Two-phase anaerobic co-digestion of food waste and sewage sludge

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ABSTRACT

The feasibility and performance of food waste and sewage sludge co-digestion were investigated to gain insight into their resource utilization. In this study, two-phase anaerobic digestion (TPAD) was operated under a total solids mixing ratio of 1:1 and different sludge retention times (SRTs). Results show that an acidogenic reactor with a 5-day SRT obtained the highest acidification efficiency, and its acetic acid content was dominant. The organic removal rate of a methanogenic reactor (MR) with a 20-day SRT and its corresponding TPAD system with a 25-day SRT were both the highest among the MRs and TPAD systems. Volatile solids and total chemical oxygen demand average removal efficiencies of the TPAD system with a 25-day SRT reached 64.7 and 60.8%, respectively. The MR with a 30-day SRT obtained the minimum ratio of volatile fatty acid to alkalinity (0.12). The methane content generated from the different MRs fluctuated at around 70%. All of the above results can provide reference for future research.

Key words | co-digestion, food waste, sewage sludge, two-phase anaerobic digestion

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INTRODUCTION

Food waste is a type of resource mainly generated from restaurants, family kitchens, canteens, and food manufacturers. The amount of food waste in urban cities around the world has rapidly increased in recent years. The Korean government reported that in 2007 a total of 14,452 tons of food waste was generated each day (Zhang & Jahng 2012). In the United Kingdom, 7.2 million tons of food and drink waste were generated from homes in 2010 (Quested *et al.* 2013). In the United States, more than 36 million tons of food waste were generated in 2011 (Agyeman & Tao 2014). In China, the generated food waste reached 40 million tons in 2009, and this value is continuously increasing at an annual rate of more than 10% because of population growth as well as the steady and rapid development of the catering industry (Jiang *et al.* 2014).

People from different areas develop different dietary habits, and the properties of food wastes highly depend on their sources. Several food waste characteristics have been reported in the literature, including moisture content ranging from 74 to 90%, volatile solids to total solids ratio (VS/TS) ranging from 80 to 97%, and carbon to nitrogen ratio (C/N) ranging from 14.7 to 36.4 (Zhang *et al.* 2007). Food waste disposal has become a challenging task because of these characteristics. Food waste typically has a water content of more than 80% and therefore requires high amounts of energy to incinerate it (Nagao *et al.* 2012). Moreover, the excessively high presence of organics makes food waste the main source of decay, odor, and leachates (Cho *et al.* 2013), which could cause environmental pollution. In addition to these properties, the high salt and lipid content of food waste in China is causing several problems. Thus, food waste treatment has attracted the attention of many scientists.

Although anaerobic digestion has been widely applied for treating organic wastes that are easily biodegraded (Zhang *et al.* 2007), its application is limited because of the special characteristics of food waste. For instance, the excessively high presence of organics in food waste allows for the easy accumulation of volatile fatty acid (VFA) during the food waste anaerobic process (El-Mashad *et al.* 2008). In addition, salts and oil are usually abundant in Chinese food. Salts in the food waste can inhibit the activity of anaerobic microbes by affecting the osmotic pressure of the cell wall, and oil could lower the removal rate of organics by forming an oil layer surrounding the sludge particles. This layer could cut off the contact between microbes and feedstock.

Anaerobic co-digestion of food and other solid wastes can effectively decrease the effects caused by the

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abovementioned limiting factors. The anaerobic co-digestion of food waste with piggery wastewater (Zhang *et al.* 2011), fruit and vegetable waste (Shen *et al.* 2013), green waste (Chen *et al.* 2014), cattle manure (Quiroga *et al.* 2014), and different types of sludge have been reported. Although these studies obtained different results, anaerobic co-digestion performance was improved to some extent, proving that co-digestion can improve the anaerobic effects by improving the physical and chemical properties of anaerobic substrates.

Food waste and sludge co-digestion is the most popular among various anaerobic co-digestion studies. Anaerobic digestion is used for sewage sludge; however, this process exhibits inefficiency in gas production and organics removal (Iacovidou *et al.* 2012; Murto *et al.* 2004). Low organic content (VS/TS) and low C/N ratio in a combined sewer system in China are the two primary reasons for this inefficient performance. Adding food waste to sewage sludge for co-digestion not only increases the organic content and C/N ratio of the anaerobic substrate but also improves biogas production; at the same time, salinity and oil concentration in the food waste could also be diluted (Kim et al. 2011). These changes in anaerobic substrates directly improve anaerobic digestion performance.

Different anaerobic processes have been applied in the anaerobic co-digestion of food waste and sludge. Gou *et al.* (2014) used continuously stirred single-stage tank reactors. Kim *et al.* (2011) studied a temperature-phased anaerobic sequencing batch reactor system. Liu *et al.* (2013) performed two-stage mesophilic fermentation. Sosnowski *et al.* (2008) conducted batch experiments in a 40 L bioreactor. However, only a limited number of reports exist on the application of a two-phase anaerobic digestion (TPAD) process on the anaerobic co-digestion of food waste and sewage sludge. This process, which involves the physical separation of acidogenic and methanogenic biomass in two reactors, improves the overall performance of the anaerobic digestion process (Rubio-Loza & Noyola 2010). This paper investigates the feasibility and performance of the semi-continuous two-phase anaerobic co-digestion of food waste and sewage sludge with the use of continuously stirred tank reactors. The results can provide reference for future research.

MATERIALS AND METHODS

Feedstock and inoculum

A food waste sample was collected from the canteen of a wastewater treatment plant in Shanghai, China. The sample was first washed five times with tap water to decrease oil and salt content. Then, bones, toothpicks, paper, and other debris were sorted manually. After these pretreatments, the remaining food waste consisted mainly of rice, eggs, and vegetables. The sample was then pulverized to a particle size of less than 5 mm with a micromill, and its moisture content was adjusted to approximately 90% by adding tap water. Food waste was prepared two to three times per week.

Sewage sludge, which was a mixture of gravity-thickened primary sludge and gravity-thickened waste activated sludge with a volume ratio of 1–1.5:1, and seed sludge were both obtained from another wastewater treatment plant in Shanghai, China. All of the sludge types were prepared once a week. Food waste, primary sludge, waste activated sludge, and seed sludge were all stored in a refrigerator at 4 °C.

In the experiment, the feedstock was a mixture of food waste and sewage sludge with a TS ratio of 1:1, and its moisture content was maintained at approximately 95%. Feedstock and digested substrate discharge were added at a fixed time once a day. Table 1 summarizes the main physical and chemical properties of all substrate types.

Experimental setup

Figure 1 shows the schematic of an anaerobic digester. One impeller was installed and agitated at a constant speed of 80 rpm to keep the reactor homogeneous. Its temperature was maintained in the range of 35 ± 1 °C by hot water circulation in double jackets, and the pump provided power for hot water circulation. Daily sampling was conducted from the middle outlet on the right of the reactor. The gas volume generated from the anaerobic digesters was measured by a wet gas flow meter, which was followed by a biogas pocket. The biogas was collected regularly by the pocket for its composition detection.

Operating procedure

In this experiment, the acidogenic reactor (AR) and the methanogenic reactor (MR) are two different reactors. Table 2 shows their natural parameters and operating conditions.

The test combined two stages (i.e. acidogenic and methanogenic stages) in sequence. At the first stage, AR1, AR2, and AR3 with different sludge retention times (SRTs; Table 2) were run at the same time. The best SRT was selected by comparing the acid-producing performance at the end of the process. At the second stage, AR was run with the best SRT chosen from the first stage, and the MRs were fed with

Table 1 | Physical and chemical properties of all substrate types

Parameter	Unit	Food waste	Primary sludge	Waste activated sludge	Seed sludge	Food waste (50% TS) + sewage sludge (50% TS)
pH	–	4.5–5.4	6.4–6.9	6.1–6.6	6.9–7.3	5.5–6.3
Moisture content	%	86.7–92.3	93.5–95.2	97.4–98.8	94.6–96.2	94.5–95.5
Alkalinity	mg/L as $CaCO_3$	118.8–149.7	898.4–1,011.9	220.7–326.6	2,356.0–2,497.5	307.5–434.6
VFA	mg/L	1,574.9–1,918.7	60.5–104.1	13.3–26.7	24.5–39.7	1,337.0–1,556.0
TS	g/L	80.2–135.3	46.5–57.6	14.3–26.6	39.6–42.5	48.0–55.1
VS	g/L	74.0–125.5	19.0–23.2	6.9–14.1	16.7–18.6	32.0–39.3
TCOD[a]	g/L	133.1–188.0	29.6–41.6	20.5–27.7	23.5–26.1	44.0–54.2
SCOD[b]	g/L	35.5–48.2	0.2–0.7	0.28–0.67	0.65–0.73	8.6–12.7

[a]TCOD = total chemical oxygen demand.
[b]SCOD = soluble chemical oxygen demand.

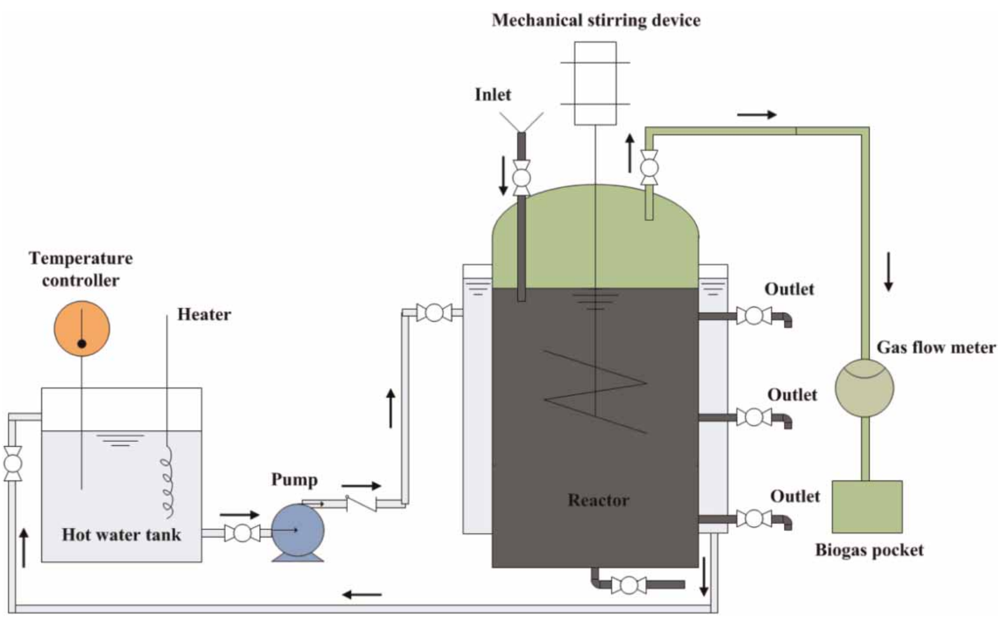

Figure 1 | Schematic of a semi-continuous anaerobic digester.

the effluent of AR. MR1, MR2, MR3, and MR4 with different SRTs (Table 2) were run, and the effects of different SRTs on the anaerobic process were analyzed. At the beginning of the second stage of the test, the MRs were inoculated with seed sludge for starting-up, and the inoculating ratio was 80%.

Analytical method

During the experiment, the parameters were measured as follows: pH was measured with a pH meter (YSI professional plus); alkalinity, TS, VS, total chemical oxygen demand (TCOD), and soluble chemical oxygen demand (SCOD) were measured in accordance with standard methods (CJ/T221-2005); biogas volume was measured with a wet gas flow meter (LML-2); biogas components, VFA concentration, and VFA components were measured with a gas chromatograph (GEM Plus 2000). pH and biogas volume were measured once every 2 days, whereas alkalinity, TS, VS, TCOD, SCOD, VFA concentration, and VFA components were measured three times a week.

Table 2 | Parameters and operating conditions of different reactors

Reactor	Total volume (L)	Working volume (L)	SRT (days)	Temperature (°C)	Steering speed (rpm)
AR1	10	7	1	35 ± 1	80
AR2	10	7	3	35 ± 1	80
AR3	10	7	5	35 ± 1	80
MR1	40	30	5	35 ± 1	80
MR2	40	30	10	35 ± 1	80
MR3	40	30	20	35 ± 1	80
MR4	40	30	30	35 ± 1	80

When SCOD and alkalinity were to be analysed, the samples were first centrifuged at 4,500 rpm for 15 min. Then, the lipid supernatant was filtered with 0.45 μm filter papers. Finally, the supernatant samples after filtering were obtained for analysis.

RESULTS AND DISCUSSION

Acid-producing phase analysis

VFA concentration is considered one of the most important parameters in anaerobic digestion (Ahring *et al.* 1995), especially when it comes to the acid-producing phase of the TPAD process. In this study, the acidification efficiency (AE) was calculated based on Equation (1) as follows:

$$AE = \frac{C_o}{C_i} \tag{1}$$

where C_o is the VFA concentration of the discharged substrate from AR, and C_i is the VFA concentration of the feeding substrate to AR.

The acidification efficiencies of three ARs are shown in Table 3. AR3 with a 5-day SRT achieved the highest AE, indicating that AE increased gradually as the SRT increased in this test. This condition can be attributed to vegetables being one of the dominant components of the food waste in this test, which made the substrate relatively difficult to hydrolyze under conditions of short SRT. The following acidogenetic reactions were also inhibited, so the highest AE was obtained by AR3 with a 5-day SRT.

Table 3 shows the VFA components of three ARs in the first stage of this test. Acetic and propionic acids were clearly the two dominant VFA components. Propionic acid was dominant in AR1 with a 1-day SRT, but the acetic acid content became dominant in AR2 with a 3-day SRT and AR3 with a 5-day SRT. The latter reactor obtained higher acid content. Acetic acid can be easily used by methanogens for methane production, whereas propionic acid is not. Thus, AR3 with a 5-day SRT had the best performance in this test. Generally, substrate characteristics are important in producing different VFA types (Lata *et al.* 2002). Considering that the substrate is a mixture of food waste and sewage sludge in this test, its composition is very complex. High propionic acid concentration in the discharged substrate might relate to the complex compositions of the feeding substrate.

Methane-producing phase analysis

Stability analysis in terms of pH, VFA, and alkalinity

Methanogens grow well when the pH ranges from 6.5 to 8.0, although the optimum pH range is between 6.8 and 7.2 (Zhang *et al.* 2013). As shown in Figure 2, the pH value of the four MRs remained between 7.0 and 7.3 during almost the whole process, indicating that food waste addition did not cause too much adverse effects on the anaerobic digestion process. The pH value was slightly higher than the optimum range in this test, which could be attributed to the best pH for the survival of methanogens changing according to their species.

Table 3 | Acid-producing phase performance of different acidogenic reactors

Reactor	AE 1,472.5 ± 96.4[a]	VFA components (%)			
		Acetic acid	Propionic acid	Butyric acid	Pentanoic acid
AR1	2.5 ± 1.1	32.6 ± 1.5	34.3 ± 1.8	20.3 ± 1.2	12.8 ± 2.9
AR2	3.3 ± 1.6	28.7 ± 2.5	26.5 ± 4.2	24.2 ± 0.6	20.6 ± 3.0
AR3	4.4 ± 1.2	32.0 ± 1.3	29.2 ± 1.2	21.7 ± 2.0	17.1 ± 3.8

[a]VFA concentration of substrates feeding to AR, mg/L.

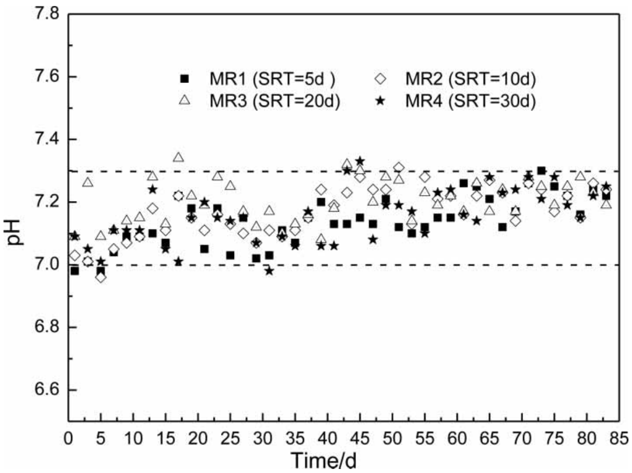

Figure 2 | pH variation of different MRs.

In this test, methanogenetic reactions mainly occur in MRs by consumption of VFA generated from AR under the TPAD process. Table 4 shows the VFA concentrations in all four MRs during this test. All VFA concentration values were lower than 900 mg/L, demonstrating that the methanogens in each MR consumed the majority of the VFA. The longer the residence time was, the lower the VFA concentration became. VFA accumulation was prohibited under the TPAD process in this test.

Alkalinity, which can buffer the system and lower pH fluctuations, is a measurement of the buffering capacity of an anaerobic digestion system. Usually, the ideal alkalinity ($CaCO_3$) concentration is between 2,000 and 5,000 mg/L. Table 4 shows that the alkalinity of the four MRs falls under the ideal range, indicating that the buffering capacity of each MR performed well. This condition could be attributed to the high inoculating ratio (80%) and alkalinity of seed sludge (2,454 mg/L) in this test. As the SRT increased, the alkalinity also increased when SRT $\leq$ 20 days, whereas it decreased when SRT = 30 days.

The MR's VFA concentration was apparently lower than that of AR and clearly decreased as the SRT increased (Table 4). A complete phase separation is difficult to realize, acidogenetic and methanogenetic reactions occur in MRs simultaneously, and the acidogenesis rates were relatively high at short SRTs. Thus, the VFA concentration of MR1 was the highest among all MRs.

The stability of the anaerobic digestion system can be evaluated by the VFA to alkalinity ratio (VFA/alkalinity). When this ratio is lower than 0.4 (Song *et al.* 2004), the anaerobic digestion system could be considered as a stable one. The stronger the buffering capacity is, the better the stability becomes. Table 5 shows that the VFA/alkalinity ratio of the four MRs was less than 0.3, indicating that the stability of all reactors was perfect. The system stability increased with the increase in residence time. This condition can be attributed to the organic loading rate (OLR) of the system

Table 4 | VFA and alkalinity of different methanogenic reactors

Parameter	Unit	MR1	MR2	MR3	MR4
SRT	days	5	10	20	30
VFA	mg/L as HAC	662 ± 107	625 ± 154	578 ± 150	475 ± 185
Alkalinity	mg/L as $CaCO_3$	3,385 ± 73	3,892 ± 131	4,103 ± 60	3,990 ± 55
VFA/alkalinity	–	0.20	0.16	0.14	0.12

Table 5 | Organics removal efficiency of different methanogenic reactors

Parameter	Unit	MR1	MR2	MR3	MR4
SRT	days	5	10	20	30
OLR	gVS/(L·d)	4.8	2.4	1.2	0.8
TCOD of feedstock	g/L	44.8 ± 3.9			
SCOD of feedstock	g/L	12.0 ± 1.4			
VS removal rate	%	36.1 ± 2.4	41.6 ± 2.7	50.2 ± 2.2	48.7 ± 2.5
TCOD removal rate	%	38.0 ± 3.5	49.3 ± 4.4	56.1 ± 3.1	54.2 ± 4.4
SCOD removal rate	%	89.8 ± 2.2	92.5 ± 2.1	93.1 ± 1.8	93.4 ± 1.3

decreasing as the residence time increased, and the low organic loading rate leading to high stability to some extent.

Performance of organics removal efficiency

The organics removal rate is an important index in evaluating the effects of the anaerobic digestion process. Table 5 shows the effect of each MR during the experiment. The VS and TCOD removal rates of the MRs changed from 36.1 to 50.2% and from 38.0 to 56.1%, respectively. The highest organics removal rate was obtained by MR3 with a 20-day SRT, but the differences between the MRs were unclear regarding the SCOD removal rates, which were higher than 89%. The VS and TCOD removal rates were mainly determined by microbial activities and communities, which were both closely related to the survival environment of methanogens. The stable environment of the digester was favorable for enhancing microbial activities. MR3 and MR4 also obtained higher organic removal rates with a lower VFA/alkalinity ratio (Table 4). One of the main objectives of the anaerobic process is to stabilize solid waste properties by degrading organic components, so MR3 with a 20-day SRT had the best performance in this test.

Rubio-Loza & Noyola (2010) operated two-phase anaerobic sludge systems treating a mixture of primary and secondary sludge. The first acidogenic thermophilic phase was operated at hydraulic retention times of 3 days, whereas the second methanogenic mesophilic phases had 13 days. Results show that the VS reduction rate was only 31% when the system reached a stable state. Zhang & Jahng (2012) examined the anaerobic digestion of food waste in a semi-continuous single-stage reactor, but the test failed when the food waste was digested alone without supplementing trace elements. Table 6 shows the organic removal rates of TPAD systems in the present study. Given that food waste was added to the sewage sludge for co-digestion, the average VS removal rate of the TPAD system (AR3 + MR1) with a 10-day SRT reached 54.9%, whereas the VS removal rate increased gradually until the TPAD system (AR3 + MR3) with a 25-day SRT reached the highest value. Regarding the VS removal rate, the optimum SRT of the TPAD system was 25 days (AR3 + MR3). Unlike the sewage sludge digested alone, the VS removal rate slightly improved, suggesting that the anaerobic digestion's effect greatly improved the co-digestion of food waste and sewage sludge.

Table 6 | Organics removal rate of different two-phase anaerobic digestion systems

Parameter	Unit	AR1 + MR1	AR1 + MR2	AR1 + MR3	AR1 + MR4
SRT	Days	10	15	25	35
VS removal rate	%	54.9 ± 2.6	58.4 ± 3.1	64.7 ± 2.0	63.8 ± 1.9
TCOD removal rate	%	46.5 ± 3.5	54.2 ± 3.9	60.8 ± 3.5	57.9 ± 4.1

Biogas analysis

One of the most important advantages of the anaerobic digestion process is that it can recycle biogas energy. Statistics show that the methane content in biogas generated by sludge anaerobic digestion in China is between 45 and 64% (Wu *et al.* 2009). Zhang & Jahng (2012) operated single-stage anaerobic digesters by supplementing trace elements into food waste for stabilizing research. The results showed that the control reactor without receiving any trace elements had about 50–60% methane content in the biogas before the 70th day, and then it was out of work, with the methane content decreasing sharply. The gas component and gas production rate of the four MRs in this test are shown in Table 7. The methane content in biogas fluctuated at around 70%, and no significant difference existed between the two different reactors. Methane content in biogas was greater than the highest value for the sludge digested alone, suggesting that this content could be increased when food waste is added to sewage sludge for anaerobic co-digestion.

CONCLUSIONS

The performance of the two-phase anaerobic co-digestion of food waste and sewage sludge, which were mixed as anaerobic feedstock according to the TS ratio of 1:1, was investigated. An anaerobic digester was operated semi-continuously at a temperature of 35 ± 1 °C. Results show that AR with a 5-day SRT obtained the best acidification effect. MR with a 30-day SRT was the most stable MR with the lowest VFA/alkalinity ratio (0.12). The TPAD system (AR3 + MR3) with a 25-day SRT achieved the highest removal efficiency of VS (64.7%) and TCOD (60.8%). The

Table 7 | Biogas components of different methanogenic reactors

Reactor (%)	MR1	MR2	MR3	MR4
CH_4	72.6 ± 4.4	73.4 ± 1.8	71.3 ± 1.5	69.7 ± 1.0
CO_2	26.5 ± 2.1	26.4 ± 0.9	25.7 ± 1.8	29.7 ± 0.5

methane content in biogas produced by the four MRs fluctuated at around 70%. These results suggest that the anaerobic co-digestion of food waste and sewage sludge yields synergistic and complementary effects. The anaerobic digestion performance also improved comprehensively compared with food waste or sewage sludge digested alone.

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