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Biogas Production Kinetic Studies from Yam Peels

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Abstract

This study aimed at evaluating the biogas production kinetics of anaerobic digestion of yam peels (YMP). The models applied in the study of the kinetics of biogas production were the linear, exponential, Gaussian, exponential rise to maxima, logistic, modified logistic, modified Gompertz and, transference models. The cumulative biogas volume of 440 ml was applied for the kinetics study. The COD, TSS and pH values recorded before and during the digestion process were plotted against HRT. Error analysis on modelling were carried out with coefficient determination (R^2), root mean square error (RMSE) and sum of squares error values (SSE) functions. Model acceptability was based on the models whose R^2 values were $\geq$0.95. This was due to the fact that the closer the R^2 value to unity, the better the model fit. The biogas production kinetics results showed that the modified Gompertz model was most acceptable for describing the kinetics of YMP digestion with the R^2 value of 0.9934. The constants evaluated from the modified Gompertz model for P, R_m and λ were 424.5 ml, 111.9 ml and, 3.878 days respectively. The predicted cumulative biogas volume calculated with the use of the modified Gompertz model was 424.1228 ml and was comparable to the experimental cumulative volume. The R^2 values of the biogas production models simulated indicated that these models with the exception of the linear, Gaussian and exponential rise to maxima models can be used for designing a batch reactor for the treatment of YMP by anaerobic digestion.

Keywords: Anaerobic digestion; Yam peel; Biogas volume; Biogas production kinetic models, Model simulation

Abbreviations and Nomenclature

APHA	American Public Health Association
COD	Chemical Oxygen Demand
HRT	Hydraulic Retention Time (day)
DOE	Design of experiments
RMSE	Root mean square error
TSS	Total suspended solids
SSE	Standard square error
YMP	Yam peel
a	Maximum specific rate of biogas yield (ml/gm/day)
b	Constant (ml/day2)
c	Constant (day^{-1})
B_p, M, y	Predicted cumulative biogas volume (ml)
B_{max}	Ultimate methane/biogas potential or production (ml)
P	Biogas potential of the substrate (ml)
R^2	Correlation coefficient
R_m , μ_m	Maximum biogas production rate
t or T	Retention time for batch digestion (day)
λ	Lag phase (day) (minimum time required to produce biogas)
e	Euler's constant = exp (1) = 2.7183
k	Kinetic rate constant (day^{-1})
T_0	The time where the maximum/peak biogas production rate took place (days)
y	Biogas production rate in ml/day

1. Introduction

Vast amounts of waste are produced by agricultural-based industries yearly (Sadh, Duhan & Duhan, 2018). Most of these wastes are released into the environment without proper treatment and disposal procedures. These wastes are either disposed inappropriately leading to environmental pollution and harmful effects on both human and animal health (Sadh, Duhan & Duhan, 2018). It is very necessary to have proper identification and management of these wastes to ensure desirable environmental sanitation. One of the ways that can be used to achieve this is by biotransformation of these wastes into commercially valuable products (Aruna *et al*., 2017). Fossils fuel, which include oil and natural gas, are depleting assets, and efforts are geared towards the search for new sources of energy that are also environment-friendly (Omer, 2017). This brings about the need to use alternative renewable and cleaner bioenergy resources (Sadh, Duhan & Duhan, 2018). The energy obtained from treatment by anaerobic digestion has the advantages of being environment-friendly leading to the reduction in the emissions of pollutants and the improvement in energy security in the form of biogas with residue as the end product that could be applied as manure (Rahmat *et al*., 2019).

The use of energy crops is not competitive with fossils fuel energy, hence the need to apply crop and forest residues, animal manure, and the organic fraction of municipal solid waste and agro-industrial by-products, such as bagasse, oil-palm residues, sawdust and, wood off-cuts (Omer, 2017). Nigeria is the leading producer of yams (Dioscorea spp.) in the world (Longjan & Dehouche, 2018; Aruna *et al*., 2017). In 2012, this accounted for over 65% (38 million metric tonnes) of the world's production and it is more widely distributed and abundantly available when compared to cereals (Aruna *et al*., 2017). One of the ways of controlling the problems associated with the abundance of its peels and its improper disposal methods is the use of these yam waste to produce renewable energy through anaerobic digestion (Longjan & Dehouche, 2018). The application of yam peel in the anaerobic digestion process serves as a solution to curb environmental pollution due to unhealthy disposal in developing countries, including Nigeria. The biogas generated from the process can be applied for heating purposes.

Kinetics can be applied in designing and operating a digester and predicting its performance (Shete & Shinkar, 2014). Information needed for the design of full-scale biodigesters and their efficiency when used under the same operating conditions can be estimated from the results of kinetic studies obtained (Nor-Faekah, Fatihah & Mohamed, 2020). The purpose of the study was to investigate the effect of kinetic parameters on the batch anaerobic digestion of yam peels (YMP) using the kinetic parameters obtained from the batch anaerobic digestion of yam peel in Nweke & Nwabanne (2021). Also, linear, exponential, exponential rise to maxima, logistic, modified logistic, modified Gompertz and, transference models were used to study the kinetics of biogas production from the daily and cumulative biogas volumes.

2.0 Material and Methods

2.1 Experimental procedure

The batch digestion procedure was carried out as stated by Nweke & Nwabanne (2021).

2.2 Kinetic study

The daily and cumulative biogas volumes obtained during digestion were used in the evaluation of the biogas production kinetic parameters. The kinetic parameters were determined using both polynomial and non-linear curve fitting toolbox available in MATLAB 8.5.0.197613 (version R2015a). These kinetic parameters were used to plot the predictive daily and cumulative biogas production. The summary of the kinetic models used in the study is shown in Table 1.

Table 1: Summary of kinetic models applied in the digestion of YMP

Kinetic model	Equation	Reference
Linear	$y = a + bt$	Manyuchi, Mbohwa & Muzenda, (2018); Das & Mahanta, (2014a)
Exponential	$y = a + bexp(ct)$	Das & Mahanta (2014a)
Gaussian	$y = a \exp\left[-0.5\left(\frac{T - T_0}{b}\right)^2\right]$	Kim *et al*. (2018); Das & Mahanta (2014a)
Exponential rise to maxima	$M = B_{max}(1 - \exp(-kt))$	Pagliaccia *et al*. (2016)
Logistic	$M = \frac{a}{1 + bexp(-kT)}$	Latinwo & Agarry (2015)
Modified logistic	$M = \frac{P}{\left[1 + \exp\left\{4R_m \times \frac{\lambda - t}{P} + 2)\right\}\right]}$	Parra-Orobio, Donoso-Bravo & Torres-Lozada (2017)
Modified Gompertz	$M = P.exp\left\{-exp\left[\frac{R_m.e}{P}(\lambda - t) + 1\right]\right\}$	Parra-Orobio, Donoso-Bravo & Torres-Lozada (2017)
Transference	$M = P \times \left\{1 - \exp\left[\frac{-R_m(t - \lambda)}{P}\right]\right\}$	Parra-Orobio, Donoso-Bravo & Torres-Lozada (2017)

3.0 Results and Discussions

3.1 The production of biogas

The yam peel waste (YMP) being considered for kinetic study had been analyzed by Nweke & Nwabanne (2021) from the batch digestion of YP. Hence, the daily and cumulative biogas volumes produced from the anaerobic digestion of YMP in addition to the pH, TSS and COD values obtained during digestion are already known. The cumulative biogas volume obtained was 440 ml. The table of the daily biogas volumes obtained is shown in Table 2. Hence, the biogas production kinetic constants and predictive biogas volumes to be evaluated from the kinetic models are obtainable.

Table 2: Biogas Volume Produced from YMP Digestion (ml)

HRT (day)	Daily biogas volume (ml)	Cumulative biogas volume (ml)
1	0	0
2	0	0
3	10	10
4	30	40
5	60	100
6	165	265
7	55	320
8	40	360
9	25	385
10	10	395
11	5	400
12	20	420
13	10	430
14	10	440
15	0	440

3.2 The effect of hydraulic retention time on the kinetic parameters

The effect of hydraulic retention time of 15 days on the pH, TSS and COD removal during YMP digestion are shown in Figures 1, 2, and 3 respectively.

3.2.1 Effect of hydraulic retention time on chemical oxygen demand (COD) removal

The total concentration of organic matter is measured by the COD analysis and the elimination of COD measures the efficiency of removal of biodegradable organic compounds as biogas is produced (Chandra *et al*., 2012). The effect of COD with hydraulic retention time on the digestion of YMP is shown in Fig. 1. The initial COD value of YMP was small and was represented with an influent COD of 102.36 mg/l which was initially analyzed by Nweke & Nwabanne, (2021). The COD removal efficiency for YMP at the end of digestion was 48.31%. COD parameter was also evaluated by Saragih *et al*. (2019) who treated anaerobic digestion of food waste. The result showed that there was COD reduction at the end of digestion. This was due to the degradation of the organic matter in the waste.

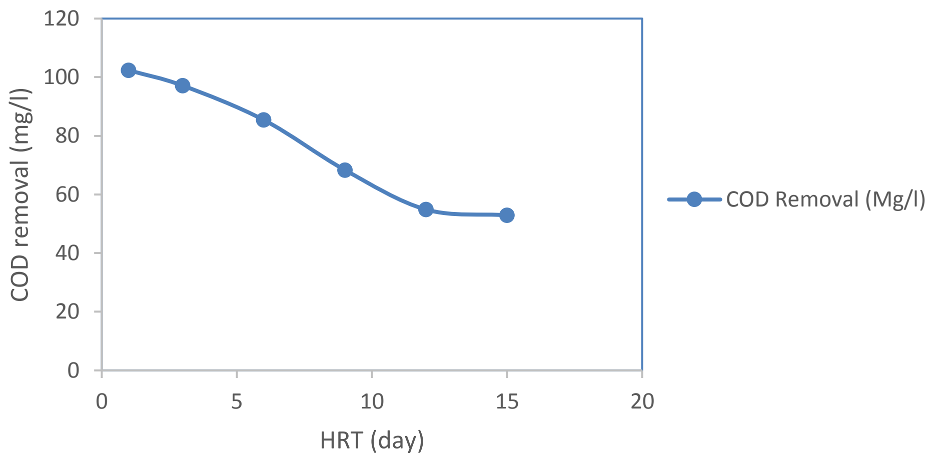

Fig. 1: COD removal with HRT on YMP digestion

3.2.2 Effect of hydraulic retention time on total suspended solids (TSS)

The TSS concentration in the digester was measured to know the insoluble organic present in the substrates (Musa *et al*., 2018). The effect of total suspended solids (TSS) with hydraulic retention time on the digestion of YMP is shown in Fig. 2. The TSS of the substrate was observed to reduce with time during digestion. Reduction of TSS concentration was also reported by Musa *et al*., (2018) after the digestion of cattle slaughterhouse wastewater from a concentration of 1955 mg/L to 47–158 mg/L after digestion.

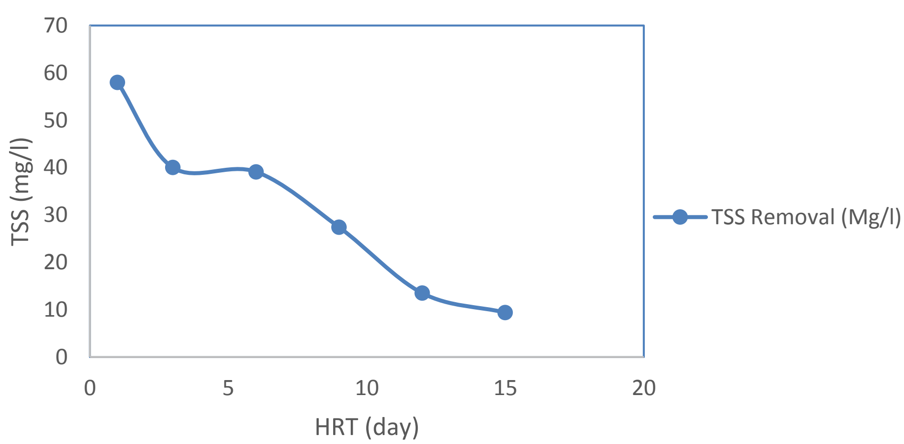

Fig. 2: Variation of TSS with HRT on YMP digestion

3.2.3 Effect of hydraulic retention time on Ph

The pH determines the health of anaerobic microorganisms and the performance of the AD system (Sarker *et al.*, 2019). The pH of the substrates was initially alkaline but turned acidic as HRT increased. This is shown in Fig. 3. Olanrewaju (2018) reported that the pH of yam peel, during the anaerobic digestion of yam peel was 6.92 on the first day but later reduced to 5.70 on the last day of the experiment.

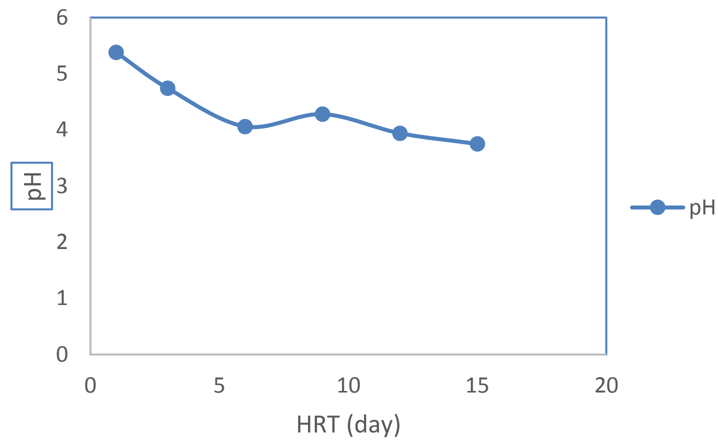

Fig. 3: Variation of pH with HRT on YMP digestion

3.3 Biogas production kinetic evaluation

The kinetic validations and simulations for biogas production are shown in this section. Error analysis were carried out to reduce bias. These functions included coefficient of determination (R^2), root mean square error (RMSE) and sum of squares error values (SSE). The use of R^2 has been proved as a standard metric to evaluate regression analyses in any scientific domain. Its value varies from -∞ to 1 (Chicco, Warrens & Jurman, 2021). The closer the R^2 value to unity, the better the model fit (Sarva & Muhammad, 2020). Obtaining an R^2 value close to 1 shows a high correlation between the experimental and predicted values. In addition, values of less than 0.2 as the difference between predicted and adjusted R^2 indicated a fewer efficacy of the model (Sarva & Muhammad, 2020). The values of RMSE and SSE varies from 0 to +∞. The closer the values to 0, the better the curve fit the experimental values (Chicco, Warrens & Jurman, 2021).

3.3.1 Linear model validation for YMP digestion

Figs. 4 and 5 showed ascending and descending limbs of the linear plots of the daily biogas production rates for YMP digestion. The coefficient of determination (R^2) in the ascending limb for YMP was 0.7459 while the descending limb gave an R^2 value of 0.5435 respectively. The coefficient of determination (R^2), adjusted R^2, constants *a* and *b* evaluated from the model equation, the sum of squares error values (SSE) and, root mean square error values (RMSE) obtained for YMP are tabulated in Table 3. A low value of SSE and RMSE, close to 0 indicates a better model goodness-of-fit (Pham, 2019). Shitophyta & Maryudi (2018) obtained regression coefficients ranging between 0.88 to 0.93 while digesting corn cob. These values were all obtained from both the rising and falling limbs of the plots. Conclusively, the low R^2 values obtained from the ascending and descending limbs indicated that YMP digestion did not followed the linear model.

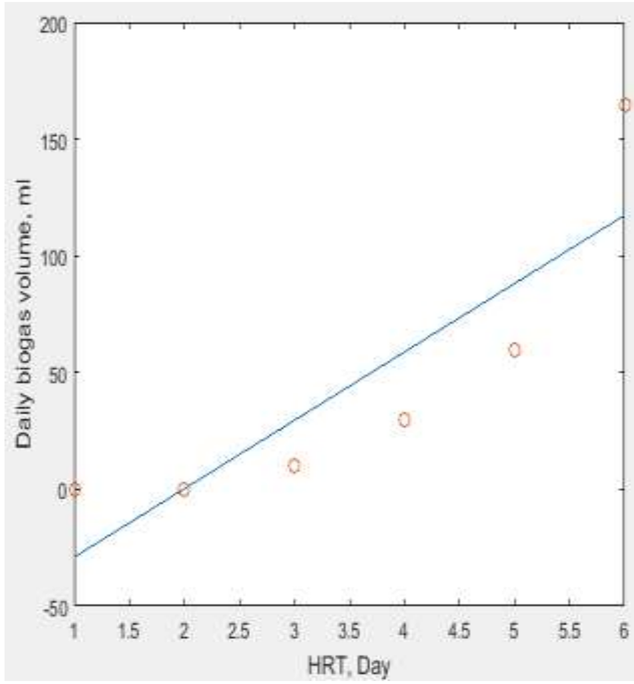

Fig. 4: Biogas production rate from linear model (ascending limb) of YMP digestion

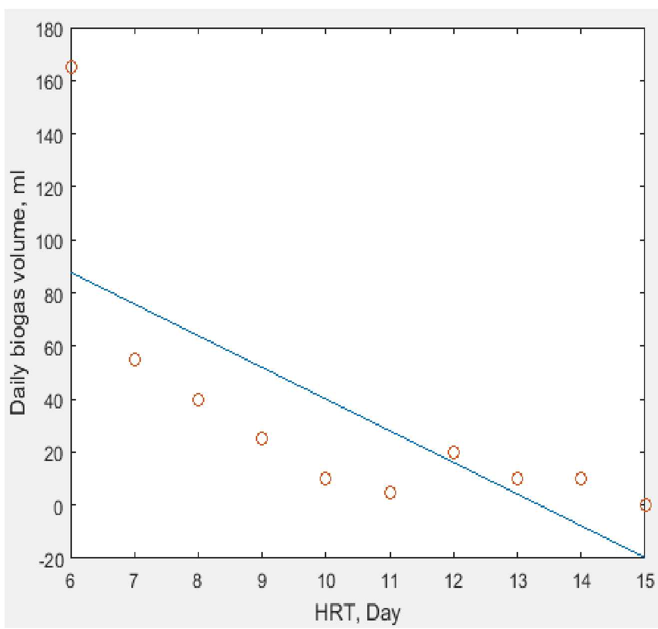

Fig. 5: Biogas production rate from linear model (descending limb) of YMP digestion

3.3.2 Exponential model validation for YMP digestion

As presented in Figs. 6 and 7, the exponential plot of daily biogas production rates in the ascending and descending limb of YMP digestion was carried out to determine the ability of the model in describing the experimental process. The coefficient of determination (R^2) obtained in the ascending limb was 0.9972. The descending limb gave an R^2 value of 0.9764. It was observed that the digestion simulation correlated more in the ascending limb than in the descending limb, as also observed in the linear model. The coefficient of determination (R^2), constants *a*, *b*, and *c* in the model equation, the sum of squares error values (SSE), and root mean square error values (RMSE) determined for YMP is tabulated in Table 3. The value, *c* is positive and negative for ascending and descending limbs respectively.

Generally, the R^2 values of the ascending plots have been reported to be higher than those on the descending plots when modeled with the exponential equation. The work of Shitophyta & Maryudi (2018) revealed that $R^2 > 0.9$ was obtained in the ascending limbs of the exponential model while the descending graph gave $R^2 < 0.9$. Shitophyta & Maryudi (2018) and Das & Mahanta, (2014b) also reported that higher R^2 values were obtained from the exponential model when compared to the linear model. The ascending limb of the linear model gave a higher R^2 than the exponential model. Das & Mahanta (2014b) observed that the R^2 values from exponential modeling in the ascending and descending limb ranged from 0.967 to 0.995 and were better than the linear model. From the results obtained, it could be concluded that the exponential modeling of YMP showed a better simulation than the linear model and can be applied in simulating the biogas production process.

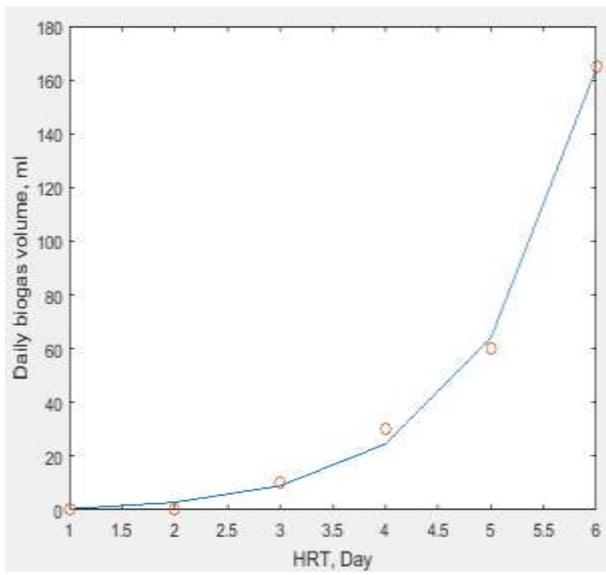

Fig. 6: Biogas production rate from exponential model (ascending limb) of YMP digestion

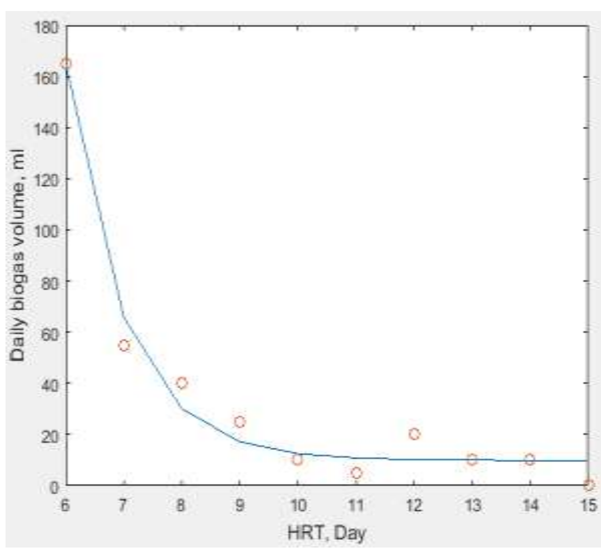

Fig. 7: Biogas production rate from exponential model (descending limb) of YMP digestion

3.3.3 Gaussian model validation for YMP digestion

The Gaussian model was used to simulate the daily biogas production rate of YMP as can be seen in Fig. 8. The coefficient of determination (R^2) obtained was 0.8588. The R^2 value, adjusted R^2 value, constants *a*, *b*, and T_0 in the model equation, the sum of squares error value (SSE), and root mean square error value (RMSE) obtained from the kinetic model are tabulated in Table 3. The root-mean-square error obtained was low indicating that the model could be used to simulate the biogas production from the process. Das & Mahanta (2014b) and Lo *et al*. (2010) reported R^2 values of >0.7 after simulating the co-digestion of sawdust and cattle dung, and the digestion of corn cob respectively with the Gaussian model. However, the R^2 value of less than 0.95 obtained from Gaussian model the indicated that the model cannot be used to describe the digestion process.

Table 3: Model Simulation from Daily Biogas Volume for YMP Digestion

Constant	Linear Ascending	Linear Descending	Exponential Ascending	Exponential Descending	Gaussian
***a* (ml/day)**	-58.33	159.4	-1.188	9.876	159.6
***b* (ml/day2))**	29.29	-11.94	0.6224	7.005e+04	0.7541
***c* (day^{-1})**	Not calc.	Not calc.	0.9305	-1.019	Not calc.
T_0 (day)	Not calc.	Not calc.	Not calc.	Not calc.	5.985
R^2	0.7459	0.5435	0.9972	0.9764	0.8588
Adjusted R^2	0.6824	0.4864	0.9954	0.9696	0.8352
RMSE	35.75	35.14	4.319	8.548	17.12
SSE	5112	9880	55.95	511.5	3516

Not calc. = not calculated/not part of the constants of the model

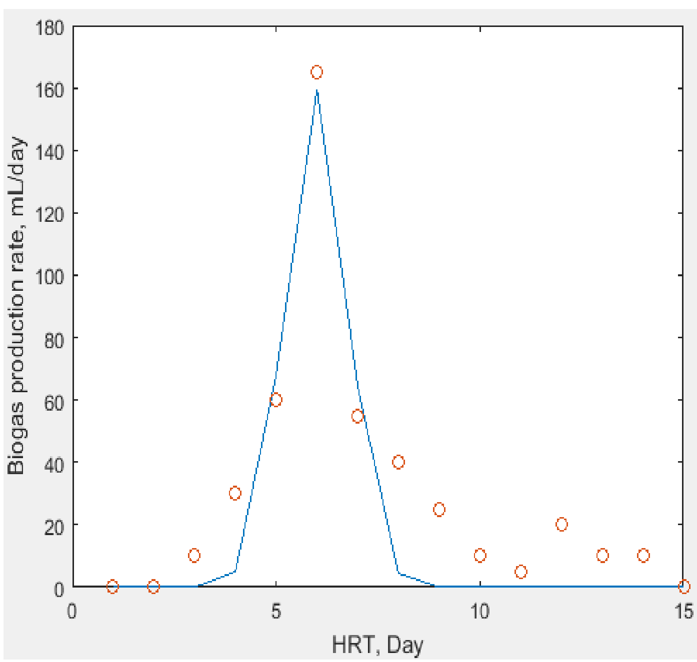

Fig. 8: Biogas production rate from Gaussian model of YMP digestion

3.3.4 Exponential rise to maxima model validation for YMP digestion

The experimental and predicted cumulative biogas volumes for YMP were 400 and 123.112986 ml respectively with R^2 and adjusted R^2 values of -0.6253 and -0.7503 respectively. These negative values indicated that the exponential rise to maxima model could not simulate the biogas production from the anaerobic digestion of YMP. The kinetic constant, k obtained was 0.4837 day^{-1} as shown in Table 4. The plot of the exponential rise to maxima model simulation for YMP digestion is shown in Fig. 9.

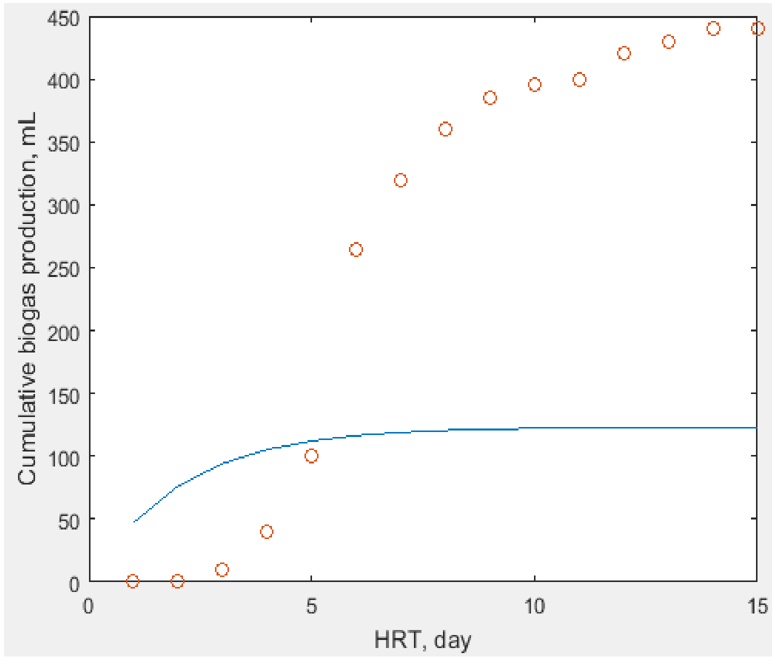

Fig. 9: Cumulative biogas production from exponential rise to maxima model of YMP digestion

3.3.5 Logistic model validation for YMP digestion
The cumulative biogas production from YMP digestion was simulated into the logistic model. The R^2, adjusted R^2, RMSE, and SSE values evaluated were 0.9898, 0.9881, 19.69, and 4650 respectively. The predicted cumulative biogas volume was evaluated as 416.4840 ml and had a difference of $\pm$ 16.5 ml when compared to the experimental volume. The kinetic constants a, b, and k obtained are shown in Table 4. The plot of the logistic model simulation on YMP digestion is shown in Fig. 10. The logistic model could be applied for the simulation of YMP digestion due to the high R^2 value ($\geq$0.95) obtained Manyuchi *et al*. (2015) reported that the logistic model was best at simulating bio-methane production using acti-zyme when compared to other models due to the high R^2 value of 0.9977 obtained from simulating the model.

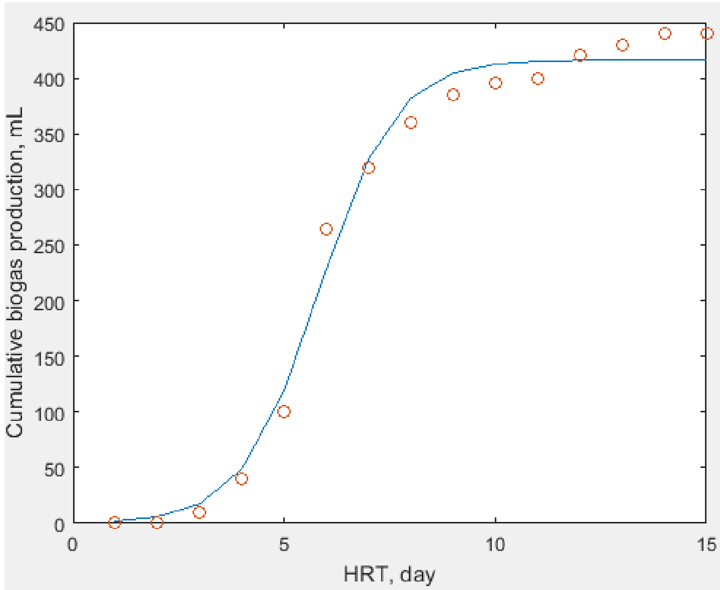

Fig. 10: Cumulative biogas production from logistic model of YMP digestion

3.3.6 Modified Logistic model validation for YMP digestion

The performance of modified logistic model simulation in the cumulative biogas production from YMP digestion was studied. The simulation results for YMP digestion were 0.9898, 0.9881, 19.69, and 4650 as R^2, adjusted R^2, RMSE, and SSE values respectively. These values were observed to be the same as obtained from the logistic model. The experimental and predictive cumulative biogas volumes from the model had a difference of $\pm$16.5 ml. The kinetic constants P, R_m and λ obtained from the simulation are shown in Table 4. It was concluded that the modified logistic model was suitable to predict biogas production from YMP digestion due to the high R^2 value ($\geq$0.95). The plots of modified logistic model simulations for YMP digestions are shown in Fig. 11.

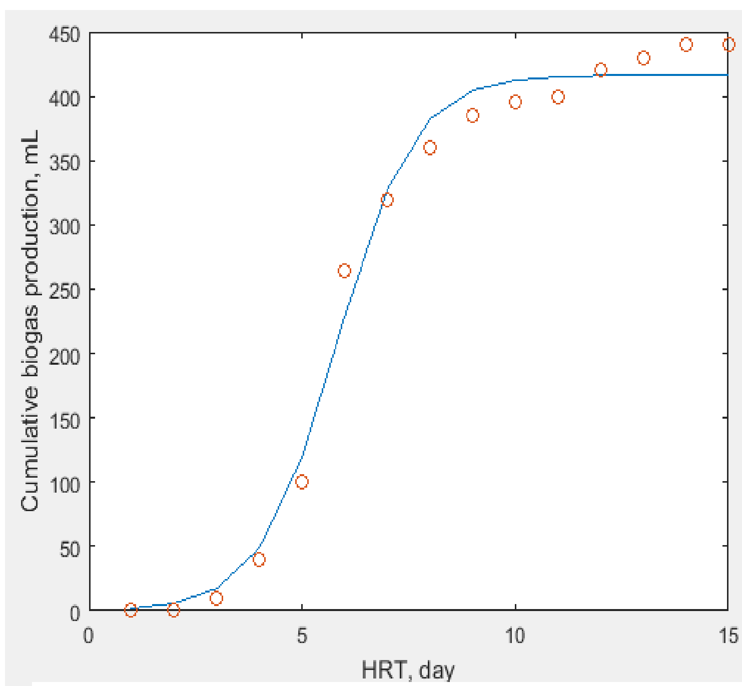

Fig. 11: Cumulative biogas production from modified logistic model of YMP digestion

3.3.7 Modified Gompertz model validation for YMP digestion

The result of the modified Gompertz model on the biogas production from YMP digestion gave R^2, adjusted R^2, RMSE, and SSE values of 0.9934, 0.9924, 15.81, and 2998 respectively. The predicted cumulative biogas volume was evaluated as 424.1228 ml and had a difference of $\pm$ 24.1 ml when compared to the experimental volume. The kinetic constants P, R_m and λ were 424.5 ml, 111.9 ml, and 3.878 days respectively as shown in Table 4. The high R^2 value (closest to 1) obtained indicated that the modified Gompertz model was the best at predicting biogas production from YMP digestion. The plot of the modified Gompertz model simulation for YMP digestion is shown in Fig. 12.

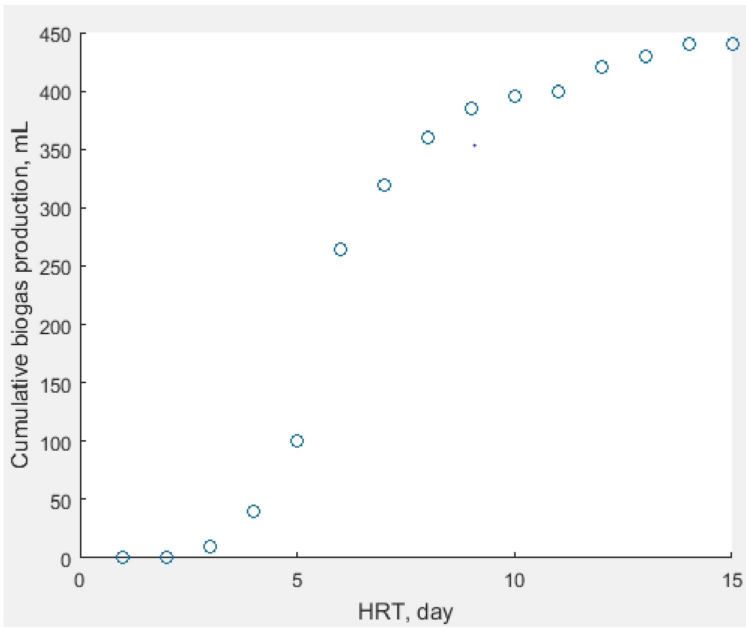

Fig. 12: Cumulative biogas production from modified Gompertz model of YMP digestion

3.3.8 Transference model validation for YMP digestion

The transference model provided a high R^2 value of 0.972 with RMSE and SSE of 32.65 and 1.279e+04 respectively after simulation. The experimental and predictive cumulative biogas volumes for YMP were comparable with a difference of $\pm$48.16 ml. The kinetic constants P, R_m and λ determined are shown in Table 4. The R^2 value obtained from modelling the biogas production from YMP digestion indicated that the model was acceptable in describing the process. The plot of transference model simulation for YMP cumulative biogas volume is shown in Fig. 13.

The model that best simulated the biogas productions from YMP digestion was evaluated from the values of R^2, RMSE, and SEE. The model simulation results showed that the cumulative biogas yield followed a non-linear relationship with time. The model with 95% confidence level was termed significant in describing the biogas production process. Hence, the exponential, logistic, modified logistic, modified Gompertz and transference models were acceptable since their R^2 values were $\geq$0.95. However, the modified Gompertz model was observed to best simulate the biogas production process because it provided the highest values of R^2 with minimum RMSE and SEE. High correlation was observed between the predicted and experimental cumulative biogas production from the models with the exception of exponential rise to maxima model. This confirmed that the models could be applied in simulating the biogas production obtained from the anaerobic digestion of YMP. Latinwo & Agarry (2015) and Das & Mondal (2015) indicated that modified Gompertz and logistic models gave better R^2 values than exponential rise to maxima model. This observation was made with YMP model simulation where the modified Gompertz, modified logistic and logistic models gave higher R^2 values than exponential rise to maxima model. Deepanraj, Sivasubramanian & Jayaraj (2015) reported that a better fit was obtained from the modified Gompertz model when compared to the logistic model.

Hence, the results obtained from modelling the biogas production from YMP digestion indicated that the models could be applied in fitting the experimental data except the linear, Gaussian and exponential rise to maxima models.

Table 4: Model Simulation from Cumulative Biogas Volume for YMP Digestion

Constant	Exponential rise to maxima	Logistic	Modified logistic	Modified Gompertz	Transference
M_{exp} (ml)	440	440	440	440	440
M_{pred} (ml)	123.1130	416.4840	Not calc.	424.1228	448.1629
B_{max} (ml)	123.2	Not calc.	Not calc.	Not calc.	Not calc.
k (day^{-1})	0.4837	1.108	Not calc.	Not calc.	Not calc.
a (ml/day)	Not calc.	416.5	Not calc.	Not calc.	Not calc.
b (ml/day)	Not calc.	633.7	Not calc.	Not calc.	Not calc.
P (ml)	Not calc.	Not calc.	416.5	424.5	485.5
R_m (ml)	Not calc.	Not calc.	115.4	111.9	95.8
λ (day)	Not calc.	Not calc.	4.017	3.878	2
R^2	-0.6253	0.9898	0.9898	0.9934	0.972
Adjusted R^2	-0.7503	0.9881	0.9881	0.9924	0.9674
RMSE	239.1	19.69	19.69	15.81	32.65
SSE	7.433e+05	4650	4650	2998	1.279e+04

Not calc. = not calculated/not part of the constants of the model

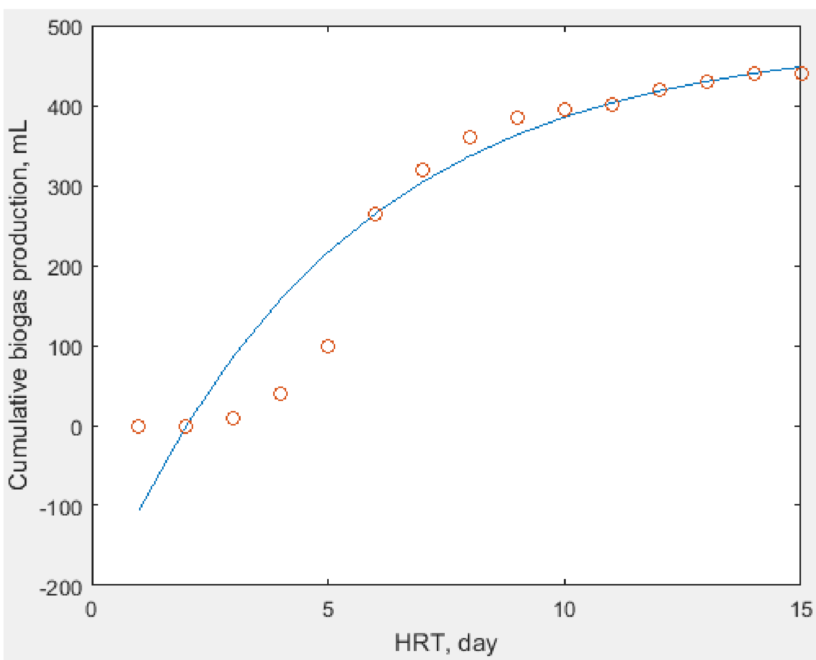

Figure 13: Cumulative biogas production from transference model of YMP digestion

4.0. Conclusion

Eight kinetic models were used for the biogas production kinetic study of YMP digestion. These models were the linear, exponential, Gaussian, exponential rise to maxima, logistic, modified logistic, modified Gompertz, and transference models. The modified Gompertz model gave the best simulation with the highest R^2 value of 0.9934, being the closest to infinity. The predicted cumulative biogas volume from the modified Gompertz model was

424.1228 ml with the difference of ±24.1 ml obtained between the experimental and predicted cumulative biogas volume. The adjusted R^2, RMSE, and SSE values were 0.9924, 15.81, and 2998 respectively. The RMSE and SSE were closest to zero when compared to the other models. The kinetic constants P, U_m and λ of 424.5 ml, 111.9 ml, and 3.878 days respectively were also obtained from the model. The coefficients of determination obtained from all the model plots for YMP digestion were also high indicating the ability of the kinetic models in evaluating the biogas production from the digestion process. However, this conclusion was with the exception of the linear, Gaussian and exponential rise to maxima models which gave R^2 values of less than 0.95 and cannot be used to describe the biogas production from YMP digestion.

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