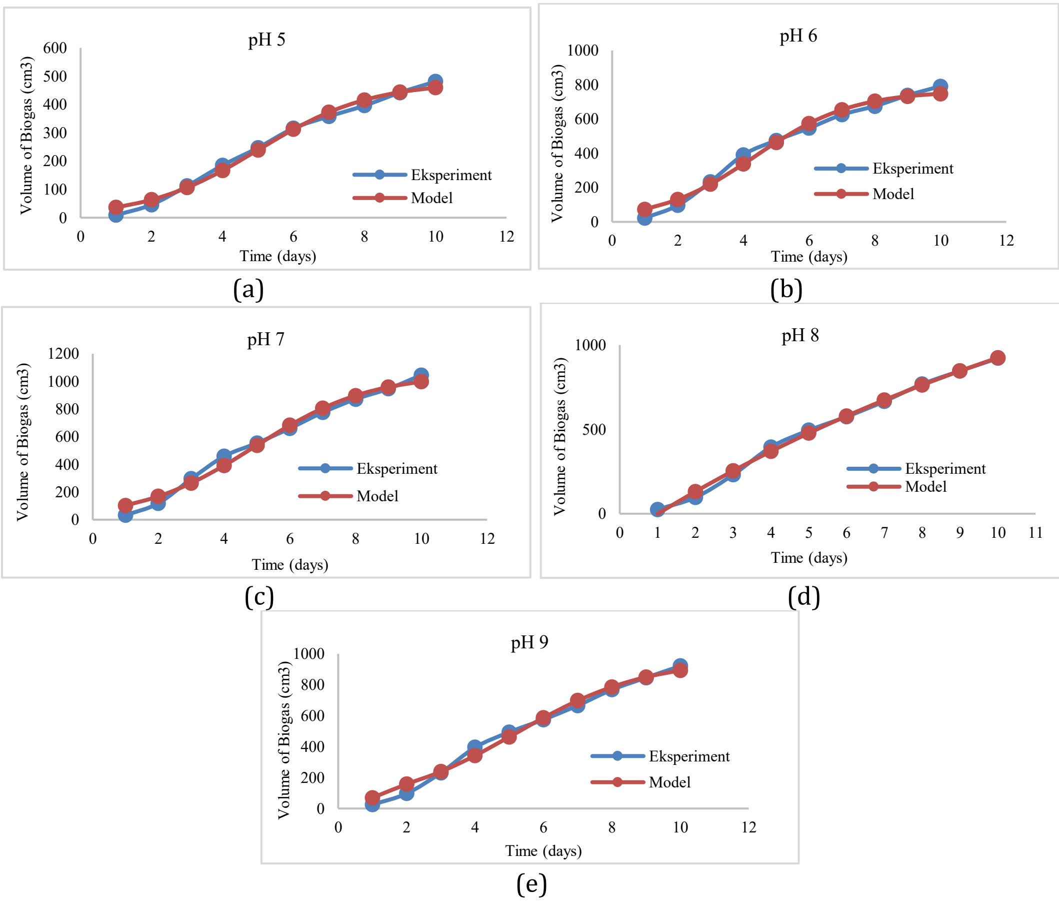

Fig. 2. Logistic model graph (a) pH 5 (b) pH 6 (c) pH 7 (d) pH 8 (e) pH 9.

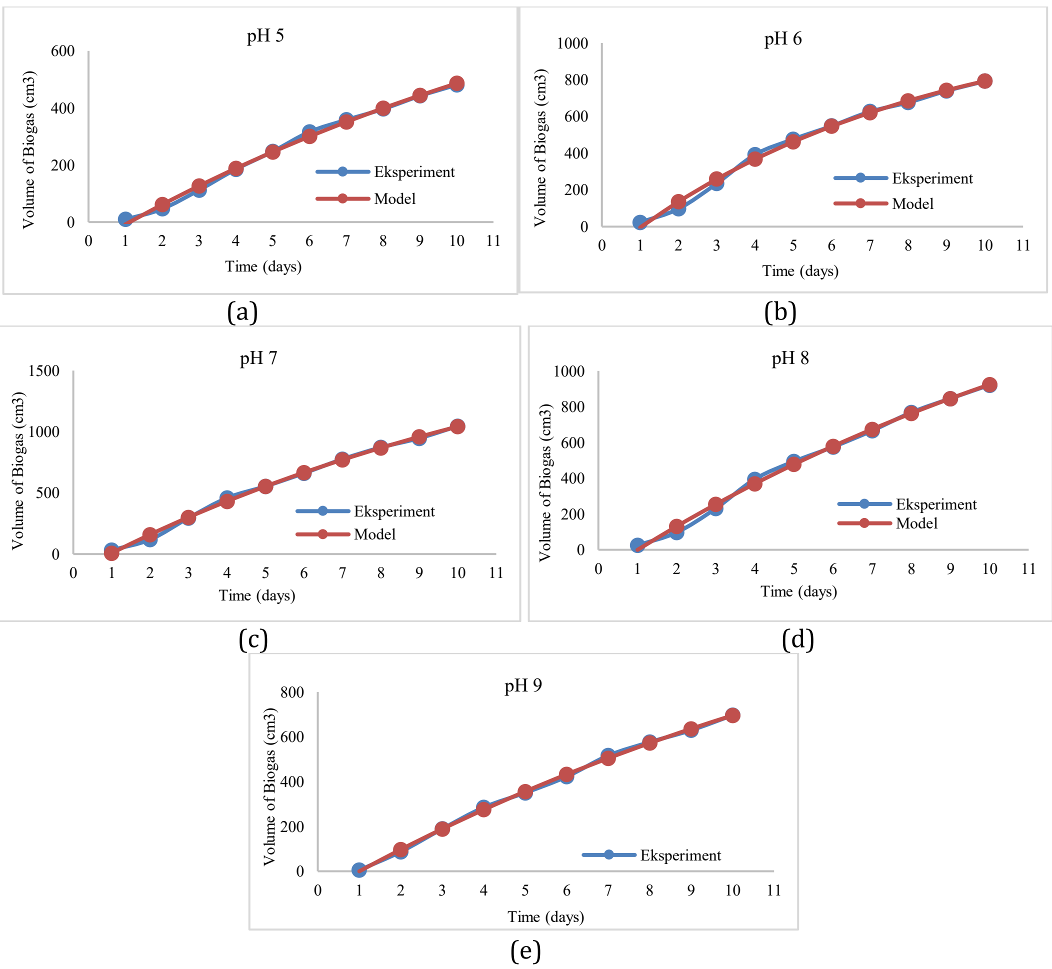

Fig. 3. Transfrence model graph (a) pH 5 (b) pH 6 (c) pH 7 (d) pH 8 (e) pH 9.

Table 2. Kinetic Constants of *Gompertz, Transference, Logistic Models.*

Constant	pH					Unit
	5	6	7	8	9	
Gompertz						
Ym	530.91	530.91	530.91	530.91	530.91	cm^3
U	70.95	125.99	143.93	128.48	93.91	cm^3/day
λ	1.53	1.19	1.15	1.28	1.25	days
SSE	723.29	4446.14	7585.43	5958.94	3346.4	
R^2	1.000	1.000	1.000	1.000	1.000	
RMSE	0.0038	0.0029	0.0028	0.0030	0.0038	
Transference						
Ym	1147.9	1163.99	2127.11	2084.75	1657.7	cm^3
U	71.14	148.29	158.23	135.73	100.22	cm^3/day
λ	1.12	1.03	0.95	1.00	1.00	days
SSE	1100.2	3735.71	3223.45	3369.29	573.56	
R^2	1.000	1.000	1.000	1.000	1.000	
RMSE	0.000	0.000	0.002	0.001	0.000	
Logistic						
Ym	479.80	765.87	1054.85	966.72	715.15	cm^3
U	75.15	128.25	149.46	125.00	98.92	cm^3/day
λ	1.82	1.36	1.40	1.30	1.55	days
SSE	2551.68	11245.87	17626.13	11660.29	7492.63	
R^2	0.9999	0.9999	0.9999	0.9998	0.9999	
RMSE	0.0059	0.0044	0.0039	0.0050	0.0049	

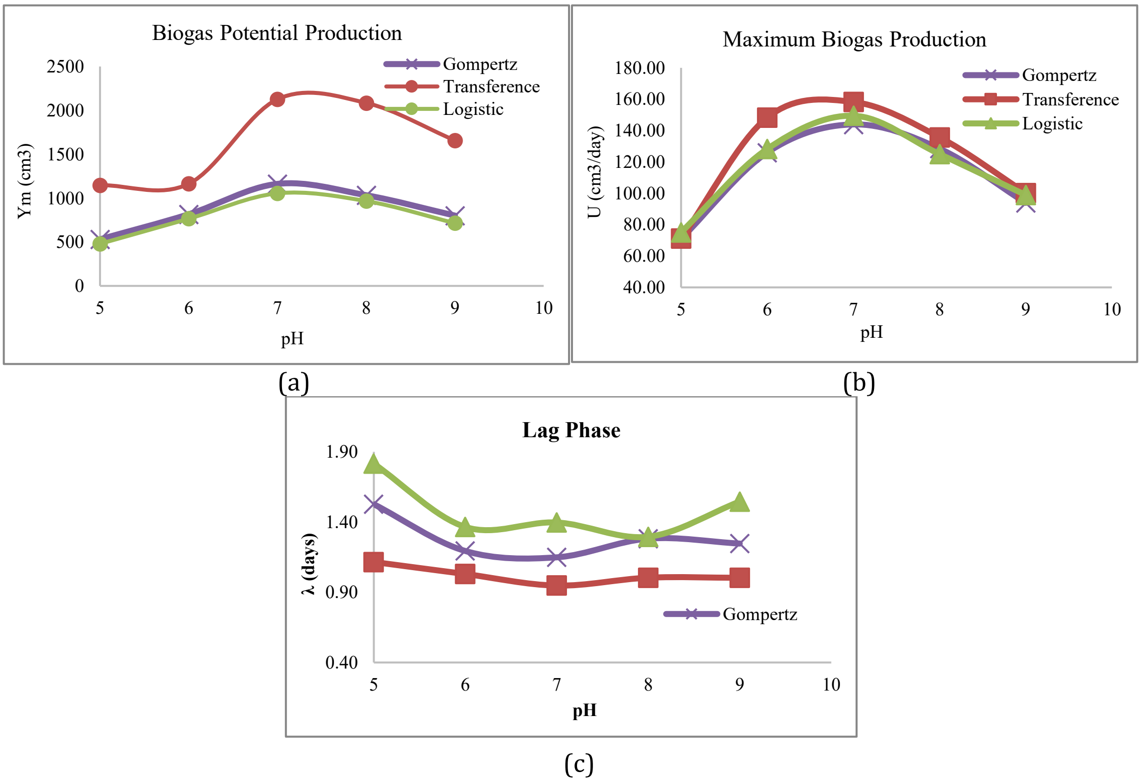

Fig. 4. Model Constant Graph, (a) Biogas Potential Production (Ym), (b) Maximum Biogas Production (U), (c) Lag Phase (λ)

3.3 Constants and the Objective Function Model

In this article, biogas production kinetics analysis was conducted using three models, namely Gompertz, Transference, and Logistic, to see how each model predicts biogas production volume at pH variations. The evaluation was carried out based on several main parameters, namely maximum production (Ym), maximum production rate (U), lag time (λ), error value (SSE and RMSE), and coefficient of determination (R^2) as an indicator of model accuracy against experimental data. From the calculation results, the Transference model was again proven to be the best model compared to the other two models. It can be seen at pH 7, in terms of maximum production rate (U), the Transference model of 158.23 cm^3/day recorded the highest value at pH 7, followed by the Logistic model of 149.46 cm^3/day and Gompertz which is 143.93 cm^3/day. Meanwhile, the Logistic model has a lower production rate and maximum production value compared to the other two models, as well as the highest SSE value at pH 7, which is 17626.13, and RMSE of 0.00386. This shows that Logistic is the model with the worst prediction performance among the three, especially in reflecting actual data, maximum biogas production potential (Ym), maximum production rate (U), and adaptation phase time or lag phase (λ) at pH variations of 5 to 9. Based on the maximum biogas production graph (Ym), the Transference model shows the highest production potential prediction consistently at all pH variations. The highest value was achieved at pH 7 of 2127.11 cm^3, far exceeding the Gompertz and Logistic models which each recorded a maximum value of 1162.60 cm^3 and 1054.85 cm^3 at the same pH.

In the lag phase, the Transference model again showed the most stable and efficient performance. The λ value in this model ranged from 0.98 to 1.12 days, which means that the adaptation time of microorganisms in the biogas production process was relatively fast and consistent at various pH. In contrast, the Logistic model showed the highest and most fluctuating λ value, with a maximum value reaching 1.82 days at pH 5. The Gompertz model showed a moderate adaptation time, which was around 1.15 days. This shows that the Transference model has better capabilities in representing the potential biogas that can be produced from the digestion process under optimum conditions.

Overall, the Transference model can be concluded as the most optimal model in predicting the biogas production process, especially at neutral pH (pH 7) which is the most ideal condition. This model not only provides predictions of high production potential, but also shows stability in rate parameters and lag phases, thus better representing the dynamics of biological processes that occur in anaerobic digestion.

The coefficient of determination (R^2) also strengthens the superiority of the Transference model. The R^2 value for this model is 1.00 at all pH variations, indicating that this model is able to explain almost all variations in experimental data (Ozili, 2023). In contrast, the Gompertz and Logistic models have R^2 values slightly below perfect, which are between 0.9998 and 0.9999, which although high, still indicate a slight deviation from the actual data. From the overall comparison of both model accuracy (SSE and RMSE), data fit (R^2), and the main kinetic parameters, the Transference model is the most superior. This model not only produces high biogas production predictions, but is also very accurate and stable, especially at pH 7, which is indeed proven to be the most ideal condition for the anaerobic digestion process. Thus, the Transference model can be considered the most representative in describing the kinetics of biogas production in this kinetic analysis.

3.3 Comparison of Cumulative Biogas Production of Experiment with Model

As can be seen in Figure 3, the Transference model graph shows the best performance in describing the kinetics of biogas production at various pH conditions. This is proven by the match between the model prediction results and the experimental data displayed in the graph. Visually, the model curve is very close to the experimental data at almost all observation points, indicating that this model is able to represent the dynamics of biogas production realistically. At pH 5 and 6, the Transference model already shows a biogas growth pattern similar to the actual data, although there is a slight deviation in the middle of the reaction time. Biogas production increased gradually from day 1 to day 10, and the model managed to follow the pattern quite accurately. This indicates that even though the acidic pH conditions are not ideal, the model is still able to describe the response of microorganisms to the environment. The best results were seen at pH 7, where the model's yield curve almost completely overlapped with the experimental results. The volume of biogas produced reached more than 1,100 cm^3, and the model predicted the growth rate and the plateau phase very accurately. This indicates that the Transference model is very effective in modeling the biogas production process at neutral pH, which is also known to be the most optimal condition for the activity of methanogenic microorganisms.

At pH 8 and 9, the model still showed consistent performance. Although there were slight differences at some points, especially towards the end of the digestion time, the growth direction and shape of the curve still resembled the experimental pattern. This proves that the Transference model is not only effective in one optimal condition, but is also quite adaptive in more alkaline environmental conditions. The quantitative suitability of the model is also strengthened by the low SSE (Sum of Squared Errors) value at all pH variations when compared to other models. The small SSE value indicates that the Transference model prediction has a low error rate against the experimental data. Overall, these results confirm that the Transference model is the most representative approach in explaining the kinetics of biogas production, both in terms of prediction accuracy and the suitability of the growth pattern of the volume of gas produced. The following is the state of the art of kinetic analysis research that has been conducted by several researchers, as presented in Table 3.

Table 3. Comparison of Biogas Production Kinetic Analysis

Authors	Title	Model	Results
(Pramanik et al., 2019)	Performance and Kinetic Model of a Single-Stage Anaerobic Digestion System Operated at Di erent Successive Operating Stages for the Treatment of Food Waste	First order, Modified Gompertz, Logistic function	The best Gompertz model with R2 value = 0.997 and RMSE = 0.622
(Velichkova et al., 2022)	Development of Simplified Models For Optimization OfBiochemical Methane Potential Procedure	Modified Models, Logistic, Transference	The modified Gompertz model with better fit with the largest R2 at 20 ml vinasse = 0.999.
(Ali et al., 2018)	Modeling the Kinetics of Methane Production from Slaughterhouse Waste and Salvinia Molesta: Batch Digester Operating at Ambient Temperature	Logistic, Gompertz, Richards, First order, Transference, Hashimoto	The Logistic model predicts cumulative methane production from CRF and CM better than other models, with rRMSE and R^2 values of 0.076 and 0.998, respectively.
(Shitophyta et al., 2023)	Evaluation and modelling of biogas production from batch anaerobic digestion of corn stover with oxalic acid	First Order, Logistic, Modified Gompertz, Transference	The coefficient of determination (R^2) obtained from all models is higher than 0.9. However, the RMSE value shows that the logistic model is more accurate at 2.3029.
(Abubakar et al., 2022)	Estimation of Biogas Potential of Liquid Manure from Kinetic Models at Different Temperature	Proposed model, Cone, Modified Gompertz, Logistic and Transference	The best models are Transference (R2 = 0.9963 and Adj.R2 = 0.9962), Cone (R2 = 0.9739 and Adj.R2 = 0.9730).

4. CONCLUSION

Based on the results of the analysis of biogas production kinetics using three models Gompertz, Logistic, and Transference, it is proven that the Transference model is the most accurate and stable in describing the biogas production process at various pH variations. This model is able to predict the highest maximum production (Ym) of 2127.11 cm^3 at pH 7, with a maximum production rate (U) of 158.23 cm^3/day and a relatively short time lag (λ), which is around 0.947 days. In addition, the Transference model has the lowest error value with an SSE of 3223.45 and a perfect coefficient of determination (R^2) of 1.000, which indicates very good agreement with the experimental data. At other pH conditions, this model also continues to show consistent performance and is able to follow the biogas production pattern realistically. In contrast, the Logistic model showed the lowest results, with a maximum production of 1054.85 cm^3 and a maximum production rate of only 149.46 cm^3/day at pH 7, and the highest SSE error of 17626.13, indicating poor prediction accuracy. The Gompertz model was in between the two with a maximum production of 1162.60 cm^3 and a production rate of 143.93 cm^3/day at the same pH. Overall, the Transference model is the best choice as a prediction tool for biogas production, especially at neutral pH conditions which are the optimal conditions for anaerobic fermentation. This model can be relied on to assist in the planning and development of biogas production systems because of its ability to provide accurate, stable, and realistic predictions.

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