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Predictive modeling of bacterial growth in anaerobic biogas digester using artificial neural networks

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Abstract

The main objective of this study is to determine the growth kinetics of mesophilic and thermophilic bacteria in biogas anaerobic digester using first order kinetic model, Monod kinetic model, diffusion model, Chen-Hashimoto model, Sing model and Cantois model. Nonlinear, stochastic models like artificial neural networks coupled with Monod kinetics was also applied for modeling the rate constants in anaerobic biogas digester. Thermophilic bacterial anaerobic digester is a found to be suitable for very hot weathers when compared with mesophilic bacterial anaerobic digester. Artificial neural network is proved to be an effective tool in predicting the rate equation when compared with other linear models.

Keywords: Biogas, rate equation, reactor, artificial neural network, anaerobic digestion

Introduction

Producing energy from renewable sources like hydroelectric power, wind power, geothermal power, solar energy and waste organic substances is an effective alternative to depleting non-renewable sources like coal, petrochemicals and nuclear waste (Ekwenchi & Yaro 2010). Based on the report by Abubakr & Zuru (1996), Energy Research and Development Administration (ERDA) has intended to include 5 to 10 percent energy from biogas to the total U. S. energy. Hall (1982) reported that 55 percent of energy in rural areas is provided through wood in developing countries and such usage of wood results in deforestation and such places biogas production should be taken into consideration to meet all energy needs. Annually, almost 15 percent of energy sources around the world is biogas and 55 percent is from oil, natural gas, and nuclear energy (Abubakr & Zuru 1996).

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Anaerobic digestion has been the most widespread process in biogas production using various raw materials like sewage sludge, fruits and vegetable wastes (Barnett & Andrews 1992). Recent developments include designing advanced digesters like fixed layer, Upflow Anaerobic Sludge Blanket (UASB) reactor and fluidized bed reactors (Metcalf & Eddy 1991). According to reports, thermophilic anaerobic digestion in all cases is superior to mesophilic in regard to required process and reactor capacity (Moset et al. 2015; Hashimoto et al. 1980; Hill 1990).

The microbiology of methane formation requires four groups of bacteria that are responsible for anaerobic digestion. A Hydrolase bacterium is the first group that transforms carbohydrate, protein, lipid, and other smaller components of organic material into fatty acids, H_2, and CO_2. The second group is hydrogen, producer of acetogenic bacterium, which transforms fatty special acids and final neutral products into acetate, CO_2, H_2. The third group of bacterium is homoacetogens that mix acetate with acetic acid, through CO_2, H_2, and hydrolase polycarbonate compositions. Finally, the fourth group is a methanogenic bacterium that uses acetate, carbonic dioxide, and hydrogen for methane production.

Reactions in each phase are as following:

Phase 1: Carbohydrate hydrolase

$$[C_6H_{10}O_5]n + nH_2O = nC_6H_{12}O_6$$

Phase 2: Acidogenic fermentation of glucose (acid formation) to acetate

$$C_6H_{12}O_6 + 2H_2O = 2CH_3COOH + 4H_2 + 2CO_2$$

Third Phase: Methanogenic reaction (methane formation)

$$CH_3COOH = CH_4 + CO_2$$
$$4H_2 + CO_2 = CH_4 + 2H_2O$$

Biogas can be extracted from raw materials such as human and animal (such as hen or roost) wastes, crop residues, food industrial residues, organic materials and so forth (Tambuwal et al, 1997). Optimizing biogas efficiency from certain substrate, through anaerobic fermentation, depends on several factors (both physical and chemical) including the solidity, temperature and substance of substrate, pH and density of water material, the proportion of carbon to nitrogen (C/N), the percentage of materials in composition, the speed of stirring and addition of nutrients (Chen & Inbar 1991). Due to the complexity of the process applications of various mathematical techniques are necessary to model the process parameters. The present study mainly concentrates on modeling of bacterial growth using various available models and compare the results with advanced nonlinear stochastic models like artificial neural networks.

Materials and Methods

Collection and treatment

Fresh dung from 50 herds of cattle present in Ardabil city, Iran, was collected. The cows were fed on grass and the dung was processed by air drying for 2 weeks and heating in oven for 3 hours at 105^0C. The cow dung was further pulverized using wooden pestle and mortar and allowed it to pass through <250 * 10^{-6} m mesh to achieve uniform particle size. The reactors were designed as per the procedure is given by Garba (1998). The reactors were sealed to maintain anaerobic conditions and were connected to an inverted measuring cylinder (500 ml) via PVC tube (50 cm length and 0.8 cm diameter). The fermentation was carried out at 37^0C for 30 days. The fermentation and gas collected were done based on Sanda et al (2001) with few modifications in the concentration of slurry and duration of the reaction. The gas production, microorganism density and substrate density in the reactor were monitored for 30 hours and results were tabulated.

Artificial Neural Networks

The following mathematical models listed in Table 1 were chosen for evaluation of the performance of substrate for enhanced biogas yield (Garba (1998)).

The present study aims at determining the rate equation, analyze anaerobic digestion process, kinetic of bacterial growth, and model an artificial neural network of a biogas reactor with the help of above models.

To achieve an accurate mathematical model in anaerobic digester is difficult, since digestion and hydrodynamic process are complicated issues. Anaerobic digestion, for its gas circulation and solid availability, is a three-phase process. The Monod growth kinetics was applied and the equation developed by Hashimoto et al (1981) was considered for this process for finding the maximum growth rate.

$\mu_{max}=0.013T-0.129$ -- Equation 1

T is temperature (^{0}C) in this equation.

The following equation can be used for biogas production (Karim et al. 2007)

$$G = VY_g \frac{\mu X}{Y_x}$$

In this equation, G and Yg are respectively biogas production rate and gas efficiency.

At steady state:

$\mu = \frac{Q}{V}$;

S=$K_s \frac{\mu}{\mu_{max-} \mu}$

Substituting, equation 1,

$$S = K_s \frac{Q/V}{(0.013T-0.129)-Q/V}$$

Table 1: List of mathematical models used for modeling bacterial growth in anaerobic biogas digester

Mathematical Model	**Equations**	**Constants**
First-order kinetic model	$W=W_0\,(1-e^{-kt})$	W = The amount of product (biogas) in time t; W_O = The maximum product achieved at infinite time t∞; K = The constant speed of biogas production (day^{-1}); T = Temperature (K)
Monod model	$\mu = \frac{\mu_{max} S}{K_s + S}$	μ= Specific growth rate (day^{-1}), μ_{max}= Maximum growth rate (day^{-1}), S= Substrate concentration in terms of (mg COD/L), and Ks= Saturation concentration (mg COD/L)
Diffusion model	$Ds=KS^{1/2}$	Ds=The change in density of substrate; K=The apparent kinetic constant of reaction; S=The density of substrate (g/m^3).
Chen-Hashimoto model	$U = \frac{Um\,(S/S_0)}{K + (1-K)\,(S/S_0)}$	U= The speed of microorganism growth (day^{-1}), U_m=The maximum speed in microorganism growth (day^{-1}); K=Chen-Hashimoto kinetic dimensionless constant; S=Substrate density in digester (day^{-1}) at time t∞; So= The primary substrate density (day^{-1}) before digestion
Sing model	$\frac{ds}{dt} = \frac{-K[S]}{1+t}$	ds/dt = The change in substrate density based on digestion time; K=The first-order kinetic constant speed (day^{-1}); [S]=The density of substrate (g/m^3); t=Time (day).
Cantois model	$\frac{dx}{dt} = Ux$	ds/dt = The change in substrate density based on digestion time and Ux=The balance of microorganisms in digestion

Rearranging the above equation and solving dS/dt = 0;

$$\frac{Q}{V}(S_i - S) - \frac{\mu X}{Y_x} = 0$$

At X=(S_i-S) Y_x; dT/dt = 0;

$$\frac{Q}{V}(T_i - T) + G_u = 0 \text{ and } G_u = -\frac{Q}{V}(T_i - T)$$

The efficiency of gas is calculated based on gas composition of 55 % methane and 90 % real transformation of COD into methane (Metcalf & Eddy, 1991). With theoretical value of 0.35 m^3 COD methane/ kg, gas efficiency is achieved:

$$Y_g = \frac{0.35}{0.55} \times 0.9 = 0.57 m^3 gas\ kg^{-1} COD$$
$$= 5.7 \times 10^{-7} m^3\ gas\ mg^{-1}\ COD$$

So, the reduction of COD in digester based on average speed of gas production 1965 m3/day is calculated by using below equation.

$$\frac{\mu X}{Y_x} = \frac{G}{VY_g} = \frac{1965}{81\times10^5\times5.7\times10^{-7}} = 425.6 mg\ L^{-1} d^{-1}$$

The following equation is achieved through equation (17) and putting it instead of hydraulic retention time V/Q=30 days:

$$(S_i - S) = \frac{\mu X}{(Q/V)Y_x} = 425.6 \times 30 = 12768\ mg\ L^{-1}$$

Now, “f” coefficient is considered which is the relation between S and Si in VSS and COD:

$$(S_i - S) = (37670 - 22440) \times f$$

So,

$$f = \frac{12768}{15230} = 0.83835$$

Thus,

$$S_i = 31580.5\ mg\ L^{-1}$$

$$S = 18812.5\ mg\ L^{-1}$$

All constants were calculated based on the above equations and tabulated in Table 1.

Table 1: Values of Parameters in the Model in Steady State

Parameter		Thermophilic	Mesophilic
Q_s	$m^3\ d^{-1}$	270 (30 day)	810 (10 day)
V	m^3	8100	8100
G	$m^3\ d^{-1}$ STP	1965	5895
G_u	°C d^{-1}	0.0166667	2.5
T_i	°C	30	30
T	°C	35	55
Si	mg COD L^{-1}	31580.5	31580.5
S	mg COD L^{-1}	18812.5	18812.5
X	mg L^{-1}	549	549
K_s	mg COD L^{-1}	165173.8	91428.8
Y_x	mg X mg^{-1} COD	0.043	0.043
Y_g	$m^3\ mg^{-1}$ COD	5.7×10^{-7}	5.7×10^{-7}
μ_{max}	L d^{-1}	0.326	0.586
μ	L d^{-1}	0.033333	0.1

The following data was used for modeling artificial neural networks.

Table 2: Data input for artificial neural networks

Time (days)	Substrate (mg/L^{-1})	Microorganism (mg/L)	Temp. (^{0}C)	Gas rate (m^3)
0.00	9.11	-0.37	54.87	0.00
0.50	8.98	-0.30	54.47	0.60
1.00	8.85	-0.25	54.07	1.10
1.50	8.73	-0.19	53.68	1.50
2.00	8.62	-0.15	53.30	1.81
2.50	8.51	-0.10	52.92	2.04
3.00	8.40	-0.07	52.55	2.21
3.50	8.30	-0.04	52.18	2.33
4.00	8.21	-0.01	51.82	2.39
4.50	8.12	0.01	51.47	2.41
5.00	8.03	0.03	51.12	2.40
5.50	7.95	0.05	50.78	2.37
6.00	7.87	0.07	50.44	2.32
6.50	7.80	0.08	50.11	2.26
7.00	7.72	0.09	49.79	2.20
7.50	7.66	0.09	49.47	2.13
8.00	7.59	0.10	49.15	2.07
8.50	7.53	0.11	48.84	2.03
9.00	7.47	0.11	48.54	2.00
9.50	7.41	0.11	48.24	1.99
10.00	7.35	0.12	47.95	2.00
10.50	7.30	0.12	47.66	2.04
11.00	7.24	0.13	47.37	2.11
11.50	7.19	0.14	47.09	2.21
12.00	7.14	0.15	46.82	2.34
12.50	7.09	0.16	46.55	2.51
13.00	7.04	0.17	46.28	2.71
13.50	6.99	0.19	46.00	2.95
14.00	6.94	0.21	45.77	3.22
14.50	6.90	0.23	45.52	3.53
15.00	6.85	0.26	45.27	3.88
15.50	6.80	0.29	45.03	4.25
16.00	6.75	0.33	44.79	4.66
16.50	6.70	0.37	44.55	5.09
17.00	6.64	0.41	44.32	5.55
17.50	6.59	0.47	44.10	6.03
18.00	6.53	0.52	43.87	6.54
18.50	6.48	0.59	43.65	7.05
19.00	6.42	0.66	43.44	7.58
19.50	6.36	0.74	43.20	8.10
20.00	6.29	0.83	43.00	8.64
20.50	6.23	0.92	42.80	9.16
21.00	6.16	1.03	42.60	9.67
21.50	6.08	1.14	42.42	10.16
22.00	6.01	1.26	42.22	10.63
22.50	5.93	1.39	42.03	11.06
23.00	5.84	1.53	41.85	11.44
23.50	5.75	1.68	41.60	11.78
24.00	5.66	1.85	41.48	12.06
24.50	5.56	2.02	41.30	12.20
25.00	5.46	2.20	41.12	12.39
25.50	5.36	2.40	40.95	12.41
26.00	5.24	2.61	40.78	12.35
26.50	5.13	2.83	40.60	12.17
27.00	5.00	3.06	40.45	11.86
27.50	4.87	3.31	40.28	11.42
28.00	4.74	3.57	40.10	10.83
28.50	4.60	3.84	39.96	10.00
29.00	4.45	4.13	39.80	9.15
29.50	4.30	4.44	39.65	8.03
30.00	4.13	4.76	39.50	6.71

An artificial neural network was used for analyzing the effect of the above parameters in the reactor. This network includes four variables in input layer and gas production rate value in output layer.

Results and Discussion

As shown in Table 2, the density of microorganisms in reactor increases directly through time due to the growth of bacteria. The substrate concentration decreases with increase in the time. As the bacteria grows the substrate decreases. Results indicated that the reactor temperature decreases in time, which is variable with mesophilic and thermophilic conditions temperature of digester, remaining time, and the density of input materials to reactor.

In regard to the relationship between the amount of gas production with time, there is an optimum point in a way the gas production is increasing to a specific day and then it starts decreasing. It seems microorganisms lose the ability of function before the time is over, as gas production is not increasing after its peak in 28 days (Figure 1).

According to considered equations for enzyme reaction, rate equation can be achieved by drawing diagram related to 1/-ra in contrast to 1/Ca and its fitting (Figure 5).

It is achieved for an enzyme reaction as following and rate equation is equivalent to:

y = -3E-07x6 + 2E-05x5 - 0.0005x4 - 0.0035x3 + 0.1511x2 - 0.5085x + 4.375

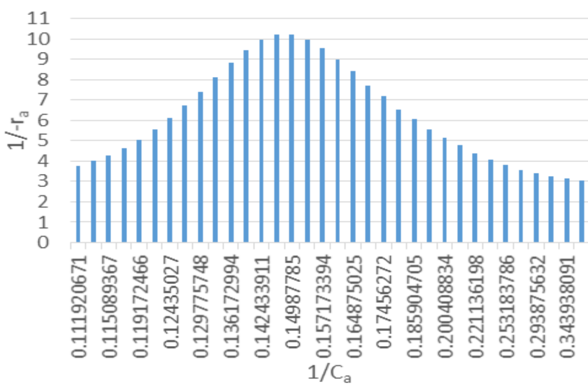

Figure 1: Diagram relating reaction rate and concentration

Based on the size of experimental data, an artificial neural network with a hidden layer was used. Data was normalized in the scope of 1 and -1, and a sigmoid function was used in order to link network output with hidden layer. Four algorithms namely, *traingdx*, *trainscg*, *trainlm*, and *trainrp* were utilized for network modeling. The volume of considered data comprised in three sections of education, test, and validation are respectively 70, 20, and 10 percent of total data achieved.

According to results, a neural network with *trainlm* feed forward learning algorithm, the following structure (1-7-5) was confirmed to give optimal results with 0.9999 R^2. The value of MSE in about 0.023 which is the most appropriate structure for selected network. The artificial neural networks successfully modeled the process parameters with coefficient of regression value of 0.99999 with 20 neurons in hidden layer and mean square error of 0.1.

Conclusion

The artificial neural networks were successfully applied to model the rate equation based on several reator parameters. Based on our study, thermophilic anaerobic digestion is a reliable alternative for mesophilic process particularly in digesters with water overcurrent in hot weather and optimum hydraulic retention time in thermophilic process is 10 days that restores capacity of digester.

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