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Experimental and kinetic study on anaerobic co-digestion of poultry manure and food waste

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ABSTRACT

Enhancement of biogas production by adding external substrates as a co-digestion material is one of the solution to increase energy self-sufficiency of the anaerobic digestion process. The aim of this work is to analyze the impact of anaerobic co-digestion of poultry manure with food waste on the biogas production. Experiments were conducted on a range of 0, 10, 20, 30 and 40% of poultry manure with 100, 90, 80, 70 and 60% of food waste (CD0, CD10, CD20, CD30 and CD40) respectively. Five laboratory scale batch reactors of capacity 2 L were used for this work. The solid concentration, pH and temperature values taken in all the reactors were 7.5% of total solids, 7 pH and 50°C respectively. It was observed that the highest cumulative biogas yield of 8469 mL and methane concentration of 62.03% were obtained with the co-digested substrate CD30 (30% of poultry manure with 70% of food waste), whereas 7556 mL was obtained with raw food waste (CD0). The degradation efficiencies (TS, VS and COD) were also higher for CD30 compared to the other four substrates. First order kinetic model, modified Gompertz model and Logistic model were evaluated for the biogas yield and the predicted results were compared with the experimental results.

Keywords: Biogas; Co-digestion; Anaerobic digestion; Food waste; Poultry manure

1. Introduction

Increase in energy demand and the issues about current non-renewable energy resources led researchers to investigate alternative energy sources during the last two decades. Renewable energy resources have drawn attention all over the world because they are sustainable, improve the environmental quality and provide new job opportunities in rural areas [1]. Every year in the world several million tons of organic wastes are being disposed through different ways such as incineration, anaerobic digestion, land applications, land filling, etc. This global waste has a high potential as a bio renewable energy resource and can be turned into high-value by-products. Anaerobic digestion is a well-known method for the treatment of organic wastes such as municipal solid waste, sewage sludge, animal manure and crop residues. Properly functioning anaerobic digestion system not only can achieve high biogas production to supply the increasing societal energy demands but also can transform organic waste into high quality fertilizer [2,3].

Numerous studies had been conducted by several researchers in order to improve and optimize the yield of biogas from anaerobic digestion process. The techniques include effect of particle size, inoculum volume, improving substrate composition by co-digestion, optimization of dilution level (solid-water concentration), etc. Wei et al [4] evaluated the biogas production potential from the co-digestion of highland barley straw (BS) with Tibet pig manure and cow manure at Tibet plateau under psychrophilic temperature condition. The effect of inoculum to substrate (I/S) ratio and BS to manure ratio on the biogas production was studied using a series of batch digesters. The results

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showed that biogas production from BS was feasible at low temperature and low air pressure condition. High I/S ratio (>2/1) and BS to manure ratio of 1/1 could increase the biogas production. Kafle et al [5] investigated the potential for anaerobic co-digestion of Chinese cabbage waste silage with swine manure for biogas production in a batch and continuous reactor. They reported that there is no significant difference in biogas yield up to 25–33% of CCWS; however, biogas yield was significantly decreased when CCWS contents in feed increased to 67% and 100%. Gelegenis et al [6] studied the effect of co-digestion on biogas production with various mixtures of diluted poultry manure and whey. Whey was gradually introduced in the feed, at increasing rates, replacing equivalent volumes of manure, in such a way, that total COD of the feed remained constant. For an hydraulic retention time of 18 d at 35°C and organic loading rate of 4.9 g COD/L_Rd, it was found that biogas production increased from 1.5 to 2.2L/L_Rd (almost 40%). Kafle et al [7] studied the effect of co-digestion of Kimchi factory waste silage and swine manure under mesophilic conditions. The results suggested that Kimchi factory waste could be effectively treated by making silage, and the silage could be used as a potential co-substrate to enhance biogas production from swine manure digester.

There have been many studies on the co-digestion of crop residual and animal manure; however, there is little information available concerning anaerobic co-digestion of poultry manure with food waste. The objective of this present study is to investigate the viability of co-digesting food waste with poultry manure (10–40%) as an external nitrogen source in biogas production. In addition, the kinetic study on anaerobic co-digestion of food waste was performed using three different models namely first order kinetic model, modified Gompertz model and Logistic model.

2. Materials and methods

2.1. Feedstock preparation

Food waste is a highly desirable substrate for anaerobic digestion with regards to its higher biodegradability and biogas/methane yield. It contains a substantially large amount of organic matter, which can be digested anaerobically to produce biogas. Food waste was obtained from hostel mess of National Institute of Technology Calicut, Kerala. The waste obtained were shredded, mixed and stored at 5°C until use. The solid concentration, pH and temperature to be maintained were already optimized from the previous experiments [8–11]. Water was added to obtain the desired solid concentration (7.5% of TS) and 1N sodium bicarbonate solution was used to maintain the pH value as 7. Poultry manure was collected from Regional Poultry Farm, Chathamangalam, Calicut. The poultry manure was added with food waste in order to vary the C/N ratio before feeding into the digester. Four different substrates were prepared by co-digesting 10% (CD10), 20% (CD20), 30% (CD30) and 40% (CD40) of poultry manure with 90, 80, 70 and 60% of food waste respectively. The C/N ratios for the raw food waste, poultry manure and the substrates with mixing ratios CD10, CD20, CD30 and CD40 are 44.21, 7.43, 33.90, 26.31, 20.19 and 16.01 respectively. Cow dung was used as an inoculum for starting the experiments. Substrate to inoculum ratio was taken as 90:10 as suggested by Sivakumar et al [18].

2.2. Experimental design

A 2-L lab scale batch digesters were used for the experimental studies. Each digester was equipped with a water bath and a magnetic stirrer, which is shown in Fig. 1. The digester was seeded with substrate containing feed materials in various C/N ratios. The working volume of the digester was kept at 1.6 liter. Anaerobic digestion of vegetable/food residues was carried out at thermophilic condition (50°C) by maintaining temperature in the water bath. All the digesters were stirred twice in a day using magnetic stirrers. Biogas coming out of the digester was measured continuously by water displacement method.

2.3. Analytical methods

The C/N ratios of food waste, poultry manure and the co-digested substrates were determined using elemental analyser (Elementar Vario EL III, ELEMENTER Analysensyteme, 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 [19]. For all the digesters, the initial substrate concentration was 7.5% of TS. After digestion, the solid concentration of digester varied from 2.90 to 3.42% of TS. This shows that the performance of each of the reactor varies accordingly with respect to their respective C/N ratio of the substrate.

2.4. Kinetic model and statistical indicators

Due to the role of microorganisms in the anaerobic digestion process, the kinetic models were commonly applied to the experiments to stimulate the anaerobic biodegradation. Assuming first order reaction kinetics, Gompertz suggested a model to describe the cumulative biogas production [12,13].

$$C = B\left[1 - \exp(-kt)\right] \tag{1}$$

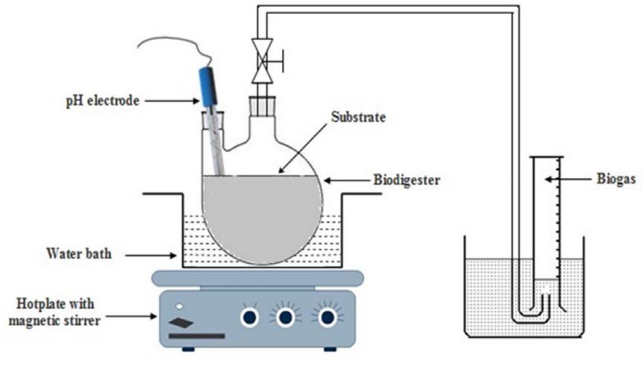

Fig. 1. Schematic diagram of experimental setup.

where, C is the cumulative biogas production at digestion time 't' days, B is the biogas potential of the substrate, k is the first order disintegration rate constant (biogas production rate constant), t is the time in days.

Along with biogas production, the duration of lag phase is also an important factor in determining the efficiency of anaerobic digestion. The lag phase can be calculated from modified Gompertz model (Eq. (2)) and Logistic model (Eq. (3) [14,15].

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

$$C = \frac{B}{1 + \exp\left[4R_b\frac{\lambda - t}{B} + 2\right]} \tag{3}$$

where R_b is the maximum biogas production rate; λ is the lag phase; e is the exp(1) = 2.7183.

B, k, R_b and λ were determined using the non-linear curve fitting toolbox available in MATLAB software. The coefficient of determination (R^2) and root mean square error (RMSE) were also determined from this analysis [16,17].

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

$$RMSE = \left(\frac{1}{m}\sum_{j=1}^{m}\left(\frac{d_j}{Y_j}\right)^2\right)^{1/2} \tag{5}$$

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

3. Results and discussion

Fig. 2a, b shows the daily and cumulative biogas production for all the bioreactors during the anaerobic digestion of food waste and food waste co-digested with poultry manure. Biogas in all reactors could be produced immediately from the first day and increased obviously during the first 10 days, then decreased gradually. From the daily biogas production, the peak values were calculated to be 628, 680, 713, 780 and 732 mL for the digesters with CD0, CD10, CD20, CD30 and CD40 respectively. Data obtained from metering the production capacity of the anaerobic processes for the various mixing ratios are as follows: Raw food waste (CD10) produced a cumulative biogas production of 7556 mL, whereas the reactors with CD10, CD20, CD 30 and CD40 produced 7894, 8469, 8921, and 8538 mL respectively. Compared to the raw food waste, biogas production increased upto CD 30 and decreased thereafter. The lower biogas production after CD30 was probably due to their lower biodegradability of poultry manure and the inhibition of ammonia released from their degradation [20,21]. Thus, the mixing ratio of CD30 with C/N ratio 20.19 was found to be optimal for maximum biogas production as well as degradation efficiency.

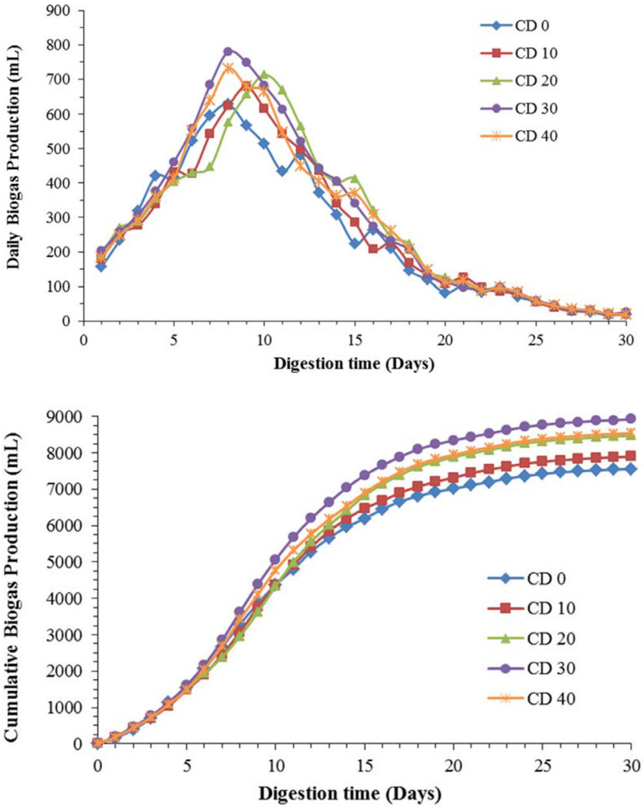

Fig. 2. (a) Daily biogas production; (b) Cumulative biogas production.

The TS, VS and COD removals were calculated at the end of 30 days digestion period for all the reactors, which is shown in Table 1 and Fig. 3. Compared to the raw food waste, the efficiencies of TS, VS and COD removal increase up to the co-digestion of 30% of poultry manure and then decreases. The C/N ratio of 20.19 (CD30) achieved highest TS and COD removal efficiency which is 6.58 and 9.70% higher than raw food waste (CD0) respectively. While seeing VS removal, C/N ratio 26.31 (CD20) achieved better result.

The kinetic parameters estimated for all the substrates using first order kinetic model, modified Gompertz model and Logistic model were summerised in Table 2. The biogas production rate constant (k) was calculated from the first order kinetic model and lag phase (λ) was calculated from the modified Gompertz model and Logistic model. The predicted biogas yield derived from all the models were shown in Fig. 4. The difference between predicted and measured biogas yield was higher with first order kinetic model than with other two models. The lag phase duration found using modified Gompertz model for the substrates CD0, CD10, CD20, CD30 and CD 40 are 2.4, 2.8, 3.0, 2.8 and 2.9 days respectively. For the Logistic model, the lag phase ranged over 2.8 to 3.5. Compared to raw food waste, the lag phase duration of the co-digested substrates were high due to more protein and fat content in the substrate [13]. This lag phase

Table 1
Results obtained for different mixing ratios

Parameter	CD0	CD10	CD20	CD30	CD40
TS removed ($g L^{-1}$)	40.77	41.38	42.76	43.45	41.91
VS removed ($g L^{-1}$)	40.32	38.75	38.68	36.68	35.56
COD removed ($g L^{-1}$)	29.75	32.99	36.14	38.19	37.71
Cumulative Biogas production (mL)	7556	7894	8469	8921	8538
CH4 (%)	61.20	60.64	61.45	62.03	60.59
CO_2 (%)	37.13	38.02	36.54	35.19	38.76
Biogas yield (mL L^{-1} of reactor)	3778	3947	4235	4461	4269
Specific biogas yield (mL g^{-1} of COD removed)	161.09	159.52	156.22	155.73	150.94
Specific biogas yield (mL g^{-1} of VS removed)	124.94	135.81	145.96	162.14	160.06

could be reduced by co-digestion of substrates having higher carbohydrates and low proteins and fats. The best fit was obtained from modified Gompertz model with highest coeffiient of determination (R^2) value for all the reactors (above 0.9991). For first order kinetic model and Logistic model, R^2 values obtained were in between 0.9674– 0.9746 and 0.9974–0.9992 respectively. Based on the results of statistical curve fitting, the modified Gompertz model was observed to adequately describe the cumulative biogas production with high goodness of fit. The RMSE was also very less for modified Gompertz model, compared to other two models.

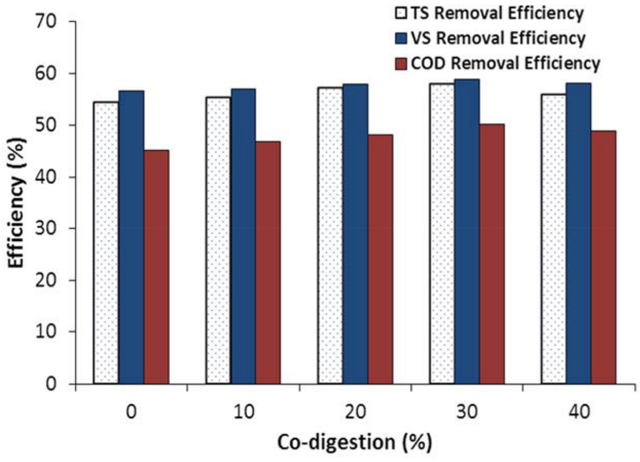

Fig. 3. TS, VS and COD removal efficiencies.

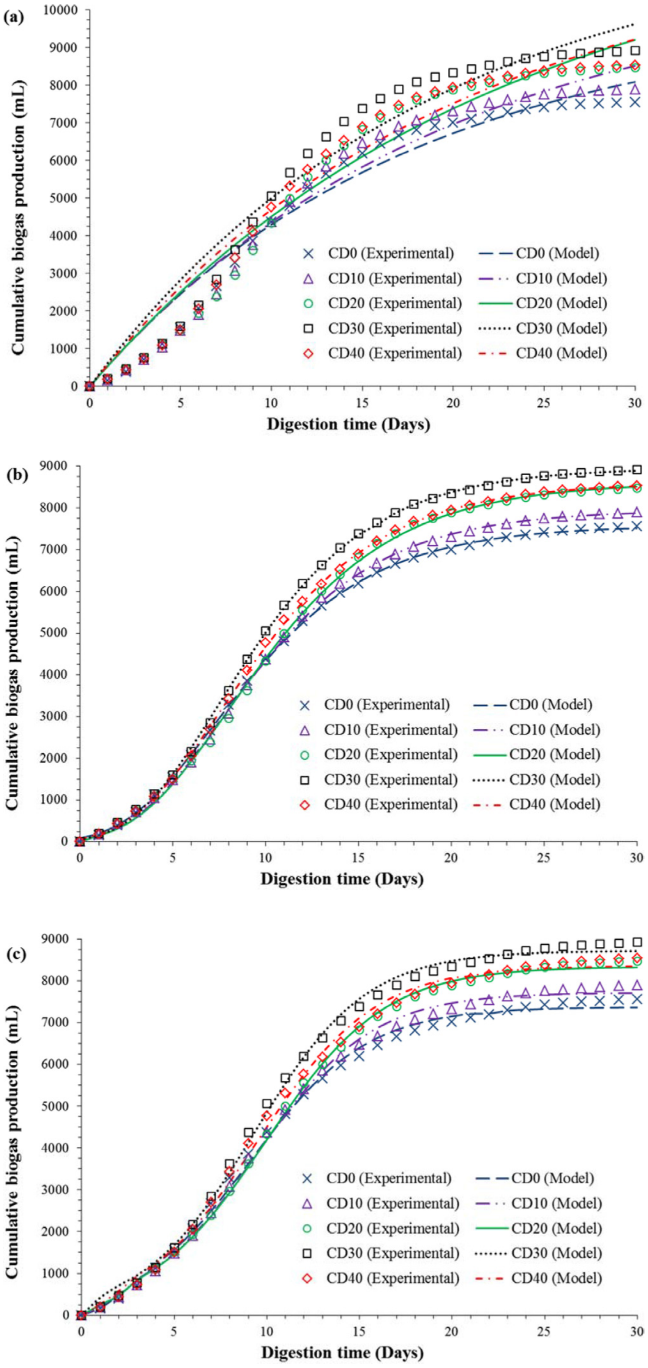

Fig. 4. Cumulative biogas production from kinetic modeling. (a) First order kinetic model, (b) Modified Gompertz model and (c) Logistic model.

4. Conclusion

In the present study, food waste was anaerobically treated with poultry manure and the effect of mixing ratio (through co-digestion) on biogas production was evaluated using lab scale batch reactors. The food waste was found to be a potential substrate for co-digestion with poultry manure for biogas production. The biogas yield and VS, TS and COD removal were higher for the mixture of food waste

Table 2
Kinetic parameters estimated using models

Parameter	First order kinetic model					Modified Gompertz model					Logistic model				
	CD0	CD10	CD20	CD30	CD40	CD0	CD10	CD20	CD30	CD40	CD0	CD10	CD20	CD30	CD40
C-Expt (mL)	7556	7894	8469	8921	8538	7556	7894	8469	8921	8538	7556	7894	8469	8921	8538
C-Pred (mL)	8093.2	8520.0	9211.1	9629.6	9223.0	7517.4	7879.5	8511.6	8894.6	8525.6	7360.6	7707.1	1319.5	8708.8	8343.7
B (mL)	9847	10810	12390	12020	11780	7583.2	7954.4	8617.7	8964.3	8610.1	7369.9	7954.4	8335.3	8717.9	8356.2
Rb (mL d^{-1})	–	–	–	–	–	581.8	609.9	634.8	712.6	655.2	587.4	621.3	651.3	722.4	663.4
k	0.0575	0.0517	0.0453	0.0538	0.0509	–	–	–	–	–	–	–	–	–	–
λ (days)	–	–	–	–	–	2.4	2.8	3.0	2.8	2.9	2.8	3.2	3.5	3.3	3.2
R^2	0.9746	0.9697	0.9674	0.9678	0.9706	0.9998	0.9996	0.9991	0.9995	0.9998	0.9974	0.9981	0.9992	0.9977	0.9975
RMSE	27.80	27.44	27.10	29.42	29.11	1.71	2.7	4.3	2.78	1.8	13.24	9.31	2.6	9.7	5.90

and poultry manure than food waste alone. Co-digestion of 30% of poultry manure (CD30) having C/N ratio 20.19 produced more biogas with high degradation efficiency compared to other substrates. The modified Gompertz model has better consistency with experimental data than other two models based on R^2 and RSME.

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