Comparative investigations on pilot-scale anaerobic digestion of food waste at 30°C and 35°C

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Abstract: Parallel pilot-scale anaerobic digestion systems were conducted to evaluate the influence of system temperatures (30°C and 35°C) on digestion performance, greenhouse gas control and economic efficiency. Biogas productions (6.64-12.96 m^3/d) and methane yields (0.46-0.61 m^3/kg VS) of 35°C digestion system were significantly higher than those of 30°C digestion system with the organic loading rate (OLR) of 2.0-4.5 kg VS/m^3·d. Two regression equations of methane yields with increasing OLRs were fitted at 30°C and 35°C to predict the methane production of practical food waste (FW) digestion plants. By analyzing process stability, the optimal operating OLRs of 35°C digestion system (4.0 kg VS/m^3·d) was found to be higher than that of 30°C digestion system (3.0 kg VS/m^3·d), indicating that the 35°C digestion system had better processing capacity. The greenhouse gas emission under corresponding optimal operating OLR of 35°C digestion system was also calculated to be better than that of 30°C digestion system. Even the system temperature of 30°C was found to be more suitable for the digestion where OLR was less than 3.0 kg VS/m^3·d, a higher operational temperature of 35°C was still a better choice for conventional high-solid digestion.

Keywords: food waste, anaerobic digestion, pilot-scale, organic loading rate, greenhouse gas, economic efficiency

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1 Introduction

The concerns about the disposal and management of the growing municipal solid waste (MSW) are currently among the greatest environmental issues in every part of the world, which need large amount of investments for safe treatments. The pressure of MSW management is getting higher in China, particularly in major cities which are very gigantic with high population densities. Large amounts of MSW (17.1× 10^{10} kg) were collected in China in the year of 2012[1], which were predominantly the food waste (FW) such as fruit/vegetable waste (FVW) and kitchen waste (KW). Due to rapid urbanization of China, FW is produced at an ever-increasing rate (higher than 10% per year)[2]. As a result, the reasonable FW treatment methods become progressively important to reduce and reutilize MSW.

Recently, landfill is the dominant technology to treat MSW in most developing countries; specifically, landfill accounted for 72.5% of the total treatment capacity of MSW in China[1]. However, because of the abundant biodegradable compositions and high moisture content, FW landfill caused huge leachate discharge which also wasted of potential raw materials for renewable energy generation in the past years[3]. Moreover, a large

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amount of greenhouse gas was discharged from MSW landfill, which exacerbated global warming. However, anaerobic digestion can be a quite beneficial technology to treat FW with higher energy recovery ability (biogas and nourishing leachate) and lower greenhouse gas emission[4]. Thus, anaerobic digestion is a promising way to treat degradable organic MSW and at the same time generate bioenergy by anaerobic digestion technology in ecofriendly mechanism[5-7].

Additionally, the compositions of FW are very complicated. FW as feedstock have been reported by many researchers in anaerobic digestion process[8-11]. Similar conclusions have been drawn that rapid hydrolysis and over acidification took place easily when these different kinds of FW were mono-digested. As two of the largest compositions of FW, FVW and KW have been successfully co-digested[12]. Besides, two-phase anaerobic digestion was reported to be more suitable for treating the mixture of FVW and KW than single-phase digestion[13]. So, two-phase anaerobic co-digestion of FVW and KW were used in this work.

Technically, temperature is one of the most important factors which have great influences on the performances of anaerobic digestion process. Among different anaerobic digestion conditions, mesophilic (30-35°C) and thermophilic (55-60°C) digestion conditions have been most commonly applied[8]. According to Arrhenius equation, the chemical reaction rates will be accelerated as the reaction temperature increases. Thermophilic digestion has been thus regarded as a potential way to improve the digestion efficiency because of the higher reaction rate[14,15]. However, the initial investment and operation costs of thermophilic digestion are significantly higher than those of mesophilic digestion, which implies that mesophilic digestion is practically more suitable for FW digestion plants, especially in developing countries like China. Therefore, only mesophilic digestion was discussed in this paper. On the other hand, methane yields were more concerned in mesophilic FW digestion studies[7,16,17]. Few researchers specifically compared the optimal operating organic lording rate (OLR), greenhouse gas emission, and economic efficiency between the 30°C and 35°C digestion systems, which could be very important in practical FW digestion plants.

The aims of this study include: anaerobic digestion of two-phase pilot-scale anaerobic digestion systems with the feedstock of KW and FVW were operated at 30°C and 35°C, respectively. Firstly, the digestion performances and process stability were comprehensively compared between these two systems in terms of biogas production, energy recovery and optimal operating OLR. Then, greenhouse gas emission at respective optimal operating OLR was analyzed due to the gigantic carbon dioxide production of China. Finally, economic efficiency at each OLR of 30°C and 35°C digestion systems was compared, which could be helpful for choosing suitable mesophilic digestion temperature according to practical OLR.

2 Methods

2.1 Raw materials and inoculation

Both FVW and KW were collected from the student canteen of Beijing University of Chemistry Technology, Beijing. The inorganic compositions, such as plastic and metal were initially separated before shredding. FVW and KW were crushed to less than 4 mm in size by a FW shredder (Wenzhou Light Industrial Machinery, BTP-01) and then were mixed together with the VS ratio of 5:21[18]. The pretreated substrates were stored in a −20°C before digestion. The main characteristics of FVW, KW and their mixture are shown in Table 1. The VS/TS ratio of FVW and KW are both more than 80%, implying the mixture of FVW and KW is suitable for anaerobic digestion. Additionally, the specific organic compositions of these two substrates are obviously different. The high lipids content of KW is due to the Chinese traditional dietary habit and the high crude fiber content of FVW is due to the cellulose in fruit and vegetable.

The inoculum was collected from the anaerobic stream of the Xiaohongmen Wastewater Treatment Plant, Beijing (operation temperature, 30-35°C). The TS, VS, TS/VS, pH and C/N of the inoculum were 5.43%, 2.29%, 42.17%, 7.74 and 6.14, respectively.

Table 1 Characteristics of feedstock

	Mixture (5:21)	FVW	KW
Total solids (TS) (fresh matter)/%	16.70	7.94	22.17
Volatile solids (VS) (fresh matter)/%	13.59	6.74	17.87
VS/TS/%	81.38	84.89	80.60
pH value	5.14	5.28	5.08
Crude fat (dry matter)/%	28.33	3.78	33.82
Crude fiber (dry matter)/%	10.13	24.50	6.93
Crude protein (dry matter)/%	16.32	13.80	16.88
Soluble carbohydrate (dry matter)/%	19.81	11.80	21.60
C/N[a]	14.18	17.21	13.98

Note: [a] C/N means the ratio of total carbon to total nitrogen.

2.2 Digesters and operation conditions

Two two-phase completely stirred tank reactor (CSTR) systems were established in this work. Both the CSTR systems contained one acidogenic reactor and one methanogenic reactor. The temperatures of acidogenic reactor and methanogenic reactor were always identical. The working volume of acidogenic reactor and methanogenic reactor were 2.0 m^3 and 4.0 m^3, respectively. One of the CSTR systems was controlled at (30±1)°C, the other was controlled at (35±1)°C. Both of these two pilot-scale systems contained the units of feedstock adjustment, substrates pumping, digestion reactor, effluent reservoir and biogas storage. All reactors were fed once a day with screw pumps and were completely mixed by impellers (120 r/min) with an agitation time of 5 min every two hours. The hydraulic retention time (HRT) of acidogenic phase and methanogenic phase was 10 d and 20 d, respectively.

2.3 System start-up

Initially, 1.6 and 2.0 m^3 inoculum inoculum were pumped into acidogenic and methanogenic reactors, respectively. The start-up OLRs of these two methanogenic reactors in both 30°C and 35°C FW digestion systems were 1.0 kg VS/m^3·d (the start-up OLR of acidogenic reactors were 2.0 kg VS/m^3·d).

2.4 Analytical methods

The volumes of biogas production were measured by wet-test meters (Changchun Automobile Filter, LML-1) and were converted to standard temperature (0°C) and pressure (1101.3 kPa). The significant differences between 30°C and 35°C systems biogas productions were determined by *t*-test using Excel software 2010. The analyses of gas contents and volatile fatty acid (VFA) were taken place based on the literature [19]. The biogas contents were analyzed by a gas chromatograph (GC) (Shimadzu, SP2100) equipped with a stainless steel column and a thermal conductivity detector. The VFAs were detected by another GC (Shimadzu, GC-2014) equipped with a capillary column and a flame-ionization detector.

The TS, VS, alkalinity, NH_4^+-N and pH in the effluent were analyzed according to standard methods of American Public Health Association[20].

2.5 Greenhouse gas reduction calculation

The greenhouse gas emission was calculated according to Guideline to PAS 2050[21] and the methods adopted from Liu et al.[6] Three scenarios of carbon footprint were assessed: baseline scenario (scenario 1), anaerobic digestion with power generation (scenario 2), and anaerobic digestion with biogas recovery (scenario 3). Since landfill is still the most widely used technology to treat MSW in the developing countries, MSW landfill was thereby chosen as the baseline scenario. Landfill gas was assumed to generate power with the gas collection rate of 50%. According to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories[22], the FW fraction and degradable organic carbon (DOC) fraction in FW were 26% and 15%, respectively in MSW of East Asia. The decomposable degradable organic carbon (DDOC) of FW was thus estimated to be 0.039. The fraction of the degradable organic carbon (DOC_f) which could be decomposed under anaerobic condition was 0.5 (based on fresh matter).

3 Results and discussion

OLR has great influence on digestion performances, process stability, greenhouse gas emission and economic efficiency of anaerobic digestion process[23]. Therefore, the 30°C and 35°C digestion systems were carried out with increasing OLRs after stabilization of the start-up period. The specific OLRs of methanogenic reactors were 2.0, 3.0, 4.0 and 4.5 kg VS/m^3·d (acidogenic phase was not discussed because of its low methane production). The operating parameters such as agitation, HRT, and influent OLRs of these two systems were intentionally controlled to be the same. Since the stable operation performances were more concerned in practical application.

3.1 Biogas production

In the 30°C digestion process, the biogas production kept increasing for 60 d with the OLR of 2 kg VS/m^3·d and 3 kg VS/m^3·d. The average biogas productions of these OLRs were 6.08 and 8.68 m^3/d. The increase of biogas production was due to more fed degradable substrates to the digestion system. When the OLR reached 4.0 kg VS/m^3·d, the biogas production continued to increase for 12 d before suffered drastic decrease (see Figure 1), which was because that the input substrates exceeded the digestion capacity of the system and then inhibition happened. The average biogas productions of 4.0 kg VS/m^3·d and 4.5 kg VS/m^3·d were 7.92 m^3/d and 5.80 m^3/d. Correspondingly, the methane contents showed slight decrease (62.5%-58.6%) with the increase of OLR (see Table 2). The methane yields varied in the range of 0.21-0.49 m^3/kg VS, which were higher than those of the 30°C waster sorted organic fraction of MSW digestion (0.27-0.34 m^3/kg VS)[17].

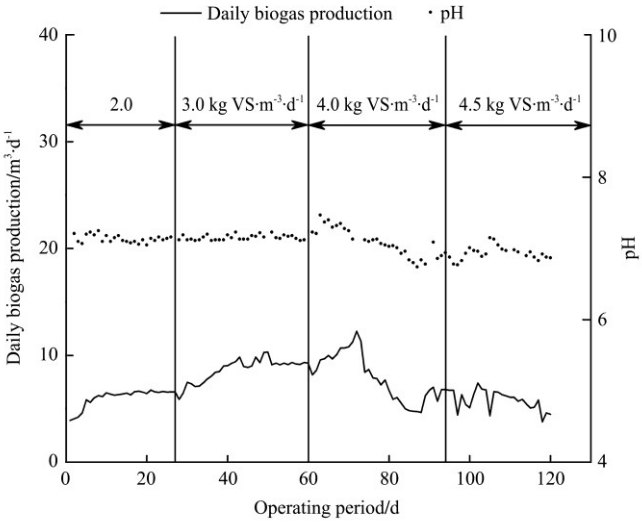

Figure 1 Daily biogas production and pH of 30°C digestion system with the OLR

Table 2 Comparison of biogas production between the 30°C and 35°C digestion system

	30°C digestion system				35°C digestion system			
OLR/kg(VS)·m^{-3}·d^{-1}	2.0	3.0	4.0	4.5	2.0	3.0	4.0	4.5
Duration/d	27	33	33	27	22	25	43	32
VS of influent/kg·m^{-3}	1.99	2.98	3.97	4.47	1.99	2.98	3.97	4.47
Biogas production/m^3·d^{-1}	6.08±0.84	8.68±1.08	7.92±2.26	5.80±0.92	6.64±0.84	10.64±1.84	12.96±1.80	12.68±1.72
Methane content/%	62.5	62.1	59.0	58.6	66.2	66.8	65.7	64.8
Methane yield/m^3·kg(VS)$^{-1}$	0.49±0.04	0.46±0.04	0.29±0.08	0.21±0.03	0.57±0.03	0.61±0.09	0.53±0.07	0.46±0.06

Note: The ‘‘±’’ in the table represent standard deviations.

In the case of 35°C digestion process, the biogas productions were kept increasing for 90 d with the OLR of 2.0-4.0 kg VS/m^3·d, although it fluctuated severely at the middle period of 4.0 kg VS/m^3·d (see Figure 2). The fluctuation of biogas production might be attributed to the different characteristics of feedstock fed to pilot-scale system daily. The average biogas productions of these OLRs were 6.64-12.96 m^3/d. As the OLR reached 4.5 kg VS/m^3·d, the biogas production decreased for a few days initially and then began to increase and fluctuate with an average of 12.68 m^3/d. The methane yields were in the range of 0.46-0.61 m^3/kg VS at the applied OLRs. According to literatures, methane yields of 0.33-0.55 m^3/kg VS were reported[15,24,25], which demonstrated that this 35°C digest system operated well.

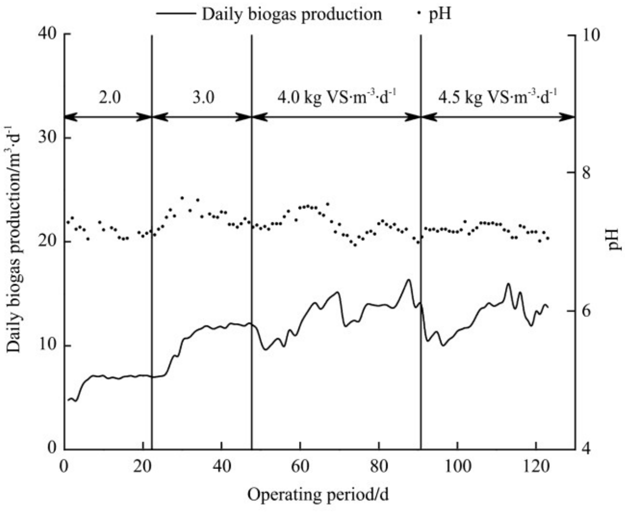

Figure 2 Daily biogas production and pH of 35°C digestion system with the OLR

According to Table 2, the average biogas productions of 35°C digestion system were 9.2%-118.6% higher than those of 30°C digestion system, which could be explained by the effect of temperature on reaction, i.e. Arrhenius equation. The differences of daily biogas production between these two systems were significant ($p<0.01$) by t-test analyses. A statistical coefficient of variation (C_{var}) was also calculated to compare the stability of biogas production between the 30°C and 35°C digestion systems[13]. The C_{var} of 30°C digestion system were 4.3%, 6.1%, 29.30% and 16.8% with the OLR of 2.0-4.5 kg VS/m^3·d, which were all higher than those of 35°C digestion system, indicating the 35°C digestion system resulted better biogas production stability than 30°C digestion system. The results above implied that the 35°C digestion system had better adaptability to the different characteristics of daily fed FW.

The methane yields varied with certain trends as the OLR increased in both 30°C and 35°C digestion systems (see Table 2). As shown in Figure 3, two functions were fitted with 98% of correlation coefficients, suggesting clear differences between these two systems. The methane yields of 30°C digestion system kept decreasing as the OLR increased, which is caused by the relatively low methanogen activity at this temperature. As for the 35°C digestion system, the methane yields increased a little bit when the OLR reached 3.0 kg VS/m^3·d and then began to decrease, indicating methanogen was more active at 35°C. In practical mesophilic FW digestion plants, these two equations (y_1 and y_2 are regression equations for 35°C and 30°C, respectively) could be helpful for predicting the methane output under different OLRs. Besides, energy recoveries in terms of methane yields from 35°C digestion system were 16.3%-119.0% higher than those of 30°C digestion system with the increasing OLRs. As a result, it could be deduced that energy recovery of 35°C digestion system was better than 30°C digestion system, especially under high OLR conditions.

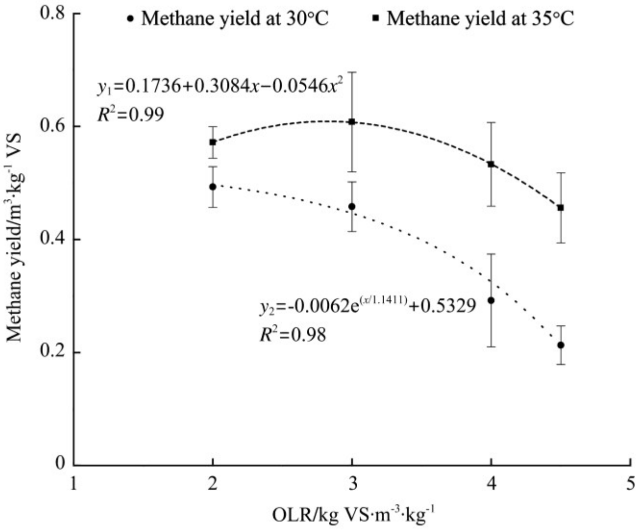

Figure 3 Methane yield with the OLR

3.2 Process stability and optimal operating OLR

VS, VFA, NH_4^+-N, alkalinity and pH value are the most important parameters of process stability in anaerobic digestion system and the pH value is mainly determined by VFA and amine/ammonia balance[7]. Therefore, the VFA, NH_4^+-N, alkalinity and pH value of the effluent were analyzed to compare the process stability between the 30°C and 35°C digestion systems. Optimal operating OLR means the OLR with the highest biogas production at stable period of anaerobic digestion system.

The VS removal rates of these two systems were similar and were both negatively correlated with the increasing OLRs (see Table 3). NH_4^+-N concentrations of the 35°C digestion system were 17.36%-32.13% higher than those of 30°C digestion system. Since protein was the main source of NH_4^+-N in FW digestion process[26], it could be deduced that the protein in feedstock was more easily digested at 35°C.

Table 3 Comparison of effluent characteristics between the 30°C and 35°C digestion system

	OLR for 30°C digestion system/kg VS·m^{-3}·d^{-1}				OLR for 35°C digestion system/kg VS·m^{-3}·d^{-1}			
OLR/kg VS·m^{-3}·d^{-1}	2.0	3.0	4.0	4.5	2.0	3.0	4.0	4.5
VS of influent/kg·m^{-3}	1.99	2.98	3.97	4.47	1.99	2.98	3.97	4.47
VS removal rate/%	87.0	83.0	76.0	67.0	89.0	89.0	74.0	65.0
VFA/mg·L^{-1}	158.7	289.4	2056.1	2476.2	280.4	320.8	1280.7	2582.0
NH_4^+-N/mg·L^{-1}	693.2	742.5	854.4	952.6	830.7	868.0	917.3	1258.7
VFA/Alkalinity ratio	0.03	0.06	0.41	0.45	0.07	0.07	0.25	0.40

The pH value of 30°C digestion system was higher than 7.00 as the OLR was ≤3.0 kg VS/m^3·d and it decreased to 6.74-7.00 as the OLR was further increased. The production of biogas was dependent on the trend of variations in pH value (see Figure 1), which indicated that the system stability of 30°C digestion process was affected when the OLR was higher than 3.0 kg VS/m^3·d. Meanwhile, the VFA concentration was in the range of 158.7-2476.2 mg/L with the OLRs of 2.0-4.5 kg VS/m^3·d, suggesting that the increase of OLR could lead to high risk of acidification in the methanogenic phase. Generally, when the VFA/alkalinity ratio is lower than 0.40, the digester is deemed to be stable[27]. As shown in Table 3, the VFA/Alkalinity ratios were ≥0.40 as the OLRs were >3.0 kg VS/m^3·d (see Table 3), proved that the 30°C digestion system was unstable at these OLRs. Therefore, the optimal operating OLR of the 30°C digestion system was 3.0 kg VS/m^3·d from overall consideration of biogas production (see section 3.1) and process stability.

The pH value of 35°C digestion system was remained higher than 7.00 as the OLR was <4.0 kg VS/m^3·d, however, it was dropped below 7.00 occasionally after the OLR reached 4.0 kg VS/m^3·d (see Figure 2). The VFA/Alkalinity ratio was <0.40 till the OLRs reached 4.5 kg VS/m^3·d, which implied the 35°C digestion system was stable when the OLR was ≤4.0 kg VS/m^3·d. Thus, from biogas production and process stability, the optimal operating OLR of 35°C digestion system was 4.0 kg VS/m^3·d.

Generally, the optimal operating OLR of 35°C digestion system was found to be higher than that of 30°C digestion system, because the OLR enhancement potential and processing capacity of 35°C digestion were higher than 30°C digestion system.

3.3 Greenhouse gas emission

China is the second largest carbon dioxide production country in the world, facing great pressure to reduce greenhouse gas emissions. To alleviate this problem, every sectors working on greenhouse gas emission area should rethink the procedures and ways to reduce it. In this experiment the greenhouse gas emissions under corresponding optimal OLRs of the 30°C and 35°C digestion systems were also calculated. On the other hand, methane production of decomposable degradable organic carbon (DDOC$_m$) during FW landfill (Scenario 1) was calculated to be 20.02 m^3/t by the following equation.

$$\mathrm{DDOC_m} = \mathrm{DDOC} \times \mathrm{DOC_f} \times C_\mathrm{m} \times \frac{22.4}{12} = \frac{0.039 \times 0.5 \times 0.55 \times 22.4}{12 \times 10^{-2}} = 20.02\ \mathrm{m^3/t} \tag{1}$$

where, C_m is the methane content of landfill gas, using the default value of 55%. The DDOC$_m$ was assumed to be constant.

The carbon footprint of scenario 1 (G$_1$) included direct emission of landfill gas to atmosphere, greenhouse gas emission from power consumption of landfill gas utilization, and greenhouse gas offsetting by power generation of landfill gas. G$_1$ was calculated to be 176.3 kg CO$_{2e}$/t following the hypotheses and methods of Liu et al.[6] (see Table 4). The scenario 2 and scenario 3 of the 30°C and 35°C digestion systems were also assessed. The analysis process under the optimal operating OLR of 30°C digestion system was listed as an example.

Table 4 Comparison of greenhouse gas emission between 30°C and 35°C system

	Landfill	30°C digestion system		35°C digestion system	
		Power generation	Biogas recovery	Power generation	Biogas recovery
Emission to atmosphere	166.3	N.D.	N.D.	N.D.	N.D.
Emission of power consumption	35.7	194.6	13.4	218.2	14.4
Greenhouse gas offsetting	25.7	157.5	524.9	186.8	662.5
Carbon footprint	176.3	37.1	-511.5	31.4	-608.1
Greenhouse gas reduction	N.D.	139.2	677.8	144.9	774.4

The biogas produced by anaerobic digestion was used by power generation and biogas recovery (purified biogas). When the OLR was 3.0 kg VS/m^3·d at 30°C digestion system, the methane production was 61.53 m^3/t, without considering the content of the methane produced from digestate because the methane level was statistically low. When the carbon dioxide in biogas was totally removed, the scenario 2 and 3 were calculated below.

Anaerobic digestion with power generation (Scenario 2):

Step 1: Greenhouse gas emission from power consumption of utilizing biogas

$$\mathrm{G}_{21}=\frac{Q}{C_{\mathrm{m}}\times 22.4}\times 44=\frac{61.53}{0.621\times 22.4}\times 44=194.6\ \mathrm{kg\ CO_{2e}/t} \quad (2)$$

where, Q is the volume of methane production; C_{m} is the methane content of 3.0 kg VS/m^3·d, 0.621 (Table 2).

Step 2: Greenhouse gas offsetting by power generation of biogas

$$\mathrm{G}_{22}=Q\times \mathrm{LCP}_{\mathrm{CH_4}}\times E\times E_{\mathrm{f}}=61.53\times\frac{35.8\times 10^6}{3600\times 1000}\times 0.3\times 0.8578=157.5\ \mathrm{kg\ CO_{2e}/t} \quad (3)$$

where, $\mathrm{LCP_{CH_4}}$ is the lower calorific power of methane, 35.8 MJ/m^3 [6]; E is the power generation efficiency, 0.3; E_{f} is the greenhouse gas emission factor of power generation plants with capacity of over 1000 MW, 0.8578 kg $\mathrm{CO_{2e}}$/kW·h.

So, the carbon footprint of Scenario 2 is:

$$\mathrm{G}_2=\mathrm{G}_{21}-\mathrm{G}_{22}=194.6-157.5=37.1\ \mathrm{kg\ CO_{2e}/t} \quad (4)$$

Anaerobic digestion with biogas recovery (Scenario 3):

Step 1: Greenhouse gas emission from power consumption of biogas purification

The capacity of a FW digestion facility was set at 1 000 t/d with the operating OLR of 3.0 kg VS/m^3·d. The methane production is thereby estimated to be over 60 000 m^3/d. The rated power of the purification system is around 650 kW according to a few practical projects of China. Thus, the greenhouse gas emission from the power consumption of biogas purification could be calculated.

$$\mathrm{G}_{31}=\frac{650\times 24\times 0.8578}{1000}=13.4\ \mathrm{kg\ CO_{2e}/t} \quad (5)$$

Step 2: Greenhouse gas offsetting by biogas recovery

$$\mathrm{G}_{32}=Q\times \mathrm{LCP}_{\mathrm{CH_4}}\times E_{\mathrm{f}}=61.53\times\frac{35.8\times 10^6}{3600\times 1000}\times 0.8578=524.9\ \mathrm{kg\ CO_{2e}/t} \quad (6)$$

Therefore, the carbon footprint of Scenario 3 is:

$$\mathrm{G}_3=\mathrm{G}_{31}-\mathrm{G}_{32}=13.4-524.9=511.5\ \mathrm{kg\ CO_{2e}/t} \quad (7)$$

As shown in Table 4, both the 30°C and 35°C digestion systems of FW have lower greenhouse gas emissions compared to landfill, demonstrating the superiority of FW digestion. Additionally, the greenhouse gas reductions in terms of power generation and biogas recovery of 35°C digestion system were 144.9 and 774.4 kg $\mathrm{CO_{2e}}$/t, respectively, which were 4.2% and 13.9% higher than those of 30°C digestion system. The greenhouse gas emission results are similar with previous study (641-998 kg $\mathrm{CO_{2e}}$/t)[28]. Therefore, the 35°C digestion system was more environmentally-friendly in practical FW digestion plants.

3.4 Economic efficiency

The operation costs of these two systems were analyzed without considering the establishing investment. The input costs of these two digestion systems included consumed electricity, employed labor, and water consumption. Since these two systems were simultaneously operated at the same spot with identical influent OLR and HRT, the costs of employed labor and water consumption were assumed to be totally the same. Therefore, the extra cost between these two digestion systems was only temperature enhancement which came only from the differences of consumed electricity (heating power). On the other hand, the output benefits included the biogas and effluent production. The extra benefits from effluent production differences between these two systems were also ignored because of the identical output effluent volumes and similar effective compositions (nitrogen and phosphorus). So, the extra biogas production was thought to be the only extra benefit. The extra cost was calculated as:

$$\text{Extra cost}=C_{\text{electricity}}\times \text{Electricity price} \quad (8)$$

where, $C_{\text{electricity}}$ is the extra electricity consumption by temperature enhancement, kW·h; Electricity price is the price of consumed electricity, 0.859 ¥/kW·h.

According to the literature, there are two common scenarios of biogas consumption, i.e. selling it as thermal energy or as green electricity[29]. The extra benefit was thereby calculated as:

$$\text{Extra benefit}=\mathrm{LCP_{CH_4}}\times(C_{\mathrm{m35}}\times V_{35}-C_{\mathrm{m30}}\times V_{30})\times f\times \text{Biogas price} \quad (9)$$

where, C_{m} is the methane content, %; V is the average biogas production, m^3; f is the energy conversion yield factor, 85% for thermal energy and 42% for electricity; Biogas price is the selling price of biogas, 0.430 RMB

Yuan/kW·h as thermal energy[30] and 0.859 RMB Yuan/kW·h as electricity.

The extra profit between the 30°C and 35°C digestion system was calculated as:

$$\text{Extra profit} = \text{Extra benefit} - \text{Extra cost} \qquad (10)$$

As the OLR increased from 2.0 kg VS/(m^3·d) to 4.5 kg VS/m^3·d, the extra profit by increasing temperature was remarkably improved under both scenarios (−36.736-105.195 RMB Yuan/t and −36.736-106.842 RMB Yuan/t) (Table 5). The extra profits of biogas as electricity were lower than those of biogas as thermal energy, which could be explained by the relatively low energy conversion efficiency of biogas to electricity[29]. Besides, the extra profits were negative as the OLR was 2.0 kg VS/m^3·d with both scenarios, implying the 30°C digestion system was more profitable than 35°C digestion system at this condition. On the contrary, the 35°C digestion system achieved higher profits than the 30°C digestion system as the OLR was further increased. In conclusion, the 30°C digestion system was more profitable to digest FW as the OLR was low (<3.0 kg VS/m^3·d) and the 35°C digestion system was more profitable to treat FW as the OLR reached high level (≥3.0 kg VS/m^3·d). These indicate that the influent OLR was the key factor in choosing digestion temperature under mesophilic condition in practical FW digestion plants.

Table 5 Comparison of economic efficiency between the 30°C and 35°C digestion system

OLR /kg VS·m^{-3}·d^{-1}	Extra cost /¥·t^{-1}	Biogas as electricity		Biogas as thermal energy	
		Extra benefit/ Yuan·t^{-1}	Extra profit/ Yuan·t^{-1}	Extra benefit/ Yuan·t^{-1}	Extra profit / Yuan·t^{-1}
2	73.472	36.736	−36.736	36.736	−36.736
3	49.053	69.462	20.409	70.321	21.268
4	29.432	118.3	88.868	119.589	90.157
4.5	26.138	131.333	105.195	132.98	106.842

4 Conclusions

Biogas productions and energy recoveries of the 35°C digestion system were significantly better than those of 30°C digestion system with the applied OLRs. The methane yield of 30°C digestion system kept decreasing as OLR increased. As for 35°C digestion system, the methane yield increased initially and then began to decrease with increasing OLR. Optimal operating OLRs of 3.0 and 4.0 kg VS/m^3·d were found at 30°C and 35°C digestion systems, respectively, suggesting that the 35°C digestion could achieve higher processing capacity than the 30°C digestion system. Greenhouse gas reduction under corresponding optimal operating OLR of 35°C was also higher than that of 30°C. However, the 30°C digestion system was found to be more profitable when the OLR was <3.0 kg VS/m^3·d, which suggested the 35°C digestion system was suitable to practical plants only as the OLR reached high level (≥3.0 kg VS/m^3·d) in spite of all other superiorities.

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