Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2017.20167

63 (2017) 63–68
February

Effect of total solids on biogas production through anaerobic digestion of food waste

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Received 18 April 2016; Accepted 13 August 2016

ABSTRACT

Anaerobic digestion of solid food waste is considered as a perspective way for its disposal. The effect of total solids (5%, 10%, 15% and 20%) on the biogas production was investigated in the reactors with mesophilic temperature condition and hydraulic retention time of 30 d. The daily biogas production, cumulative biogas production, methane and carbon dioxide composition were measured. The volume of biogas produced was measured at regular intervals (24 h) using water displacement method. The experimental results show that the reactor with 10% of total solid content yielded higher biogas compared with other reactors. First-order reaction kinetics and modified Gompertz model were used for evaluating the kinetic study of process. The kinetic parameters were estimated for each reactor using MATLAB software.

Keywords: Biogas; Food waste; Kinetic study; Modified Gompertz model

1. Introduction

Urban waste generation and disposal will continue to be a major global issue as the world's population grows past the 7 billion mark and more people move to urban areas. As of 2008, the number of people living in cities surpassed those living in rural areas, and it has been estimated that by 2050, 6 billion people will be living in cities compared with 3.5 billion now [1]. The waste generated by this increasing urbanization of humans and industries will have to be sorted and processed. The most common waste management solution is landfilling. The main problem with this is that landfills around the world are running out of space [2,3]. In this concept, 'waste' is seen as a potential resource that can be converted into useful products through reusing, recycling and/or recovery [4]. Among various resource recovery technologies, anaerobic digestion is a commercially proven and widely employed technology for treating biomass, especially like agricultural and forest residues, municipal solid waste, etc. [5–7].

Anaerobic digestion is considered as the attractive method for the treatment of organic waste, since it reduces the waste volume and produces energy in the form of biogas [8]. Because of the many advantages of anaerobic digestion over conventional aerobic biological processes such as biogas production, lower sludge production as well as the fact that no energy for aeration is required, anaerobic digestion can be regarded as one of the most promising elements of organic waste treatment systems to meet the desired criteria for the future technology in environmentally sustainable development [9,10].

Many researchers investigated the effects of operating parameters on biogas production and reported their findings. Deepanraj et al. [11,12] investigated the effect of solid concentration on anaerobic digestion of food waste using lab-scale reactors and found that high methogenic activity and biogas yield was obtained for the solid concentration of 7.5% of total solids (TS). Katima [13] studied the effect of substrate

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concentration (5–30 g/L) and particle size on biogas production with water hyacinth and reported that the substrate concentration of 25 g/L yielded more biogas and methane yield. Also, it was reported that smaller particle sizes enhance biogas yield, because smaller the particle size, higher the contact area between the substrate and the micro-organisms. Budiyono et al. [14] studied the effect of solid concentration on biogas production from cattle manure with rumen fluid as inoculum and reported that the substrate concentration of 9.2% of TS yielded more biogas yield compared with others. Singh et al. [15] investigated the effect of solid concentration on biogas production from cattle waste and found that 13.5% of TS yielded more biogas.

The aim of the present research was to study the effect of TS on biogas production through anaerobic digestion of carbon-rich food waste.

2. Materials and methods

2.1. Feedstock

Food waste is defined as the materials resulting from the processing, storage, preparation, cooking, handling or food residual [16]. The typical food waste contained 69%–93% of moisture, volatile solids to TS ratio (VS/TS) of 85%–96%, and carbon to nitrogen ratio (C/N) of 14.6–18.3 [17,18]. According to Food and Agricultural Organization of the United Nations [19], nearly 1.3 billion tonnes of foods including fresh vegetables, fruits, meat, bakery and dairy products are lost along the food supply chain. The amount of food waste has been projected to increase in the next 25 years due to economic and population growth, mainly in Asian countries.

The food waste used in this study was collected from the canteen of Adhiparasakthi Engineering College, Melmaruvathur, India. Table 1 shows the mean chemical composition of food waste used in this present study. The collected food waste was crushed and mixed with water to get four different solid concentrations (5%, 10%, 15% and 20%). Anaerobic microbial sludge collected from an anaerobic digester operated with cattle manure was used as inoculum for the reactors.

2.2. Analytical methods

The physiochemical characteristics of the substrate and digestate were determined as per the standard method [20]. pH of the substrate and digestate was determined using pH meter (PH-100 ATC, Voltcraft). Chemical oxygen demand (COD) was measured by COD digester equipped with digital indicator (Orbit Technologies, Hyderabad). Methane and carbon dioxide contents of biogas produced were measured using gas chromatography (Shimadzu, Japan) fitted with thermal conductivity detector. Argon was used as carrier gas. Volatile fatty acids were measured using gas chromatography fitted with flame ionization detector. Elemental composition of the feedstock was found using elemental analyzer (Elementar Vario EL III, Elementar Analysensysteme, Germany).

2.3. Experimental setup

Experiments were carried out in laboratory-scale batch reactors made up of glass. The volume of each reactor is 1,000 mL with a working volume of 750 mL. The schematic view of experimental setup is shown in Fig. 1. All the reactors were purged with nitrogen before start-up in order to create anaerobic condition. Continuous mixing was performed using magnetic stirrer. The reactor was kept in a water bath to maintain constant temperature. Mesophilic temperature (30°C) was maintained throughout the experiments for the hydraulic retention of 30 d. Temperature and pH probes were installed in the reactors for daily monitoring. In this study, the volume of biogas produced was measured by water displacement method considering the volume of the generated gas equal to that of expelled water in the water collector.

2.4. Kinetic modeling

Due to the role of microorganisms in the anaerobic digestion process, the kinetic model was commonly applied to the experiments to stimulate the anaerobic biodegradation. Assuming first-order reaction kinetics for the hydrolysis of particulate organic matter, the cumulative biogas production can be described by means of Eq. (1) [21,22]:

$$C = B\left[1 - \exp\left(-kt\right)\right] \quad (1)$$

where C is the cumulative biogas production (mL); B is the biogas production potential (mL); k is biogas production rate constant (first-order disintegration rate constant) and t is the time (d).

Table 1
Elemental composition and COD of raw food waste

Characteristics	Values
Carbon (%)	46.19
Hydrogen (%)	12.05
Oxygen (%)	39.58
Nitrogen (%)	1.94
Sulfur (ppm)	2,357
Total COD (g/L)	314
Soluble COD (g/L)	152
C/N ratio	23.72

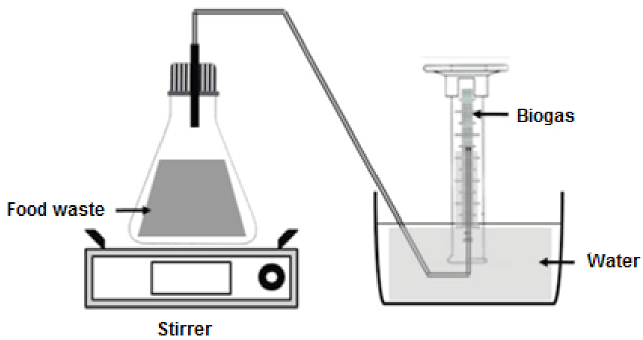

Fig. 1. Schematic view of experimental setup.

Apart from the biogas production potential and the cumulative biogas yield, the duration of the lag phase is also an important factor in determining the efficiency of anaerobic digestion. The lag phase (λ) can be calculated with the modified Gompertz model [23,24]:

$$C = B\exp\left\{-\exp\left[\frac{R_b e}{B}(\lambda - t) + 1\right]\right\} \quad (2)$$

where C is the cumulative methane production (mL); B is the methane production potential (mL); R_b the maximum methane production rate (mL/d); λ is the duration of lag phase (d) and t is the duration of the assay at which cumulative biogas production C is calculated. The parameters B, R_b and λ were estimated for data sets obtained from experiments by applying a least squares fit of the above equation using MATLAB software. The parameters were reported at 95% confident level. For the above analysis, the root mean square error (RMSE) and the coefficient of determination (R^2) were also determined [25]. The predicted cumulative biogas production obtained from kinetic study was plotted with the measured biogas value. The coefficient of determination (R^2) and RMSE was calculated using the following equations:

$$R^2 = \frac{\sum_{j=1}^{m}\left(Y_p - \ddot{Y}\right)^2}{\sum_{j=1}^{m}\left(Y - \ddot{Y}\right)^2} \quad (3)$$

$$\text{RMSE} = \left(\frac{1}{m}\sum_{j=1}^{m}\left(\frac{d_j}{Y_j}\right)^2\right)^{\frac{1}{2}} \quad (4)$$

where m is number of data pairs; d is the difference between experimental and predicted methane yield; Y is the measured biogas yield; Y_p is the predicted biogas yield and $\ddot{Y}$ is the arithmetic mean of observed data.

3. Results and discussion

3.1. Experimental study

The effect of TS (5%, 10%, 15%, 20% and 25% of TS) on anaerobic digestion of food waste was carried out in the laboratory-scale biodigesters of 1,000 mL capacity. Experiments were carried out for a hydraulic retention time of 30 d. The characteristics of food waste before and after the digestion process were given in Tables 2 and 3, respectively. The pH value in the reactor decreased after digestion process due to the formation of volatile fatty acids during acid formation stage. Daily and cumulative biogas production with respect to retention time was determined, which is shown in Figs. 2 and 3, respectively. Out of five different concentrations, reactor with 10% of TS yielded higher gas production, followed by 5%, 15%, 20% and 25% of TS. Peak biogas production rates recorded for solid concentrations of 5%, 10%, 15%, 20% and 25% of TS were 150, 162, 143, 129 and 109 mL/d, respectively. Fig. 4 shows the maximum biogas yield for all the reactors.

Table 2
Characteristics of food waste before digestion

Parameters	5%	10%	15%	20%	25%
TS (g/L)	50	100	150	200	250
VS (g/L)	44.90	89.81	134.75	180.11	224.52
FS (g/L)	5.1	10.19	15.25	19.89	25.48
pH	5.12	5.70	5.64	5.61	5.56
COD (g/L)	68.27	76.79	89.54	91.40	95.72

Table 3
Characteristics of food waste after digestion

Parameters	5%	10%	15%	20%	25%
TS (g/L)	29.37	54.10	97.75	129.6	167.25
VS (g/L)	25.50	45.04	83.79	109.72	141.67
FS (g/L)	3.87	9.06	23.96	19.88	25.58
pH	4.87	5.34	4.95	5.07	5.19
COD (g/L)	47.92	46.72	60.30	66.40	69.93

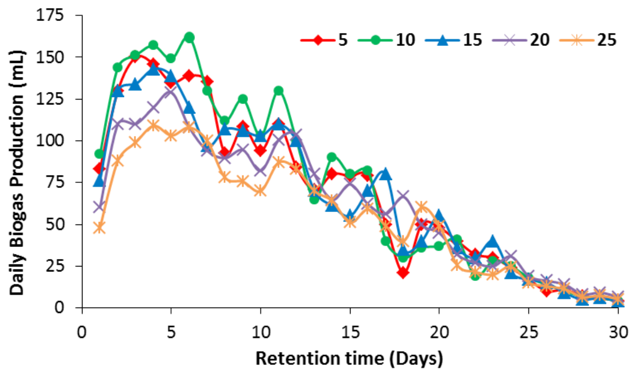

Fig. 2. Daily biogas production.

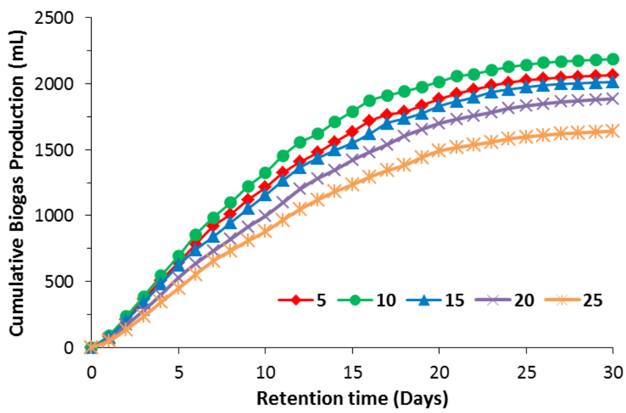

Fig. 3. Cumulative biogas production.

Biogas production is slow at the beginning and end of the digestion process. This indicates that the biogas produced in batch condition corresponds to specific growth rate of methanogenic bacteria. These results suggest that the solid concentration content affects the biogas yield. This is

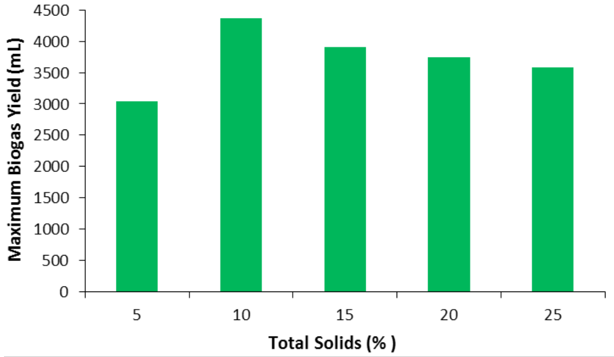

Fig. 4. Maximum biogas yield.

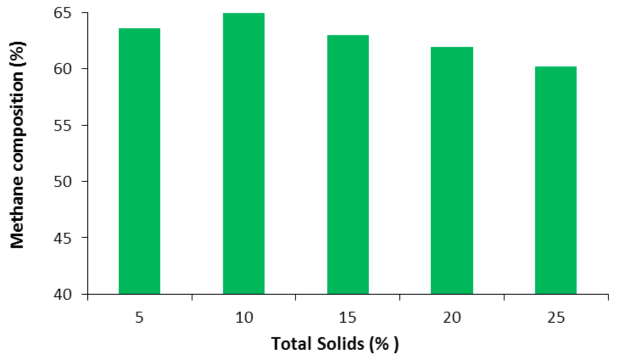

Fig. 5. Average methane composition in biogas.

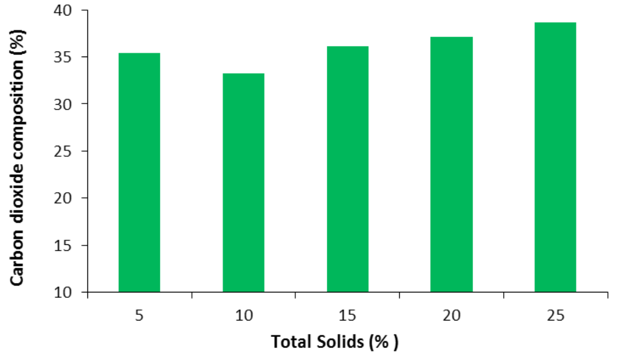

Fig. 6. Average carbon dioxide composition in biogas.

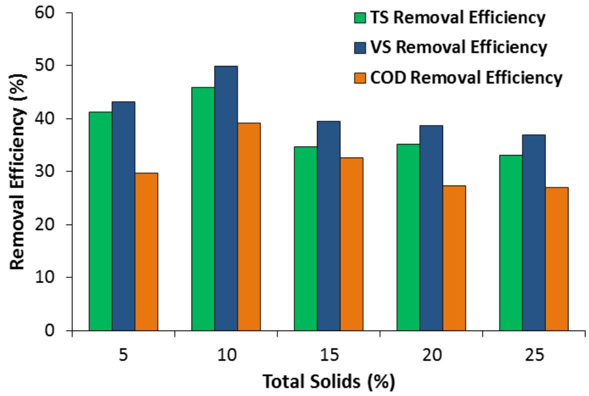

Fig. 7. TS, VS and COD removal efficiencies.

similar to the findings of Deepanraj et al. [11] and Zennaki et al. [26] that the optimum solid content is in the range 7%–9% for highest biogas production. The average methane and carbon dioxide composition present in the biogas produced is shown in Figs. 5 and 6, respectively. The average methane composition obtained during the experimental study ranged between 60.2% and 64.9%. Similarly, the average carbon dioxide composition obtained was in between 33.2% and 38.7%.

The TS, VS and COD degradation efficiencies were shown in Fig. 7. In all the three cases, reactor with 10% of TS achieved maximum degradation and 20% of TS achieved minimum degradation. The TS degradation efficiency of the reactors with substrate concentration 5%, 10%, 15%, 20% and 25% of solids are 41.27%, 45.90%, 34.71%, 35.20% and 33.10%, respectively. The VS degradation efficiency of the reactors with solid concentration 5%, 10%, 15%, 20% and 25% of solids are 43.19%, 49.84%, 39.47%, 38.62% and 36.90%, respectively. Similarly, the COD degradation efficiency of the reactors with solid concentrations 5%, 10%, 15%, 20% and 25% of solids are 29.8%, 39.15%, 32.65%, 27.35% and 26.94%, respectively. Baserja [27] reported that the process was unstable below a TS level of 7%, while a level of 10% caused an overloading of the fermenter. These results are expected due to the function of water in biodigester since the total content will directly correspond to water content. According to Rai et al. [28], water content is one of most important parameter affecting anaerobic digestion of solid wastes. There are two main reasons: (i) water makes possible the movement and growth of bacteria facilitating the dissolution and transport of nutrient and (ii) water reduces the limitation of mass transfer of non-homogenous or particulate substrate.

3.2. Kinetic study

Based on the first-order reaction kinetics (Eq. (1)), the maximum values of biogas production that could achieve during the stabilization of anaerobic digestion process were determined. The results showed that 20% of TS produced least amount of biogas during digestion while the highest amount of biogas was produced with the reactor having 10% of TS. The kinetic parameters determined using first-order reaction kinetics was given in Table 4. Very high values of coefficient of determination (R^2) ranging from 0.9914 to 0.9937 indicated a very good fit between the experimental data and the theoretical model. The RMSE during this theoretical study was in between 8.69% and 11.50%. This shows that the results taken from the model were best fitted with the experimental study. The biogas production rate constants (k) of the reaction ranged from 0.053 to 0.074. The biogas production potential (B) of the substrate with 5%, 10%, 15%, 20% and 25% of TS are 2,469.29, 2,556.6, 2,463.68, 2,458.22 and 2,128.54 mL, respectively. The comparison of experimental and predicted cumulative biogas production based on the above results is shown in Fig. 8(a).

Table 4
Estimated kinetic parameters using first-order reaction kinetics

Parameter	5%	10%	15%	20%	25%
C-experimental (mL)	2,065	2,186	2,014	1,886	1,640
C-model (mL)	2,153.9	2,279.5	2,105.59	1,980.5	1,724.52
B (mL)	2,469.29	2,556.6	2,463.68	2,458.22	2,128.54
k	0.0685	0.0740	0.0642	0.0530	0.0553
R^2	0.9937	0.9914	0.9937	0.9922	0.9916
RMSE (%)	9.35	11.50	9.02	9.57	8.69

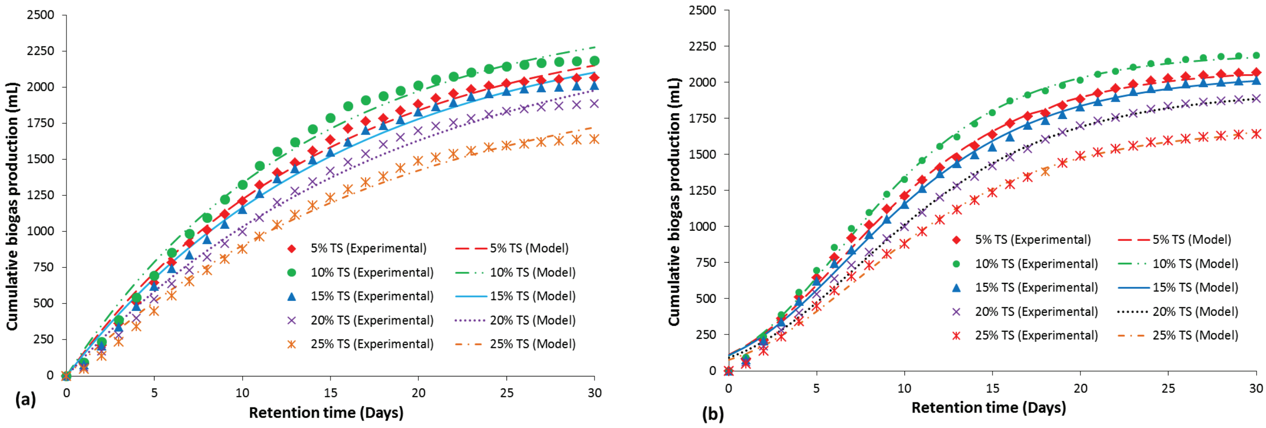

Fig. 8. Comparison of experimental and predicted results: (a) first-order kinetics and (b) modified Gompertz model.

Table 5
Estimated kinetic parameters using modified Gompertz model

Parameter	5%	10%	15%	20%	25%
C-experimental (mL)	2,065	2,186	2,014	1,886	1,640
C-model (mL)	2,057.7	2,173.4	2,011	1,889.5	1,659.2
B (mL)	2,095.8	2,201.9	2,055.4	1,942.3	1,685.3
R_b (mL/d)	130.7	147.6	123.9	111.2	98.2
λ (d)	0.6	0.4	0.5	0.8	0.8
R^2	0.9478	0.9865	0.9852	0.9934	0.9973
RMSE (%)	37.98	33.56	36.45	30.59	28.37

As like first-order reaction kinetic model, modified Gompertz model can be used to determine the kinetics of the anaerobic digestion by relating cumulative biogas production and the time of digestion through biogas yield potential (*B*), the maximum biogas production rate (R_b) and the duration of lag phase (λ). Fig. 8(b) shows the comparison of experimental and predicted cumulative biogas production, and Table 5 gives the results of kinetic parameters estimated using modified Gompertz model. The maximum predicted cumulative biogas production (*C*) for the solid concentrations 5%, 10%, 15%, 20% and 25% of TS were 2,057.7, 2,173.4, 2,011.0, 1,889.5 and 1,659.2 mL, respectively. The maximum biogas production rate estimated (R_b) for the solid concentrations 5%, 10%, 15%, 20% and 25% of TS were 130.7, 147.6, 123.9, 111.2 and 98.2 mL/d, respectively. The coefficient of determination (R^2) values for the reactors lies in between 0.9478 and 0.9973. This shows that the predicted values were best fitted with experimental values. Estimated lag phase for the reactors with 5%, 10%, 15%, 20% and 25% of TS were 0.6, 0.4, 0.5, 0.8 and 0.8 d, respectively. For all the reactors, the lag phase lies below 1 d, because of the inoculum added and the ready biodegradation component available in the substrate. Similar type of results was reported by Li et al. [29], who investigated the pig manure with modified Gompertz model for biogas production. They obtained R^2 value in between 0.9956 and 0.9963 and lag phase in between 0.88 and 1.36 d.

4. Conclusion

The characteristics of food waste confirmed that they have rich proportionate of readily biodegradable VS content, which can be easily converted into biogas. As compared with cattle manure, food waste has higher carbon and hydrogen content. Further, the anaerobic digestion of food waste with solid concentration of 5%, 10%, 15%, 20% and 25% of TS resulted in a cumulative biogas production of 2,065, 2,186, 2,014, 1,886 and 1,604 mL, respectively. The residuals from the anaerobic digestion of food waste can be used as a fertilizer. In case of biogas yield as well as degradation efficiencies, reactor with solid concentration 10% gave better results compared with other four concentrations. The use of a first-order kinetic and modified Gompertz model provides the values of the global kinetic parameters. The estimated parameters were well fitted with the experimental results. This was proved by comparing the R^2 values and RMSE of the two models.

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