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KINETIC MODEL DEVELOPMENT FOR BIOGAS PRODUCTION FROM LIGNOCELLULOSIC BIOMASS

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ABSTRACT

Lignocellulosic biomass has great potential for biogas production, but there are various factors which affect the performance of lignocellulosic biomass. Among the various factors, temperature is one of the important factors which play a significant role in biogas production from lignocellulosic biomass. Biogas production was studied for bamboo dust, sawdust, sugarcane bagasse and rice straw, all separately mixed with cattle dung. The effect of temperature on biogas production from various lignocellulosic biomasses was studied for temperature range from 35°C to 55°C at steps of 5°C. The objective of this work is to develop a mathematical model for evaluating the effect of temperature on the rate of biogas production from various lignocellulosic biomasses. The new mathematical model is derived by modification of the modified Gompertz model. The new model is found to be suitable for lignocellulosic biomass mixed with cattle dung in the temperature range 35°C to 55°C. The resulting estimated biogas production is found to be highly correlated to the experimental data of present study.

Keywords: Biogas; Kinetic study; Lignocellulosic biomass; Mathematical model; Temperature effect

1. INTRODUCTION

Demand for energy is increasing enormously due to overuse of fossil fuels in industry, automobiles, marines etc., whereas supply and availability of fossil fuels is decreasing day by day. Hence, researchers are exploring and exploiting various energy production technologies like anaerobic digestion or gasification of biomass. Implementation of biomass biodegradation processes such as gasification is gaining importance because of eco-efficient and sustainable energy conversion methods and low creation of pollutants (Sharma, 2011). Different types of gasifiers are developed for improvement of their efficiency (Winaya et al., 2015), easy operation and relatively low production of tar. Surjosatya et al. (2014) have worked on a modified updraft gasifier and they found that with recirculation of pyrolysis gases from the top of the gasifier (drying zone) to the combustion zone and the gas outlet from the reduction zone resulted in a maximum lower heating value of 4.9MJ/m^3. Also, increasing the flow of the pyrolysis gases to the combustion zone reduced the tar production. Researchers are also taking interest in studying the kinetics of the biodegradation process, as it is very important to know

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about the performance of the reactor, which helps in the design of the biogas plant operating with various feed materials. It also helps in understanding the mechanisms behind anaerobic digestion processes (Castillo et al., 1995; Abdullahi, 2011; Mata-Alvarez et al., 1993). Kinetic models are reported to be useful tools to optimize the co-digestion processes as well (Gavala et al., 2003). Several kinetic models pertaining to bio-methanation processes have been reported during the last few decades. Although temperature is the most important ambient condition for bacterial growth (Ingraham, 1962), temperature dependency of biogas digestion is not that revealing in most of the models. However, appropriate mathematical models are needed in order to overcome the problem of system instability and also to design and operate anaerobic systems effectively. This study presents the development of a kinetic model based on biogas production from lignocellulosic biomass mixed with cattle dung which can showcase the effect of temperature.

Lignocellulosic biomasses contain lignin which renders its anaerobic digestion in conventional digestion methods. As a result these bio-wastes cannot be directly used for biogas production. To break the lignin content, pre-treatment processes were implemented and were mixed with cattle dung to enhance the biogas production. On the other hand, temperature plays a very important role in bacterial growth (Ingraham, 1962). Normally, the reaction rate of a chemical reaction increases with a rise in temperature (Sarono et al., 2016), but temperature dependency of biogas digestion is not that revealing in most of the kinetic models. The modified Gompertz model is found to be fit for cumulative biogas generation from lignocellulosic biomass like bamboo dust, sawdust, sugarcane bagasse, rice straw and rice husk powder, but it does not show the effect of temperature on biogas production.

In this paper, the effect of temperature on biogas production from lignocellulosic biomass is studied for the temperature range from 35°C to 55°C. Based on the results of the experimental study, the modified Gompertz model is reformed and the temperature effect term is introduced in it. The newly developed equation is able to predict the production of biogas from lignocellulosic biomass at temperatures in the range 40°C to 55°C in a batch mode.

2. MATERIALS AND METHODS

The substrates used in this experiment are bamboo dust, sawdust, sugarcane bagasse, rice straw and rice husk powder separately mixed with cattle dung. Temperature of the substrates varied from 35°C to 55°C at a step of 5°C. The substrates were collected from the North Eastern Region of India. The samples are cleaned and dried for 5 to 6 hours in order to remove the superficial moisture and it was separately ball-milled. The ball-milled samples were used as feed material for the anaerobic digestion. Cattle dung was mixed with each biomass in 1:3 ratios for all the experiment so that the C:N ratio of the mixed substrate is controlled in the range of 25:1-30:1. As literature reveals that maximum biogas production can be achieved with C:N ratio in the range of 25:1 to 30:1, (Hills & Roberts, 1981) and the C:N ratio of the biomasses considered in the present study varies widely from 32:1 to 82:1. In case of cattle dung the same result is observed to be 21.8:1. Water was added to the mixture in 1:3 (mass: mass) so as to make the TS 9%.

Table 1 Experimental conditions of biogas production from lignocellulosic biomass bamboo dust, sawdust, sugarcane bagasse, rice straw and rice husk powder and cattle dung

Substrate Temperature	35°C, 40°C, 45°C, 50°C and 55°C
Mode of operation	Batch mode
Total solid (%)	8-9%
C:N ratio	23.7:1 to 30.19:1

3. EXPERIMENTAL SET-UP AND PROCEDURE

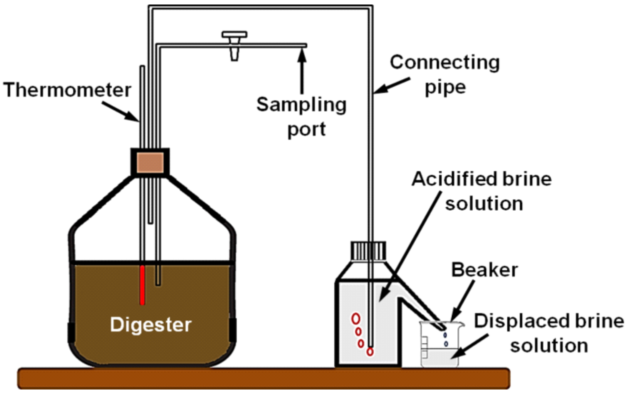

Figure 1 Schematic diagram of experimental set-up

The schematic diagram of the experimental set-up for the batch bio-methanation study is shown in Figure 1. It consists of a laboratory bio-digester made of borosilicate glass with a capacity of 1000 ml with an air tight rubber cork fitted into its opening. Thermometer and copper tubes are fitted through the holes made in the rubber cork for measuring the substrate temperature and to provide a passage for the gas flow through the connecting tube. The substrate prepared is filled into the digester up to 900 ml volume and 100 ml is kept free at the upper portion of the digester for biogas accumulation. The bio-digester is then sealed with the rubber cork along with the other accessories as mentioned above. The entire digester is then kept inside a water bath so as to regulate the temperature of the substrate contained in it. Due caution is taken to make the set up leak proof. Agitation is done manually by shaking the digesters for 10–15 minutes twice in a day. The amount of biogas produced was measured with the help of the water displacement system.

Similar set ups are replicated to conduct experiments to study the effect of temperature on biogas production from lignocellulosic biomass mixed with cattle dung.

4. RESULTS AND DISCUSSION

Biogas production from lignocellulosic biomass mixed with cattle dung at temperatures 35°C–55°C at a step of 5°C was studied and the cumulative biogas production was simulated using modified Gompertz plots. While studying the kinetic parameters of the biomasses at different temperatures, it was observed that for all the above mentioned biomasses, the kinetic parameters follow similar trends of behaviour with change in temperature. Based on these trends, the relationship between the kinetic parameters of the modified Gompertz model and temperature are developed and these are used in the parent equation of the model. The suggested mathematical model gave satisfying conformity with the experimental data.

The modified Gompertz equation which gives the cumulative biogas production from batch digesters assumes that the biogas production rate corresponds to the specific growth rate of methanogenic bacteria in the digester (Budiyono et al., 2010; Nopharatana et al., 2007; Yusuf et al., 2011). Equation 1 presents the modified Gompertz equation as given below.

$$P = A.exp\left\{-exp\left[\frac{Ue}{A}(\lambda - t) + 1\right]\right\} \tag{1}$$

where *P* is the cumulative of the specific biogas production (ml/gm VS), *A* is the biogas production potential (ml/gm VS), *U* is the maximum biogas production rate (ml/gm VS/day), λ is the lag phase period or the minimum time required to produce biogas (day), *e* is the mathematical constant having value 2.718282, and *t* is the time period of biogas production (day).

The constants *A*, *U* and λ were determined using the non-linear regression approach with the aid of the solver function of the MS Excel ToolPak.

The experimental data of biogas accumulation from lignocellulosic biomass mixed with cattle dung are plotted along with the model data in cumulative biogas production vs hydraulic retention time (HRT) plot. Figure 2 presents the experimental data along with the model data of cumulative biogas production of sawdust mixed with cattle dung vs HRT at five different temperatures. It shows that the model data fits quite well with that of the respective experimental data with co-efficient of regression (R^2) 0.99 for all the temperatures from 35°C–55°C. Similar is the case with rice straw, bamboo dust and sugarcane bagasse mixed with cattle dung as shown in Figures 3–5. P_{exp} and P_{calc} indicate the experimental data and calculated data respectively.

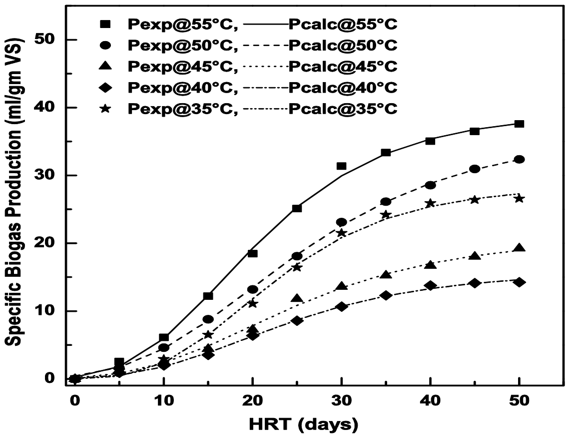

Figure 2 Comparison of experimental and model data for saw dust

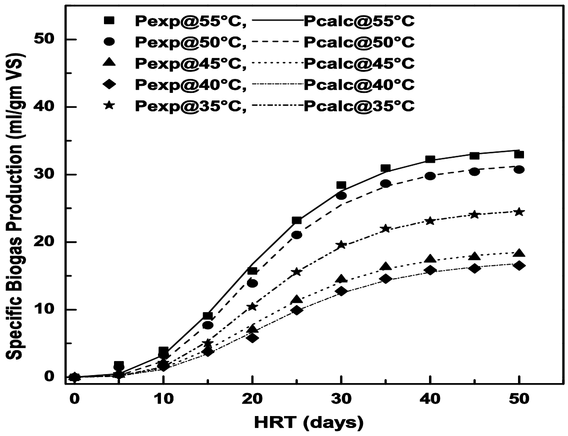

Figure 3 Comparison of experimental and model data for rice straw

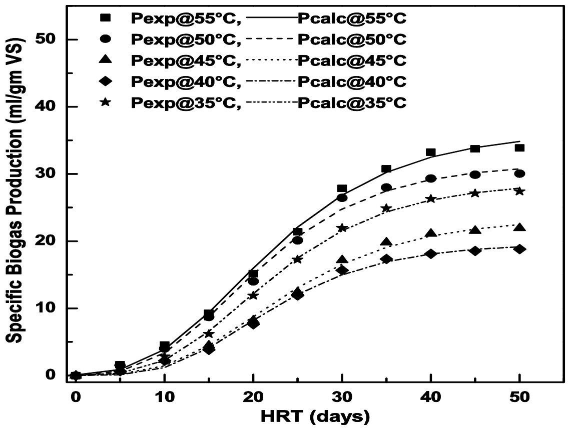

Figure 4 Comparison of experimental and model data for bamboo dust

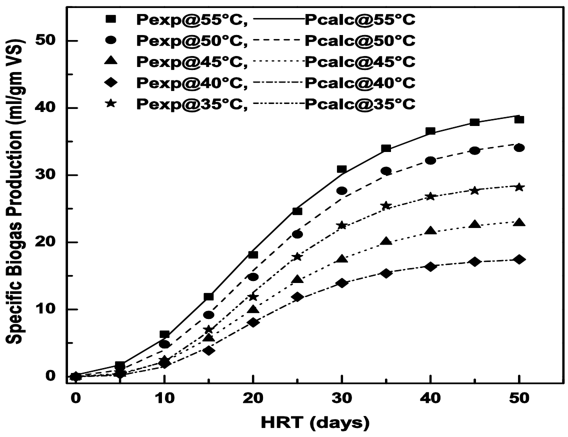

Figure 5 Comparison of experimental and model data for sugarcane bagasse

The experimental data is analyzed using non-linear regression for determining the kinetic constants, biogas production potential (*A*), maximum biogas production rate (*U*) and lowest lag phase period (λ) of the modified Gompertz model for every case. Table 2 depicts the comparison of kinetic constants at different temperatures for sawdust, rice straw, rice husk powder, sugarcane bagasse and bamboo dust mixed with cattle dung. It is observed from the table that at 55°C, all the substrates exhibit highest biogas production rate (*U*) followed by 50°C, 35°C, 45°C and finally 40°C temperature. In a thermophilic condition the highest biogas production potential (*A*), maximum biogas production rate (*U*) and lowest lag phase period (λ) is obtained at 55°C. In a mesophilic condition the highest biogas production potential (*A*) and maximum biogas production rate (*U*) is obtained at 35°C.

Table 2 Kinetic parameters at different temperatures

Substrates		35°C	40°C	45°C	50°C	55°C
Sawdust (SD)	*A*, (ml/gm VS)	28.333	15.619	20.644	35.770	39.106
	U, (ml/gm VS)	1.091	0.501	0.613	0.994	1.406
	λ, (days)	9.160	7.391	7.192	6.444	6.228
Rice straw (RS)	*A*, (ml/gm VS)	25.201	17.544	19.150	31.820	34.317
	U, (ml/gm VS)	1.091	0.669	0.759	1.445	1.493
	λ, (days)	10.261	10.016	9.760	9.621	8.735
Sugarcane bagasse (SB)	*A*, (ml/gm VS)	29.379	17.834	24.080	36.259	40.744
	U, (ml/gm VS)	1.192	0.759	0.897	1.304	1.405
	λ, (days)	9.465	9.265	8.732	7.876	6.570
Bamboo dust (SB)	*A*, (ml/gm VS)	28.820	19.682	23.447	31.576	36.278
	U, (ml/gm VS)	1.151	0.845	0.899	1.293	1.340
	λ, (days)	9.393	10.267	10.247	8.260	8.053

It is observed in Table 2 that at a particular temperature, variation of respective kinetic parameters (biogas production potential, *A*; maximum biogas production rate, *U* and lowest lag phase period, λ) of different lignocellulosic biomass is quite insignificant. The effect of temperature on biogas production potential, A of above mentioned biomass is shown in Figure 6. For the sake of simplicity the range of temperature is taken from 40–55°C. In a similar manner the maximum biogas production rate, U as well as lag phase period, λ vs temperature is plotted in Figures 7 and 8, respectively. Non-linear curve fitting is done to the mean of biogas production potential (*A*) for all the above mentioned biomasses. Similarly Non-linear curve fitting is done to the mean of maximum biogas production rate (*U*) as well as lag phase period (λ) of all the biomasses concerned. It is found that the trendline in all the three cases fits into an exponential form of equation as shown in Equation 2 with regression co-efficient $R^2 = 0.951$, 0.935 and 0.955, respectively.

$$y = y_0 . e^{R_0 x} \tag{2}$$

After doing the curve fitting of the parameters, biogas production potential (*A*), maximum biogas production rate (*U*) and lowest lag phase period (λ) with the experimental data the following three equations are obtained as shown by Equations 3–5.

$$A = 2.0264 \times e^{0.0541 \times t} \tag{3}$$
$$U = 0.0845 \times e^{0.0519 \times t} \tag{4}$$
$$\lambda = 17.512 \times e^{-0.016 \times t} \tag{5}$$

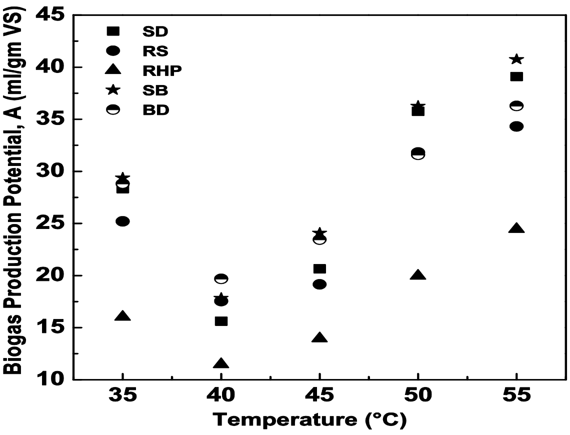

Figure 6 Effect of temperature on biogas production potential, *A*

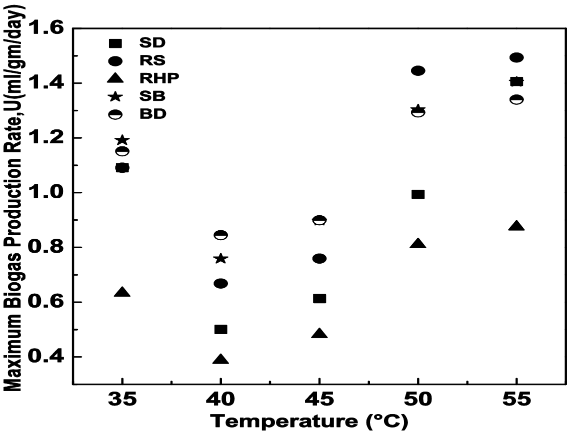

Figure 7 Effect of temperature on Maximum Biogas production rate, *U*

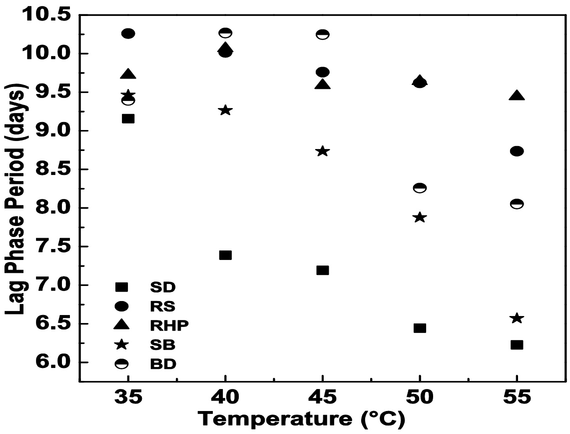

Figure 8 Effect of temperature on lag phase period, λ

The kinetic parameters biogas production potential (*A*), maximum biogas production rate (*U*) and lowest lag phase period (λ) are found to be the function of temperature, t as shown in Equations 3–5. When these three kinetic parameters are directly used in the modified Gompertz model, the temperature effect term, t automatically gets introduced in this equation. Thus the modified Gompertz equation gets reformed with the temperature effect. After introducing the temperature term in the modified Gompertz equation the following Equation 6 for lignocellulosic biomass mixed with cattle dung is obtained.

$$P = 2.0264 \times e^{0.0541 \times t}\, exp\left\{-exp\left[\frac{0.0845 \times e^{0.0519 \times t}\, e}{2.0264 \times e^{0.0541 \times t}}\left(17.512 \times e^{-0.016 \times t} - HRT\right) + 1\right]\right\} \tag{6}$$

where t is temperature in the range 40°C to 55°C, *HRT* is hydraulic retention time, 1 to 50 days. Biomasses considered are bamboo dust, sawdust, sugarcane bagasse and rice straw. Volume of feedstock slurry is 900 ml, biomass: cattle dung is 1:3, and total solid is 9%.

A, *U* and λ can be calculated using Equations 3–5, within the range 40°C to 55°C and can be directly applied in Equation 6 to obtain the expected amount of biogas generation from the above mentioned biomass for hydraulic retention time of 50 days with the total solid of substrate being 9%.

5. VALIDATION FOR LIGNOCELLULOSIC BIOMASS WITH PRESENT STUDY

Literature on biogas production from sawdust, bamboo dust, sugarcane bagasse, rice straw and rice husk mixed with cattle dung obeying the conditions of present study is hardly found. So, the validation of reformed form of the modified Gompertz model for lignocellulosic biomass mixed with cattle dung is done with the data obtained from the present study as shown in Figure 9. It is observed that the model conforms quite well to the experimental data of biogas production from lignocellulosic biomasses mixed with cattle dung.

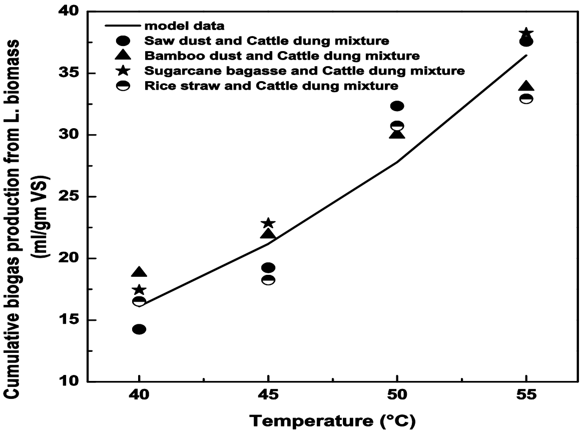

Figure 9 Validation of reformed modified Gompertz model for lignocellulosic biomass mixed with cattle dung with present study

6. CONCLUSION

Experimental data on biogas production from lignocellulosic biomass is simulated using a modified Gompertz equation and it was found that the kinetic parameters of the model have an exponential relationship with temperature. Based on this relationship, the effect of temperature on biogas production from lignocellulosic biomass is introduced in the modified Gompertz equation and the model is reformed. Literature on biogas production from lignocellulosic biomasses under similar conditions at various temperatures is hardly reported. Hence the results of biogas production from lignocellulosic biomass are validated with data obtained from present study at different temperatures.

The reformed form of the modified Gompertz equation is able to predict the amount of biogas production from lignocellulosic biomasses mixed with cattle dung under given conditions.

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