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Effect of temperature on biogas production from food waste through anaerobic digestion

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ABSTRACT

An anaerobic digestion process for the treatment of food waste was investigated in laboratory scale batch reactors. The effect of temperature (30°C–60°C) on the biogas production was investigated in the reactors with hydraulic retention time of 30 d. The volumetric yield of biogas was noted at regular intervals using water displacement method. The food wastes used in this experiment were subjected to characterization studies before and after digestion. The experimental results show that the temperature of 50°C produced higher biogas yield compared with other temperatures.

Keywords: Biogas; Food waste; Temperature; Anaerobic digestion

1. Introduction

There is a world-wide concern due to the observation that the rate of consumption of fossil fuels by far exceeds the rate of formation of the fuels. Energy production remains an important process, even at moderate energy prices in non-oil-producing countries. The climate problems due to the greenhouse effect, the recognized need for sustainable development and problems due to the ozone layer depletion have all contributed to the recognition of the value of anaerobic digestion as a technique to produce renewable energy [1,2]. It is this concern that has stimulated researches into economically viable and more environmentally friendly energy alternatives [3]. There exist many renewable sources, such as sunlight, wind and biomass, while agricultural wastes represent an important source of bioenergy. The anaerobic digestion process is one of the technologies used to produce energy as well as to reduce the organic content of waste [4,5].

Anaerobic digestion is widely being practiced as major treatment option for disposal of organic fraction of the municipal solid waste on a par with the composting technologies. It mainly combines with the energy recovery benefits, greenhouse gas mitigation and produces stable end products, which can be further upgraded as compost for land use applications [6,7]. During anaerobic digestion process, different organic materials are digested by microorganisms in the absence of air, resulting in production of energy-rich biogas that can be used for thermal power, electricity generation and automobile applications [8].

To facilitate the rate of biogas production, it is necessary to ensure that operating parameters are favourable to the bacteria involved in the digestion process. Many researchers investigated the effects of operating parameters on biogas production and reported their findings. Singh et al. [9] studied the solid concentration effect on biogas yield using cattle waste as feed and found that 13.5% of total solids yielded more biogas. Sivakumar et al. [10] investigated the effect of pH on biogas production from spoiled milk.

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Experiments were conducted with substrate of different pH values (5–8) and reported that the substrate with pH 7 resulted better biogas yield. Deepanraj et al. [11] studied the effect of temperature on biogas production using food waste in a lab-scale batch reactor and found that the operating temperature of 50°C achieved maximum cumulative biogas production of 7,556 mL with better biodegradation efficiency. Navickas [12] studied the influence of temperature on the performance of anaerobic digestion of industrial wastes and energy plants. Continuous digestion of industrial wastes and energy plants was carried out for 120 d at different temperature. The variation of temperatures ranges from 52ºC to 57ºC while keeping other parameters constant. The highest biogas yield from industrial wastes and energy plants was found at 52ºC.

This present study highlights the effect of temperature on biogas production through anaerobic digestion of carbon-rich food waste.

2. Materials and methods

2.1. Feedstock

The food waste used in this study was collected from the canteen of Surya Group of Institutions, Vikravandi, India. Table 1 shows the mean chemical composition of food waste used in the present study. The collected food waste was crushed and mixed with water to get the solid concentration of 10% of total solids. The solid concentration percentage was optimized by the previous experiments [13]. Anaerobic microbial sludge collected from an anaerobic digester operated with cattle manure was used as the inoculum for the reactors. Substrate to inoculum ratio was taken as 90:10 [10]. The Carbon, Hydrogen, Nitrogen and Sulfur values given in table was measured using elemental analyzer (Elementar Vario EL III, Germany). The total solids (TS), volatile solids (VS), fixed solids (FS) and chemical oxygen demand (COD) of all the samples were analyzed before and after digestion as per the standard method [14].

2.2. 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 operating temperature of each reactors was maintained at 30°C, 40°C, 50°C and 60°C, respectively, water 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. The methane and carbon dioxide composition in the biogas produced were measured using infrared gas analyzers.

Table 1
Elemental composition and COD of raw food waste [12]

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

2.3. Kinetic study

Many dynamic models are available to give a detailed description of bioconversion mechanism. In this study, we used Gompertz (first-order reaction kinetics) and modified Gompertz model. Using these models, the biogas production potential of the substrate, maximum biogas production rate and the lag phase of the reaction can be determined with available experimental results. The kinetic data obtained from all digesters were checked for the fitness of Gompertz and modified Gompertz model [15,16]. The equations are given by:

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

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

where C is the cumulative biogas production (mL); B is the biogas production potential (mL); k is the biogas production rate constant (first-order disintegration rate constant); R_b is 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, k and λ were estimated for data sets obtained from experiments by applying a least squares fit of the above equation using MATLAB software. The statistical indicators RMSE and R^2 (coefficient of determination) were calculated for this analysis [5]:

$$\text{RMSE} = \left(\frac{1}{m}\Sigma_{j=1}^{m}\left(\frac{d_j}{Y_j}\right)^2\right)^{1/2} \quad (3)$$

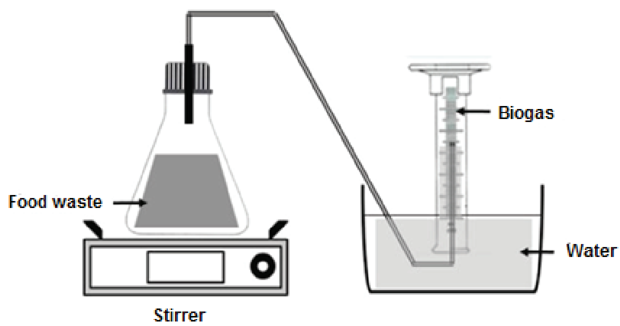

Fig. 1. Schematic view of experimental setup.

$$R^2 = \frac{\sum_{j=1}^{m}\left(Y_p - \ddot{Y}\right)^2}{\sum_{j=1}^{m}\left(Y - \ddot{Y}\right)^2} \tag{4}$$

where RMSE is the root mean square error; m is the 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 temperature (30°C, 40°C, 50°C and 60°C) on anaerobic digestion of food waste was carried out in the laboratory scale bio-digesters 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. Daily and cumulative biogas production with respect to retention time was determined which is shown in Figs. 2 and 3, respectively. Out of four different temperatures, reactor with operating temperature of 50°C yielded higher gas production, followed by 60°C, 40°C and 30°C. Peak biogas production rates recorded for the operating temperature of solid concentrations of 30°C, 40°C, 50°C and 60°C were 162, 207, 224 and 218 mL/d, respectively. Temperature magnitudes in excess of 50°C cause gas production to slow down and to eventually stop. These results indicate the microbial activity increases with increase in temperature up to 50°C and decreases thereafter. Temperature has a considerable effect both on anaerobic degradation of organic substance and growth and survival of microorganisms. Fig. 4 shows the maximum biogas yield for all the reactors. Similar trend was obtained for Deepanraj et al. [11] and Kim et al. [15], who studied the effect of temperature on biogas production from anaerobic digestion of food waste. The amount of biogas produced from the reactors at 50°C and 60°C is more than that of 30°C and 40°C. This result suggests that the activity of the methanogenic bacteria used in this study depends on the operating temperature. Therefore, a thermophilic temperature of 50°C–60°C is more effective for biogas production than a mesophilic temperature.

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 64.9% and

Table 2
Characteristics of food waste before digestion

Parameters	Values
TS (g/L)	100
VS (g/L)	89.81
FS (g/L)	10.19
pH	5.70
COD (g/L)	76.79

Table 3
Characteristics of food waste after digestion

Parameters	30°C	40°C	50°C	60°C
TS (g/L)	54.10	53.84	50.91	52.55
VS (g/L)	45.04	44.80	41.91	43.52
FS (g/L)	9.06	9.04	9.0	9.03
pH	5.34	5.51	6.10	5.83
COD (g/L)	46.72	46.14	44.92	45.46

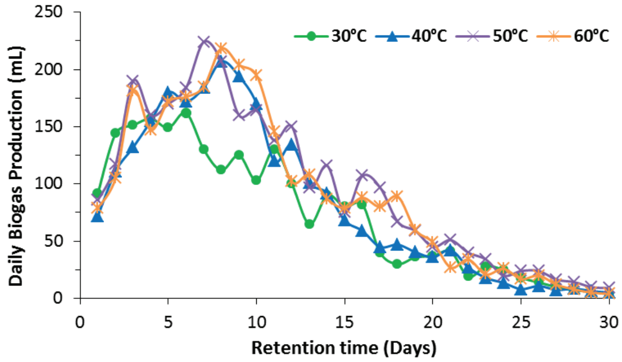

Fig. 2. Daily biogas production.

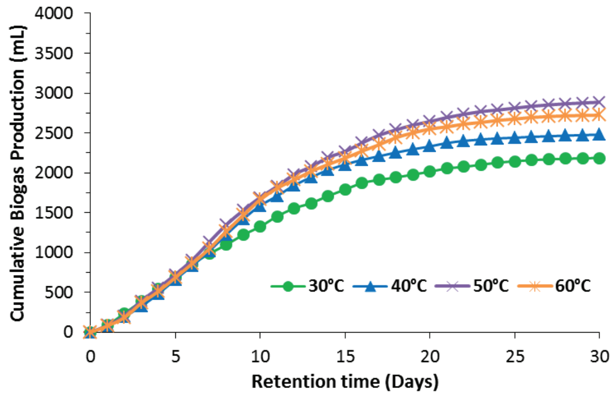

Fig. 3. Cumulative biogas production.

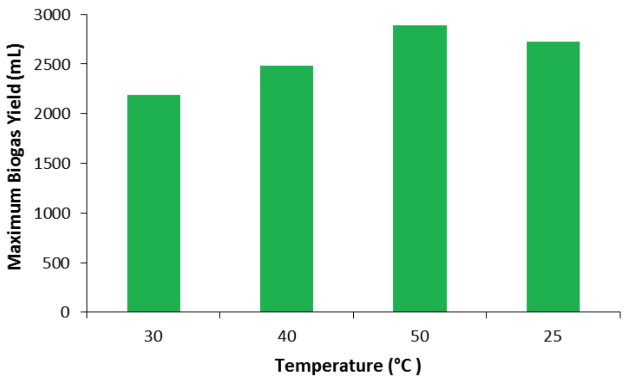

Fig. 4. Maximum biogas yield.

67.5%. Similarly, the average carbon dioxide composition obtained was in between 31.7% and 34.9%. The TS, VS and COD degradation efficiencies were shown in Fig. 7. In all the cases, reactor with operating temperature of 50°C achieved maximum degradation and 30°C achieved minimum degradation. The TS degradation efficiency of the reactors with operating temperature of 30°C, 40°C, 50°C and 60°C are 45.9%, 47.4%, 49.5% and 48.3%, respectively. The VS degradation efficiency of the reactors with operating temperature of 30°C, 40°C, 50°C and 60°C is 49.84%, 50.2%, 54.3% and 52.0%, respectively. Similarly, the COD degradation efficiency of the reactors with operating temperature of 30°C, 40°C, 50°C and 60°C is 39.15%, 40.2%, 42.5% and 40.9%, respectively.

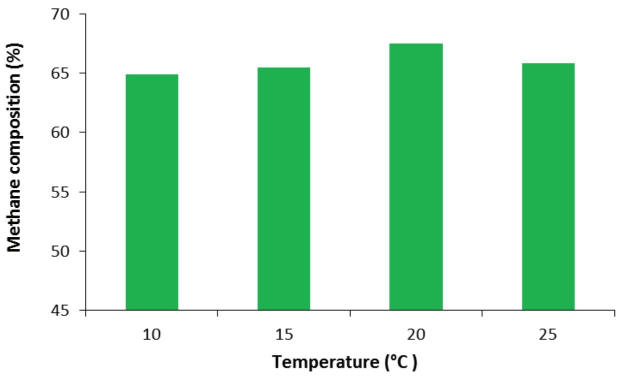

Fig. 5. Average methane composition in biogas.

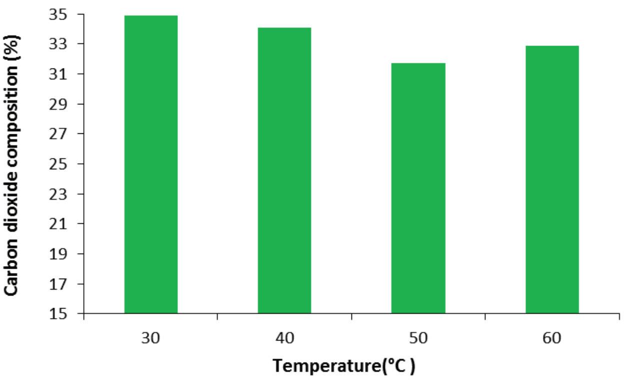

Fig. 6. Average carbon dioxide composition in biogas.

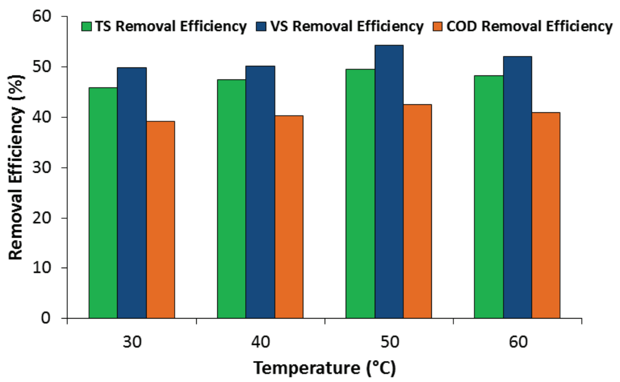

Fig. 7. TS, VS and COD removal efficiencies.

3.2. Kinetic study

Based on the Gompertz model (Eq. (1)), the maximum values of biogas production that could be achieved during the stabilization of anaerobic digestion process were determined. The kinetic constants were calculated for 30 d of digestion time because the time needed for 90% biogas production fell within this range [14]. The results showed that the operating temperature of 30°C produced least amount of biogas during digestion while the highest amount of biogas was produced with the reactor having operating temperature of 50°C. The kinetic parameters determined using first-order reaction kinetics was given in Table 4. The comparison of experimental and predicted cumulative biogas production based on the above results is shown in Fig. 8(a). The biogas production rate constant (k) for all the temperature range was found to be in between 0.0613 and 0.740. The coefficient of determination (R^2) for the reactors with operating temperatures 30°C, 40°C, 50°C and 60°C is 0.9914, 0.9752, 0.9836 and 0.9796, respectively. This shows that the results taken from the model were best fitted with the experimental study.

Fig. 8(b) shows the comparison of experimental and predictive cumulative biogas production obtained through modified Gompertz model. The coefficient of determination, root mean square error, predicted gas production and lag phase of the reaction were given in Table 5. The minimum and maximum biogas yield potential obtained from the bioreactors were 2,201.9 and 2,904.8 mL. The R^2 values lies in between 0.9608 and 0.9865. The lag phase obtained for the reactors having operating temperatures 30°C, 40°C, 50°C and 60°C is 0.4, 1.7, 1.4 and 1.6 d, respectively.

4. Conclusion

Food waste was found to be a potential substrate for biogas production. The anaerobic digestion of food waste with operating temperatures of 30°C, 40°C, 50°C and 60°C resulted in a cumulative biogas production of 2,186, 2,479, 2,885 and 2,724 mL, respectively. The experimental results were fitted with Gompertz and modified Gomperz model to determine the kinetic parameters. Modified Gompertz model fit better with the experimental results than the Gompertz model.

Table 4
Estimated kinetic parameters using first-order reaction kinetics

Parameter	30°C	40°C	50°C	60°C
C-experimental (mL)	2,186	2,479	2,885	2,724
C-model (mL)	2,279.5	2,625	3,042	2,890
B (mL)	2,556.60	2,966.53	3,616.32	3,399.55
R^2	0.9914	0.9752	0.9836	0.9796
K	0.0740	0.0720	0.0613	0.0633
RMSE (%)	11.50	23.30	21.72	23.26

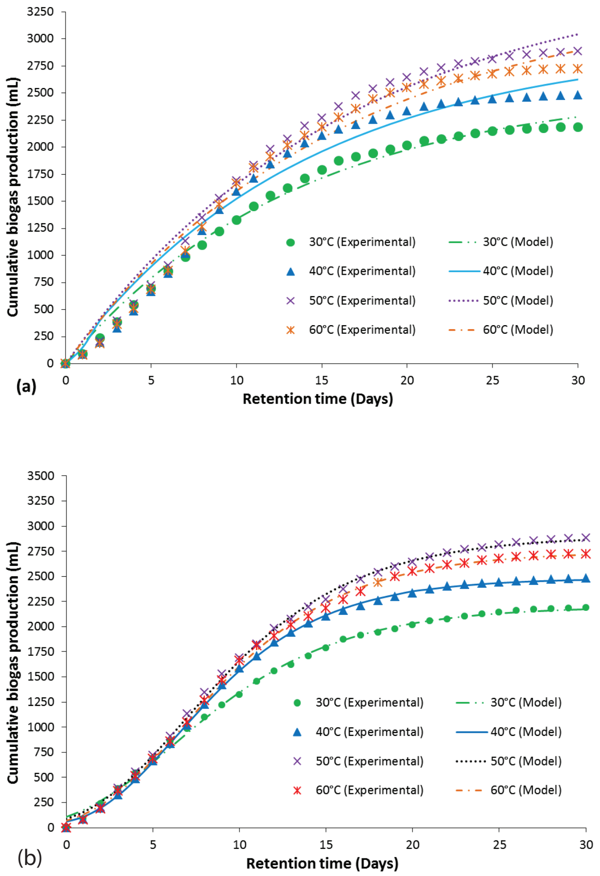

Fig. 8. Comparison of experimental and predicted results: (a) Gompertz model and (b) modified Gompertz model.

Table 5
Estimated kinetic parameters using modified Gompertz model

Parameter	30°C	40°C	50°C	60°C
C-experimental (mL)	2,186	2,479	2,885	2,724
C-model (mL)	2,173.4	2,465.6	2,864.0	2,716
B (mL)	2,201.9	2,482.1	2,904.8	2,746.8
R_b (mL/d)	147.6	194.4	197.1	195.6
λ (d)	0.4	1.7	1.4	1.6
R^2	0.9865	0.9848	0.9803	0.9608
RMSE (%)	33.56	16.72	32.30	29.25

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