Kinetic Model Development for Biogas Production from Cattle Dung

Manjula Das Ghatak[1,a)] and Prof. P. Mahanta[2,b)]

[1]*Department of Mechanical Engineering, NIT Arunachal Pradesh, Yupia, PapumPare*
[2]*Department of Mechanical Engineering, IIT Guwahati, North Guwahati, Assam, India*

[a)]Corresponding author: manjula.ghatak01@gmail.com
[b)]pinak@iitg.ernet.in

Abstract. Biogas is a mixture of methane, carbon dioxide and traces of numerous trace of elements. It is produced by anaerobic digestion of organic matters including cattle dung which depend upon various factors affecting the population and activity of microorganisms producing biogas. Among the various factors temperature is one of them which play a significant role in biogas production from cattle dung. Biogas production from cattle dung was studied at temperatures 35°C to 55°C at a step of 5°C to study the effect of temperature on biogas production from cattle dung. In this work a mathematical model is developed for evaluating the effect of temperature on the rate of biogas production from cattle dung. The new mathematical model is derived by adding the effect of temperature on the modified Gompertz model. The new model is found to be suitable for predicting the biogas production from cattle dung in the temperature range 35°C to 55°C. The results from the new model are found to be highly correlated to the experimental data of present study.

INTRODUCTION

Over reliance on fossil fuels with growth in technology and urbanization has lead to the global climate change, environmental pollution and challenges in human health. Moreover oil and natural gas price is rising up which is driving the current economy towards alternative energy sources like biogas from biomass. Biogas is produced by anaerobic digestion of organic waste like cattle dung. Anaerobic digestion technology is a process in which microorganisms degrade the biodegradable part of the organic material in absence of oxygen to produce biogas. Various factors affect the anaerobic digestion of cattle dung. Temperature is one of the important factors for bacterial growth which eventually affects the biogas production [Ingraham, 1962]. Numerous studies had been carried out to study the importance of temperature on biogas production from cattle dung. Kinetic study was also done to understand the mechanism behind the anaerobic digestion [Castilo et al., 1995, Abdullahi I., 2011, Mata-Alvarez et al., 1993]. It was observed that temperature dependency is not that revealing in most of the kinetic models. Several researchers have reported about the simulations of biogas, methane and hydrogen production rate and accumulation in their reports (Altas, 2009; Li and Fang, 2007; Lin and Shei, 2008; Bilgili et al., 2009; De Gioannis et al., 2009; Kumar et al., 2004; Tosun et al., 2008; Wang and Wan, 2009; Erses et al., 2008; Mu et al., 2007; Li et al., 2012). The biogas accumulation was also simulated by logistic growth curve, exponential rise to maximum as well as modified Gompertz equations which were commonly used in the simulation of methane and hydrogen production (Altas, 2009; Li and Fang, 2007; Lin and Shei, 2008; Wang and Wan, 2009). Lo et al., 2010 simulated cumulative biogas production from anaerobic digestion of MSW using exponential rise to maximum and modified Gompertz equations and found that Modified Gompertz plot had higher correlation than exponential rise to maximum plot for simulating cumulative biogas production. Many other researchers have applied the modified Gompertz equation in their work [Agulanna et al., 2012; Nopharatana et al., 2007; Yusuf et al., 2011]. Budiyono et al., 2010 have applied modified Gompertz equation to study the biogas production from cattle dung. Momirlan and Veziroglu, 1999, Zwietering et al., 1990and Lay et al., 1996 applied modified Gompertz equation to study the bacterial growth. In this work, biogas production from cattle dung is studied at various temperatures and based on the result of that a kinetic model is developed for evaluating the effect of temperature on the biogas production from cattle dung.

MATERIALS AND METHODS

Fresh cattle dung was collected from nearby dairy farm and cleaned. Budiyono et al., 2010 stated that TS content of 7.4 and 9.2% in cattle dung exhibit the best performance for digestibility. Mahanta et al., 2004 reported that for cattle dung the maximum gas production was obtained with 8% TS. Hence, water was added to the fresh cattle dung in 1:3 (mass: mass) so as to make the TS approximately 9% to make the substrate. Literature reveals that maximum biogas production can be achieved with C:N in the range of 25:1 to 30:1, [Hills and Roberts(1981)] and the C:N ratio of cattle dung is also found to be 21.87:1 which is within the range of 25:1-30:1. The substrates temperature was varied from 35°C to 55°C by putting the digesters in hot water bath at various temperatures. Proximate and ultimate analysis of cattle dung were carried out to investigate about the total solid content, volatile solid content, carbon content and nitrogen content of cattle dung.

EXPERIMENTAL SET-UP AND PROCEDURE

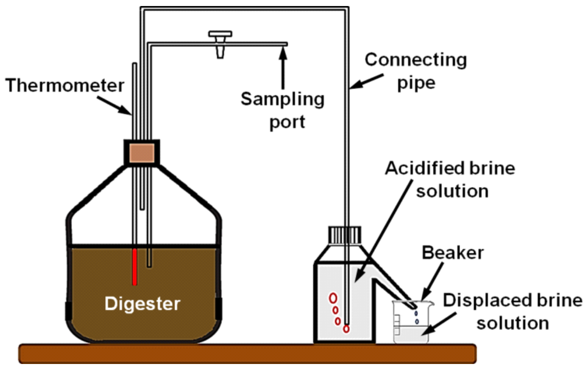

Fig. 1. Schematic diagram of experimental set-up [Ph.D thesis, M. D. Ghatak, 2015]

The experimental set-up for batch biomethanation study is shown by the Fig.1. is used as The laboratory bio-digester consisted of 1 litre capacity borosilicate glass with air tight rubber cork fitted into its opening. Thermometer and copper tubes were 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 digester was filled with the substrate upto 900 ml volume. 100 ml was kept free at the upper portion of the digester for biogas accumulation. After that the bottle were sealed and kept inside water bath with specified temperature. The digesters were stirred manually twice a day for 5 minutes to prevent settling of the substrate. The amount of biogas produced was measured with the help of water displacement system.

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

RESULTS AND DISCUSSIONS

Biogas production from 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. The kinetic parameters developed from the simulation at various temperatures were studied using non-linear regression analysis. It was observed that the kinetic parameters at different temperatures showed exponential behavior with temperature. The expressions of various kinetic parameters as a function of temperature are used in the modified Gompertz model. The suggested mathematical model gave satisfying conformity with the experimental data.

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

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

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
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 cattle dung are plotted along with the model data in cumulative biogas production vs HRT plot. Figure 2 presents the experimental data along with the model data of cumulative biogas production from 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. P_{exp} and P_{calc} indicate the experimental data and calculated data respectively.

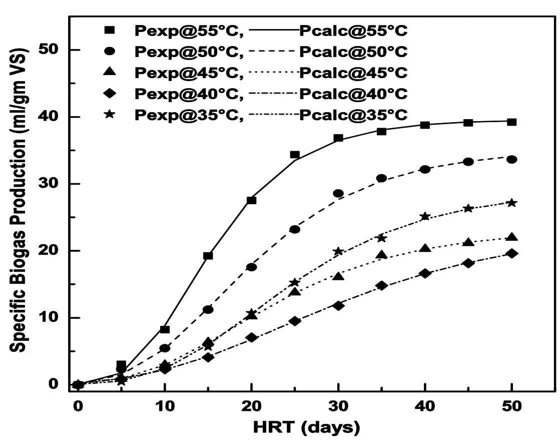

Fig. 2. Comparison of experimental and model data for cattle dung

The experimental data are analyzed using non-linear regression for determining the kinetic constants A, U and λ of the modified Gompertz model for every case. Table 1 depicts the comparison of kinetic constants at different temperatures for cattle dung. It is observed that cattle dung has got highest biogas production rate (U) at 55°C followed by 50°C, 35°C, 45°C and finally 40°C. In thermophilic condition highest biogas production potential (A), maximum biogas production rate (U) and lowest lag phase period (λ) is obtained at 55°C. In mesophilic condition highest biogas production potential (A) and maximum biogas production rate (U) is obtained at 35°C.

Table 1. Kinetic parameters at different temperatures for cattle dung

Substrates/Temperatures		**35°C**	**40°C**	**45°C**	**50°C**	**55°C**
Cattle Dung (CD)	A, (ml/gm VS)	28.990	18.463	21.643	33.951	36.708
	U, (ml/gm VS/day)	0.939	0.528	0.760	1.344	1.340
	λ, days	8.017	6.654	6.232	6.045	5.129

Non-linear curve fitting is done to the biogas production potential (A), maximum biogas production rate (U) and lag phase period (λ) for cattle dung for temperature range 40°C to 55°C. It is found that the trendline in all the three cases fit into an exponential form of equation as shown in Eq. (2) with regression co-efficient R^2=.0.927, 0.898 and 0.915, respectively.

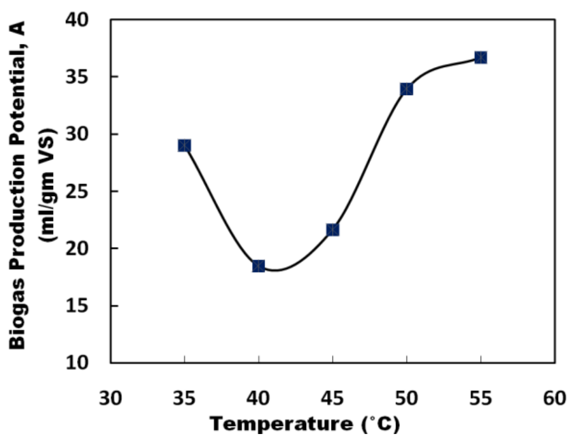

Fig. 6. Effect of temperature on biogas production potential, A

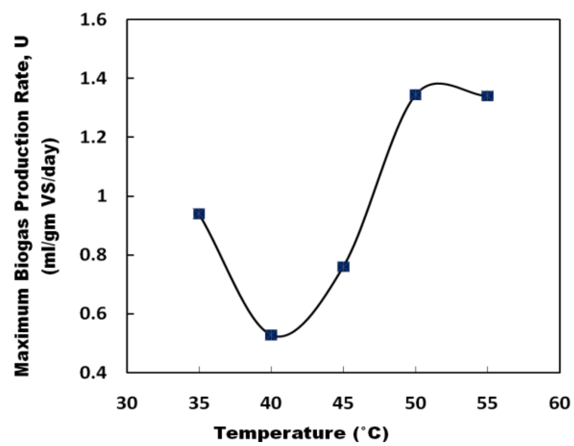

Fig. 7. Effect of temperature on Maximum Biogas production rate, U

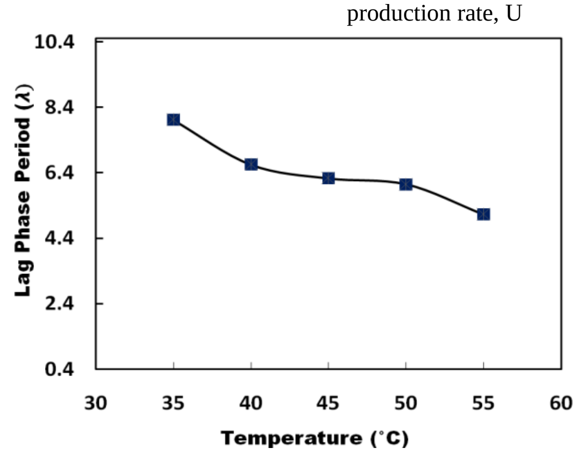

Fig. 8. Effect of temperature on lag phase period, λ

$$y = y_0.e^{R_0 x} \qquad (2)$$

After doing the curve fitting of the parameters, A, U and λ with the experimental data the following three equations are obtained as shown by Eq.3-5.

$$A = 2.4429 \times e^{0.0502 \times t} \qquad (3)$$

$$U = 0.0375 \times e^{0.0674 \times t} \qquad (4)$$

$$\lambda = 12.943 \times e^{-0.016 \times t} \qquad (5)$$

The kinetic parameters A, U and λ are found to be the function of temperature, t as shown in Eq. 3-5. The expressions of the kinetic parameters as a function of temperature are fitted in the modified Gompertz model, thus introducing the temperature term in the parent model. After introducing the temperature term in the modified Gompertz equation the following equation for cattle dung is obtained.

$$P = 2.4429 \times \mathrm{e}^{0.0502 \times \mathrm{t}} \exp\{-\exp[\frac{0.0375 \times \mathrm{e}^{0.0674 \times \mathrm{t}} \times e}{2.4429 \times \mathrm{e}^{0.0502 \times \mathrm{t}}} \times (12.943 \times \mathrm{e}^{-0.016 \times t} - HRT) + 1]\} \qquad (6)$$

where

t = temperature in the range 40°C to 55°C
HRT = hydraulic retention time, 1 to 50 days
Biomasses considered = fresh cattle dung mixed with tap water in 1:3 ratio
Volume of feedstock slurry = 900 ml
Total solid = 9%.

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

VALIDATION OF NEW MODEL FOR CATTLE DUNG WITH PRESENT STUDY

The validation of reformed form of the modified Gompertz model for cattle dung is done by comparing the data obtained from literature with the data from the present study. It is observed from Fig. 9 that the model conforms quite well to the experimental data of biogas production from cattle dung.

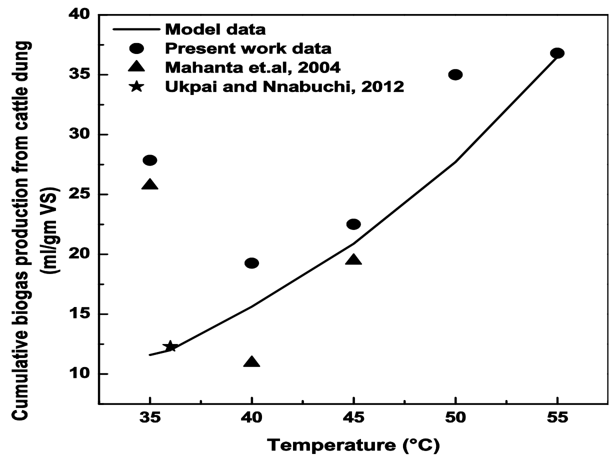

Fig. 9. Validation of reformed modified Gompertz model for cattle dung with present study

CONCLUSIONS

Experimental data on biogas production from cattle dung is simulated using modified Gompertz equation and found that the kinetic parameters of the model have got an exponential relationship with temperature. Based on this relationship, the effect of temperature on biogas production from cattle dung is introduced in the modified Gompertz equation and the model is reformed. Data from the model is validated with the data obtained from literature on biogas production from cattle dung under similar conditions as well as 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 cattle dung under specified conditions.

REFERENCES

1. Abdullahi I., "Effect of kinetic parameters on biogas production from local substrate using a batch feeding digester", European Journal of Scientific Research 57,626-634 (2011).
2. Agulanna C. N., Onuoha G. N., Anyanwu E. E., Ejike E. N. O. and Ogueke N. V., Experimental studies of anaerobic digestion of organic fraction of municipal solid waste using a bioreactor with integral flow features. Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS), 3 (3) (2012) 461-469
3. Altas L., Inhibitory effect of heavy metals on methane-producing anaerobic granular sludge.Journal of Hazardous Materials, 162(2–3)(2009) 1551–1556.
4. Bilgili M.S., Demir A., Varank G., Evaluation and modeling of biochemical methane potential (BMP) of landfilled solid waste: a pilot scale study. Bioresource Technology, 100 (2009) 4976–4980.
5. Budiyono, Widiasa I.N., Johari, S., and Sunarso., "The influence of total solid contents on biogas yield from cattle manure using rumen fluid inoculums", Energy Research Journal 1, 6-11 (2010).
6. Castillo R.T., Luengo P.L. and Alvarez J. M., "Temperature effect on anaerobic of bedding manure in a one phase system at different inoculums concentration", Agriculture, Ecosystems and Environment 54, 55-66 (1995).
7. Das Ghatak M. and Mahanta P., "Effect of Temperature on Biogas Production from Lignocellulosic Biomasses", International Journal of Engineering and Advanced Technology (IJEAT) 3, 244-249 (2014).
8. Erses A. S., Onay, T. T., Yenigun, O.,Comparison of aerobic and anaerobic degradation of municipal solid waste in bioreactor landfills. Bioresource Technology, 99 (2008) 5418–5426.
9. Gioannis G. D., Muntoni A., Cappai G., Milia S., Landfill gas generation after mechanical biological treatment of municipal solid waste. Estimation of gas generation rate constants. Waste Management, 29 (2009) 1026–1034.
10. Hills D. J. and Roberts D. W., Anaerobic digestion of dairy manure and field crop residues.Agricultural Wastes, 3 (1981) 179-189.
11. Ingraham L. L., Biochemical mechanisms. Wiley, New York, 1962.

12. Kumar S., Mondal A. N., Gaikward S. A., Devotta S., Singh R. N., Qualitative assessment of methane emission inventory from municipal solid waste disposal sites: A case study. Atmospheric Environment - Journal, 38 (2004) 4921–4929.
13. Lay J. J., Li Y.Y., Noike T., Effect of moisture content and chemical nature on methane fermentation characteristics of municipal solid wastes. J. Environ. Syst. and Eng., JSCE, No. 552/VIl-l (1996) 101-108.
14. Li C., Fang H. H. P., Inhibition of heavy metals on fermentative hydrogen production by granular sludge. Chemosphere, 67 (2007) 668–673.
15. Li L., Kong X., Yang F., Li D., Yuan Z. and Sun Y., Biogas production potential and kinetics of microwave and conventional thermal pretreatment of grass. Applied Biochemistry and Biotechnology, 166 (2012) 1183-1191.
16. Lin C. Y. and Shei S. H., Heavy metal effects on fermentative hydrogen production using natural mixed microflora. International Journal of Hydrogen Energy, 33 (2008) 587–593.
17. Lo H. M., Kurniawan T. A., Sillanpaa M. E. T., Pai T. Y. and Chiang C. F., Modelling biogas production from organic fraction of MSW co-digested with MSWI ashes in anaerobic bioreactors. Bioresource Technology, 101 (2010) 6329-6335.
18. Mahanta, P., Saha, U. K., and Kalita, P., The influence of temperature and total solid concentration on the gas production rate of a biogas digester. Journal of Energy in Southern Africa, 15 (2004) 112-117.
19. Mata-Alvarez J., Mtz.-Viturtia A., Llabr and Luengo P. and Cecchi F., Kinetic and performance study of a batch two-phase anaerobic digestion of fruit and vegetable wastes. Biomass and Bioenergy, 5 (6) (1993) 481-488.
20. Momirlan M. and VezirogluT., Recent directions of world hydrogen production. Renewable and Sustainable Energy Reviews, 3 (2) (1999) 219-231.
21. Mu Y., Yu H. Q., Wang G., A kinetic approach to anaerobic hydrogen producing process. Journal of Water Research, 41(2007) 1152–1160.
22. Nopharatana A., Pullammanappallil P. C. and Clarke W. P., “Kinetics and dynamic modeling of batch anaerobic digestion of municipal solid waste in a stirred reactor”, Waste Management 27, 595–603 (2007).
23. Tosun I., Gönüllü M. T., Arslankaya E. andGünay A., Co-composting kinetics of rose processing waste with OFMSW. Bioresource Technology, 99 (2008) 6143–6149.
24. Wang J. and Wan W., Kinetic models for fermentative hydrogen production: A review. International Journal of Hydrogen Energy, 34 (2009) 3313–3323.
25. Yusuf M. O. L., Debora A. and Ogheneruona D. E., “Ambient temperature kinetic assessment of biogas productionfromco-digestion of horse and cow-dung”, Research in Agricultural Engineering 57, 97-104 (2011).
26. Zwietering M. H., Jongenburger I., Rombouts F. M. and Riet K. V., Modelling of the bacterial growth curve. Applied and Environmental Microbiology, 56(6) (1990) 1875-1881.