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BIOLOGICAL WASTE AS RESOURCE, WITH A FOCUS ON FOOD WASTE

Effects of sludge recirculation rate and mixing time on performance of a prototype single-stage anaerobic digester for conversion of food wastes to biogas and energy recovery

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Abstract Food wastes have been recognized as the largest waste stream and accounts for 39.25 % of total municipal solid waste in Thailand. Chulalongkorn University has participated in the program of in situ energy recovery from food wastes under the Ministry of Energy (MOE), Thailand. This research aims to develop a prototype single-stage anaerobic digestion system for biogas production and energy recovery from food wastes inside Chulalongkorn University. Here, the effects of sludge recirculation rate and mixing time were investigated as the main key parameters for the system design and operation. From the results obtained in this study, it was found that the sludge recirculation rate of 100 % and the mixing time of 60 min per day were the most suitable design parameters to achieve high efficiencies in terms of chemical oxygen demand (COD), total solids (TS), and total volatile solid (TVS) removal and also biogas production by this prototype anaerobic digester. The obtained biogas production was found to be 0.71 m^3/kg COD and the composition of methane was 61.6 %. Moreover, the efficiencies of COD removal were as high as 82.9 % and TVS removal could reach 83.9 % at the optimal condition. Therefore, the developed prototype single-stage anaerobic digester can be highly promising for university canteen application to recover energy from food wastes via biogas production.

Keywords Sludge recirculation rate · Mixing time · Prototype system · Single-stage anaerobic digester · Food waste · Biogas production · Energy recovery

Introduction

At present, inappropriate solid waste management has been recognized as one of the major environmental problems of Thailand. The Pollution Control Department (2007) made an attempt to present a general qualitative and quantitative description of organic waste generation in Thailand. It is estimated that its total amount reaches about 50,000 tons a year and it is 60 % of municipal solid waste generated within the country. The whole mass of organic biodegradable waste is dominated by the waste originating from food residues, which amounts to about 70 %. Since food waste contains high moisture content and also high organic composition, it can contribute to odor problem, leachate, and greenhouse gas production in landfill (Slack et al. 2005; Tchobanoglous et al. 1993; Zhang et al. 2007). Anaerobic digestion has been recognized as a promising technology to handle biological waste, which can reduce the landfill volume required and control the organic pollutants as a source reduction method (Mata-Alvarez et al. 2000; Digman and Kim 2008; Ahn et al. 2009). The energy produced during anaerobic digestion of waste can act as a renewable energy source, while liquid digestate produced can be used as fertilizer for agriculture (Hobson 1990). Anyhow, failure in the digester operation tends to occur, when sole substrate is fed to the digester without external nutrients and buffering agent (Demirel and Scherer 2007).

The importance of mixing on the performance of anaerobic digestion was previously studied by some researchers. Babbitt and Baumann (1958) suggested the importance of mixing to enhance biogas production from anaerobic digestion. Without

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adequate mixing, insufficient contact between microorganisms and organic waste can occur. Methods of mixing include external pumped recirculation, internal mechanical mixing, and internal biogas mixing (Igoni et al. 2008). The use of external pumped recirculation was studied by Stabnikova et al. 2008; they observed an increase in biogas production with this mixing method application. Fernandez et al. (2008 and 2010) and Forster-Carneiro et al. (2008) found that a high total solid (TS) content of feed waste could reduce substrate degradation, resulting in less methanogenic activity. Droste (1996) reported that mixing helps distribute nutrients and buffering agents throughout the digester and prevent build up of intermediate metabolic by-products that can inhibit methanogenic microorganisms inside the anaerobic digester. However, Karim et al. (2005) found that similar performance of the mixed and unmixed digesters might be the result of the low solid concentration (50 g dry solids per liter of slurry) in the fed animal slurry, which could be sufficiently mixed by the naturally produced biogas.

Here, Chulalongkorn University has developed the waste-to-energy program under the Ministry of Energy's project. The single-stage anaerobic digester has been developed for energy recovery from food waste at a university canteen. The prototype Chulalongkorn University model has a total volume of 12 m^3. The system is located at the first floor of the student dormitory inside the university campus with a design maximum capacity of 250 kg of food waste per day. The main objective of this research work is to develop the compact prototype single-stage anaerobic digester and then evaluate the performance of anaerobic digestion of food waste for energy recovery together with organic waste reduction. In this research, the attention on the effects of sludge recirculation rate and mixing time on biogas production using the developed prototype single-stage anaerobic digester were mainly focused.

Materials and methods

The characteristics of feeding substrates

Food waste was collected from a canteen at the University Dormitory Building, Chulalongkorn University, which was composed of food residues, grain, vegetables, starch, grease, etc. The food waste was shredded into 5- to 10-mm-size pieces by food grinder. Here, the characteristics of food waste used in this study, in terms of TS, suspended solid (SS), total volatile solids (TVS), chemical oxygen demand (COD), volatile fatty acids (VFA), pH, total phosphorus (TP), and total Kjehldahl nitrogen (TKN) are presented in Table 1. Food waste was characterized to have high COD concentration with an average value of 232,795 mg/L as daily fresh waste. Carbohydrates and proteins were the principal waste composition. Total solid content of food waste was found to be 8 %. Due to the food waste characteristic, it is considered as a suitable substrate for anaerobic digestion process.

Table 1 Characteristics of food waste from the university canteen

Food waste parameter	Range
TS, mg/L	80,676
SS, mg/L	72,410
TVS, mg/L	78,823
COD, mg/L	232,795
VFA, mg/L	2957.8
pH	4.66
TP, mg/L	926
TKN, mg/L	6275

Development of prototype single-stage anaerobic digester for food waste management

A prototype single-stage anaerobic digester for food waste digestion was newly designed and constructed for tropical application at a student dormitory inside the Chulalongkorn University campus. The schematic diagram of the prototype single-stage anaerobic digester used in this study is illustrated in Fig. 1. The tank material is fabricated from steel plate segments. The configuration of the developed prototype system is shown in Fig. 2. The volume of the reactor was 12 m^3 with a working volume of 10 m^3. It is equipped with a paddle-type mixer that is installed inside the digester. Here, the digester was operated at a mesophilic temperature range (35±2 °C). The prototype digester was first inoculated with the anaerobic sludge from a sewage sludge digestion plant. After 6 weeks of system acclimatization, the digester performance was monitored. The digester was loaded with food waste from the canteen twice a day in semicontinuous mode of feeding. During the food waste loading, the sludge recirculation was done simultaneously, using a recirculation pump. The return sludge was recirculated from the tank outlet to the tank inlet through the return sludge pipe. Mixing was performed shortly after the substrate loading was finished. The digester was operated at a hydraulic retention time (HRT) of 40 days, corresponding to organic loading rate of 5.83 kg COD/m^3/day. The sludge recirculation rates were varied to 50 and 100 % of the feed flow rate in order to investigate the effect of sludge recirculation rate on performance of anaerobic digestion of food waste. The system was operated until the prototype digester could reach steady condition in terms of biogas production and stable system performance. Also, the mixing times for the prototype single-stage anaerobic digester were varied to 30, 60, and 90 min in order to know the optimum mixing time for biogas production rate. The mixer was operated twice a day after food waste loading (two periods of waste loading per day). Here, the screw conveyor was used to move the food wastes into the

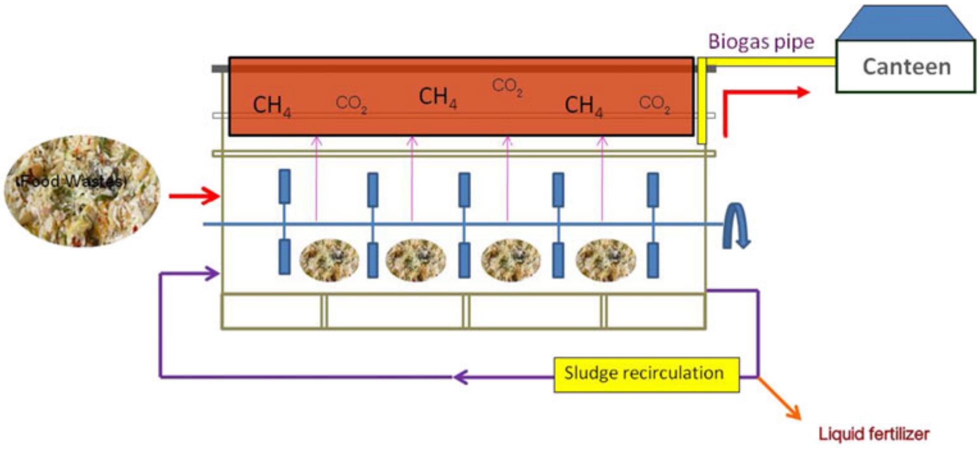


Fig. 1 Schematic diagram of the developed prototype single-stage anaerobic digester for conversion of food wastes from university canteen to biogas

single-stage anaerobic digester. Fresh food waste was mixed with the microorganism and the remaining fermented substrate. A paddle-type mixer was provided for slow mixing in the digester at a short period after the waste loading. The biogas obtained from anaerobic activity was kept in the biogas storage and sent for further use in canteen for cooking purpose. The biogas storage was designed as a floating dome, installed at the top of anaerobic digester. The biogas from the storage was sent through the biogas pipe for usage in the canteen. Furthermore, gas flow meter was provided at the digester for the measurement of biogas.

Analytical methods

COD, TS, SS, TVS, VFA, pH, alkalinity, TP, and TKN were measured based on the standard methods (APHA-AWWA-WPCF 2005). COD was analyzed by COD analyzer (HACH, DR 2500, USA). CH_4 and CO_2 compositions of biogas were determined through a TRACE GC (Thermo Finnigan) equipped with a thermal conductivity detector. The biogas volume was measured by a gas flow meter and corrected at standard temperature and pressure conditions.

Fig. 2 Configuration of the developed prototype single-stage anaerobic digester for conversion of food wastes to biogas

Results and discussion

Effect of sludge recirculation rate on performance of the prototype single-stage anaerobic digester

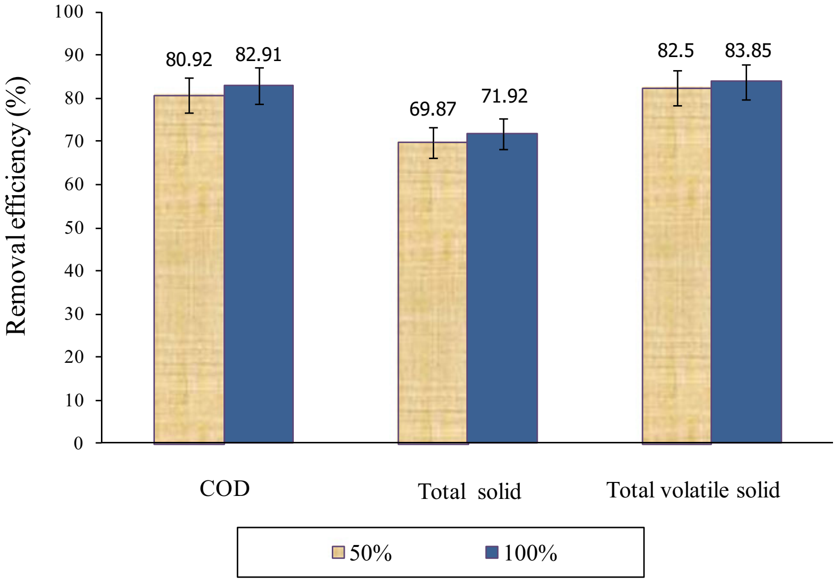
Degradation of organic matters and solid reduction

Figure 3 depicts the organic removal efficiencies obtained in terms of COD, total solid, and total volatile solid by the prototype single-stage anaerobic digester. It can be seen that an increase in sludge recirculation rate could slightly enhance the removal efficiencies for COD, total solid, and total volatile solid. High COD removal efficiency represented the high performance of the developed prototype single-stage anaerobic digester for organic removal. This might be due to the fact that mixing inside the digester was rather sufficient at both sludge recirculation rates of 50 and 100 %. However, higher sludge recirculation rate of 100 % could improve the pH stability of the digester due to more alkalinity return from higher rate of sludge recirculation. Moreover, TS and TVS also could be reduced highly as illustrated in Fig. 3. Indeed, the prototype single-stage anaerobic digester with sludge recirculation could enhance reliable organic and solid reduction efficiencies better than the digester without sludge recirculation.

pH, VFA, and alkalinity profile during system operation

pH is recognized as an important parameter to be measured in relation to VFA concentration. The optimal pH of the methane-forming microorganism is in the range of 6.8–7.2. A drop in the pH value through the production of volatile fatty acid, through hydrolysis and fermentation, can inhibit anaerobic digestion of VFA and also methanogenesis. Moreover, sufficient alkalinity is necessary for the pH stability of the digester. Therefore, pH, VFA, and alkalinity are important control parameters during digestion. It is important for a digester to operate in an optimum condition to achieve good system performance. These parameters were measured in this

Fig. 3 Performance of the prototype single-stage anaerobic digester for COD and total solid removal with different sludge recirculation of 50 and 100 %



study to evaluate the stability of the single-stage anaerobic digestion system for the food waste digestion. The results of pH variation along the operation of the prototype single-stage anaerobic digester are illustrated in Fig. 4. VFA and alkalinity in the prototype digester are shown in Table 2. It was found that the VFA concentrations for the anaerobic digester with sludge recirculation rates of 50 and 100 % were 3250±24.8 and 2500±26.5 mg/L, respectively. The values were obviously higher than 1500 mg/L, which is commonly considered to be the limit for allowing stable operation of one biogas digester (Angelidaki et al. 2005). However, this range of VFA concentrations seems to have less effect on system performance using the prototype single-single stage anaerobic digester. This could be attributed to the strong buffering capacity in the prototype anaerobic digester as the VFA/alkalinity ratios of 0.55±0.01 and 0.33±0.01 still could be maintained in normal operation at such high sludge recirculation rates of 50 and 100 %, respectively, although no any alkaline was added to the single-stage anaerobic digester. It can be seen that the pHs in the digester with both sludge recirculation rates were still able to maintain between 7.5 and 7.8, which are in the range for normal operation of anaerobic digestion process. Moreover, digester stability could be enhanced by a high alkalinity concentration. Here, our digester was acclimatized for 6 weeks before starting the experiment, the steady-state condition was achieved within 4 weeks of system operation in terms of system performance and biogas production.

For the daily biogas production at different sludge recirculation rates, the obtained biogas from the digestion of food waste for the same total feeding are illustrated in Table 3. The biogas production rates of the prototype single-stage anaerobic digester with sludge recirculation rate of 50 and 100 % were 24 and 22.5 m^3/day, respectively, and the methane contents were 54.1 and 60.9 %, respectively. Therefore, the prototype single-stage anaerobic digester can achieve higher methane content and higher yield of biogas production per gTVS added or per gCOD added with the sludge recirculation rate of 100 %. Alkalinity return by sludge recirculation rate

Fig. 4 pH profile of the prototype single-stage anaerobic digester along the operation period (case of sludge recirculation rate of 100 %)

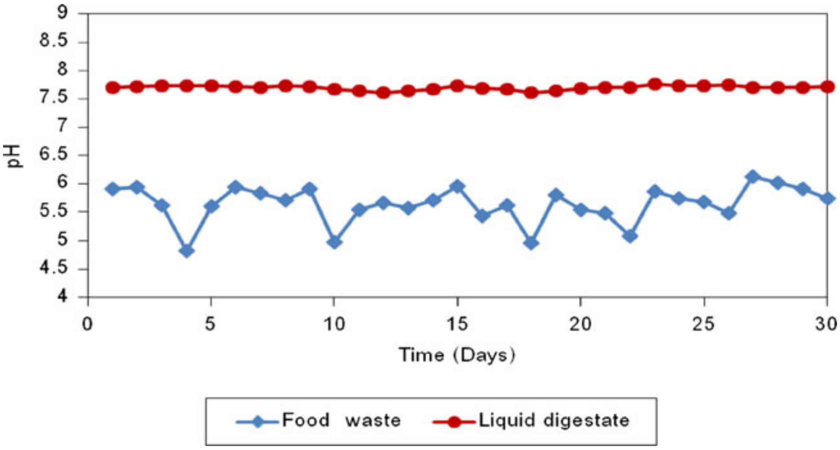


Table 2 VFA and alkalinity in the prototype single-stage anaerobic digester

Sludge recirculation rate (%)	VFA (mg/L)	VFA/Alk
50	3250±24.8	0.55±0.01
100	2500±26.5	0.33±0.01

could enhance the system stability of anaerobic digestion system. Then, enhancement of methane content of biogas could be apparently achieved with the sludge recirculation rate as illustrated in Table 3. Therefore, the stability of the digester is improved by increasing sludge recirculation rate to 100 % of the influent flow rate.

Effect of mixing time on performance of the prototype single-stage anaerobic digester

In this study, the sludge recirculation rate of 100 % was selected from the previous experiment. The mixing time was varied to 30, 60, and 90 min/day to investigate the effect of mixing time on system performance and biogas production.

Degradation of organic matters and solid reduction

The average COD removal efficiencies by the prototype single-stage anaerobic digestion system for different mixing times of the food waste digestion process were found in the same range at 87–90 %, as illustrated in Fig. 5. Here, the optimal sludge recirculation rate of 100 % was selected from the previous experiment. The highest COD removal efficiency of 90 % was achieved with the mixing time of 60 min. While total solid and total volatile solid removal efficiencies were found the highest value at the mixing time of 90 min. Since the mixing practice is rather sufficient even at a mixing time of 30 min, nevertheless, prolonging the mixing time could enhance total solid and total volatile solid reduction efficiencies to some extent.

Figure 6 shows a COD balance in the developed prototype single-stage anaerobic digester for food waste digestion. It was apparent that approximately 87–90 % of the COD was removed by the digester. The remaining COD in the treated liquid digestate (excluding biomass) was in the range of 5–8 %, while the COD utilized for biomass synthesis was 5 % on average.

Table 3 Average biogas production as a function of sludge recirculation rate

Sludge recirculation rate (%)	Amount of biogas production (m^3/d)	Average biogas production per gCOD added (m^3/kg COD added)	Average biogas production per gTVS added (m^3/kg TVS added)	Methane content (%)
50	24.0±2.3	0.57	1.22	54.1±4.8
100	22.5±2.1	0.58	1.14	60.9±3.9

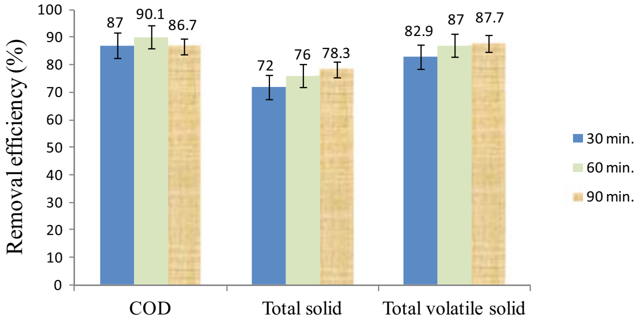


Fig. 5 COD, total solid, and total volatile solid removal efficiencies by the prototype single-stage anaerobic digester at different mixing times

It has been recognized that the major intermediate products of anaerobic digestion were acetic acid (HAc), propionic acid (HPr), and butyric acid (HBu). HPr is recognized as a leading volatile fatty acid indicator since the rise of the propionic acid concentration could be the sign of acidification in the digester. The anaerobic degradation of HPr and HBu can be more accomplished through the syntrophic cooperation of HPr and HBu-oxidizing bacteria and H_2/formate scavenging partners (Amani et al. 2010). From the analysis of volatile fatty acid production in our prototype single-stage anaerobic digester with different mixing times as shown in Fig. 7, it was found that lower concentrations of HPr and HBu were obtained with longer mixing times of 60 and 90 min/day. This means that HPr and HBu could be converted to HAc effectively. Therefore, mixing time at least 60 min/day is considered sufficient. Moreover, lower acetic acid concentrations were also obtained for a mixing time of 60 and 90 min/day. This indicates that the conversion of HAc to methane is promising at a mixing time of at least 60 min/day. Excessive mixing increases energy consumption, deteriorates the energy balance, and disturbs the microorganisms, thus ultimately decreasing the biogas production. Here, the paddle mixer is suitable to generate horizontal plug flow in a horizontal digester. This can save energy due to slow rotation of the paddle mixer. Moreover, the long horizontal paddle might reduce the formation of scum in the digester. A slowly rotating agitator can remove the fine gas bubbles which stick to the solid particle side the digester.

Biogas production

Biogas is produced through the conversion of organic matters by anaerobic microorganisms. With the conversion of organic

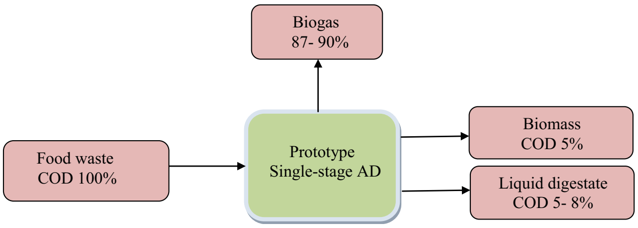


Fig. 6 COD balance of the prototype single-stage anaerobic digester

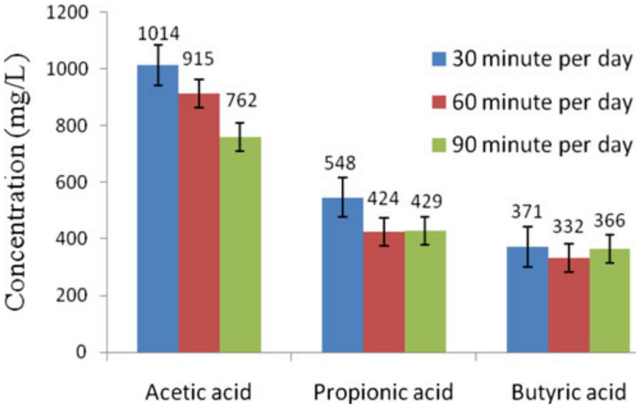


Fig. 7 Volatile fatty acid production as a function of mixing time

matters into biogas, the amount of organic dry matters would be reduced accordingly. The daily biogas production observed at different mixing times of the digestion of food waste for the same total feeding is illustrated in Fig. 8a. The average biogas production rates of the prototype single-stage anaerobic digester with mixing times of 30, 60, and 90 min were 14.2, 16, and 11 m^3/day, respectively, and the methane content was approximately in the range of 58.4, 61.6, and 55.9 %, respectively, as shown in Fig. 8b. When the mixing time is longer than 60 min, a small decrease in total biogas production was found and less methane content was also generated. Therefore, the mixing time of 60 min is selected as an optimal mixing condition for the prototype single-single stage digester.

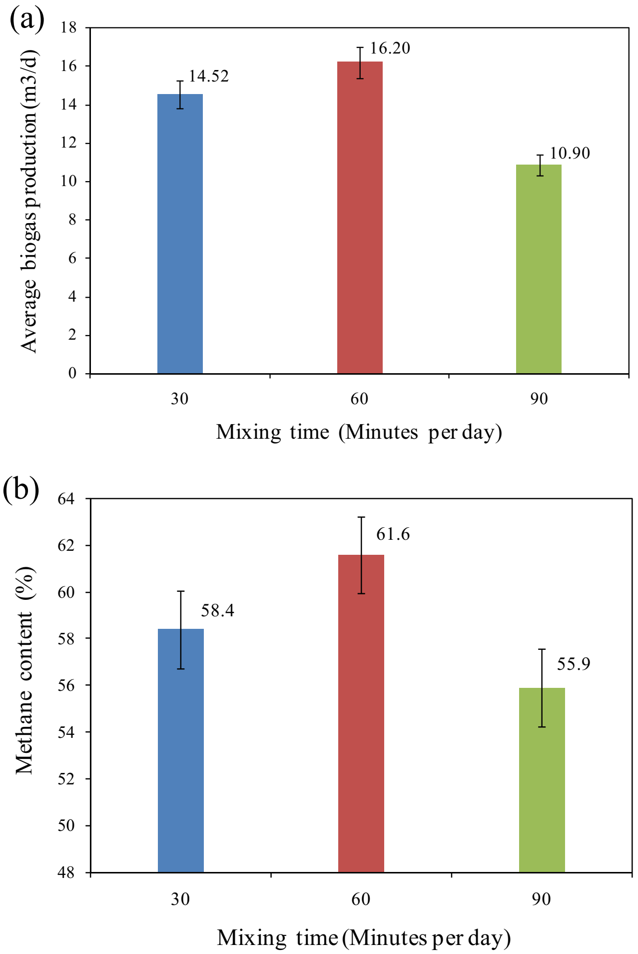


Fig. 8 Biogas production and methane content at different mixing times

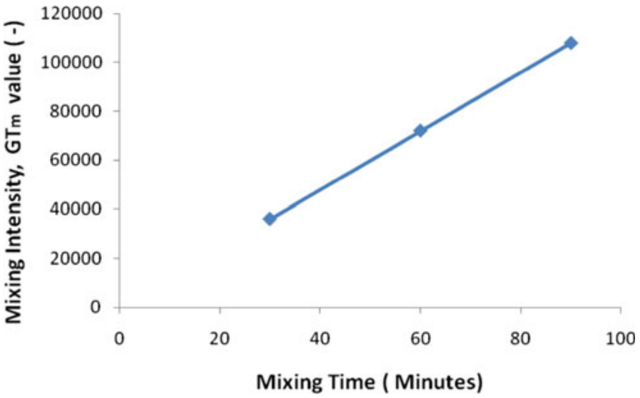


Fig. 9 Relationship between mixing intensity number and mixing time

Propose a new parameter on system mixing intensity for semicontinuous mixing mode

The need for efficient mixing of sludge in anaerobic digesters has been recognized as an important design criterion for full-scale anaerobic digester. Camp and Stein (1943) established the term of velocity gradient for use in the design and operation of systems with mechanical mixing devices:

$$G = [P/\mu V]^{1/2} \tag{1}$$

Where G is the average velocity gradient, P the power dissipation, V the reactor volume, and μ the liquid viscosity.

The power input per unit volume of liquid can be used as a rough measure of mixing effectiveness (Metcalf & Eddy 2003). In this design and construction, the G value of 20 S^{-1} as a slow mixing value was applied to the system by adjusting the mixing power to achieve this velocity gradient.

Here, the prototype single-stage anaerobic digester was operated in semicontinuous mixing mode as an energy-saving system. The mixing time was investigated to ensure intimate contact between microorganisms and food waste and prevent settling of large particles inside the digester.

Due to not only velocity gradient, G value, but also mixing time can have influence on the system performance in the case of semicontinuous mixing mode, we propose a new parameter

Table 4 Comparison of methane content of biogas with different mixing intensity number

Mixing intensity no.	Methane (%)
36,000	58.4±1.6
72,000	61.6±1.8
108,000	55.9±1.8

called velocity gradient mixing time integral in the case of semicontinuous mixing mode. This new parameter shows that the velocity gradient, as well as the mixing time, is characterized by a dimensionless number called mixing intensity number.

$$G \times T_\mathrm{m} = \text{mixing intensity number} \tag{2}$$

Where G is the average velocity gradient and T_m is the mixing time. The mixing intensity number can be used to identify proper mixing level as shown in Fig. 9. It is shown in Table 4 that the optimal mixing intensity number is nearly 72,000 to achieve high methane content of the biogas production by the prototype single-stage anaerobic digester.

Conclusions

The developed prototype single-stage anaerobic digester can convert organic matters from food waste to biogas effectively. It was found that the sludge recirculation rate of 100 % and the mixing time of 60 min/day could enhance biogas production and improve digester stability. Alkalinity return by the sludge recirculation apparently could improve the pH stability of the prototype digester. The obtained biogas production with the optimal condition was found to be 0.71 m^3/kg COD and the methane content was 61.6 %. Moreover, the efficiency for COD removal was 90.1 %, whereas TVS removal could reach 83.9 %. Therefore, the prototype single-stage anaerobic digester can be highly promising to recover energy from food wastes via biogas production for university canteen application.

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