Thermophilic co-digestion of food waste and sewage sludge

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ABSTRACT

Due to the rising concerns regarding food waste disposal as well as the increasing demand for renewable energy nowadays, a number of European countries have adopted anaerobic co-digestion, a technology that deals with food waste and sewage sludge. As stated in the HKSAR Government's Policy Address 2016, the feasibility of using existing sewage treatment facilities for co-digestion of food waste and sewage sludge has been under exploration. A trial scheme has been commenced in 2019. This paper aims to compare the efficiency of biogas production and volatile solid reduction in co-digestion of food waste and sewage with mono-digestion in laboratory scale.

KEYWORDS Thermophilic; co-digestion; anaerobic digestion; food waste; sewage sludge; biogas

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1. Introduction

1.1. Background

Sewage sludge is a major, yet inevitable by-product of the wastewater treatment process (Show et al., 2012). Since sewage sludge is a mixture of primary and biological sludge (Iacovidou et al., 2012), which primarily consists of a rich amount of pathogens, heavy metals and environmental pollutants (Show et al., 2012a), anaerobic digestion has been adopted widely for the digestion of sewage sludge, during which stabilisation and volatile solid reduction can be achieved before final disposal. In anaerobic digestion, organic matters are digested, and as a consequence, biogas and digestates are produced. Biogas, such as methane, is a good renewable source for energy generation.

In recent years, many studies have investigated the possibility of adding other substrates such as grease waste (Silvestre et al., 2011), shredded grass (Hidaka et al., 2013) and landfill leachate (Montusiewicz and Lebiacka, 2011) into sewage sludge. The process of adding other substrates to the digestion of sewage sludge is termed co-digestion, which allows the two substrates to provide supplementary effect to the process; for instance, improving the generation of biogas by increasing the efficiency of digestion, when compared to mono-digestion. Various studies have focused on the governing factors of co-digestion. With the high organic contents in food waste, studies have found that the combination of food waste and sewage sludge can help optimise the performance of anaerobic digestion. In this project, the co-digestion of food waste and sewage sludge will be examined under controlled and stable environment with pre-determined mixing ratio of food waste and sewage sludge in reactors, with the aim to study the performance of co-digestion in the local context in Hong Kong.

1.2. Motivation

The demand for renewable energy generation has increased in recent years; as a result, there is a pressing need to divert municipal waste from landfill. The total solid waste, under the framework of solid waste statistics, comprises municipal solid waste, overall construction waste and special waste (Census and Statistics Department, 2018). Among solid waste, food waste accounts for 3,337 tonnes, over one-third of municipal solid waste in Hong Kong. The disposal of food waste to landfill is not sustainable due to the limited space, and causes a series of environmental problems due to the landfill gas and odour generated (Environmental Protection Department, 2018). Despite the fact that a number of alternatives, such as incineration, use of food waste disposal units and composting, have been proposed for the management of food waste, food waste is difficult to handle because of its high water content and high degradability (Iacovidou et al., 2012). Conversely, the suggestion of adopting anaerobic digestion for food waste management has attracted more interest of policy makers due to the possibility of the generation of energy in the process (Iacovidou et al., 2012). On the other hand, sewage sludge is classified as one of the major special waste, under the classification of solid wastes, produced from wastewater treatment plants. From the 11 sewage treatment works in Hong Kong, over 1,200 tonnes of sludge are generated every day (T•PARK, 2018). In 2017, the total amount of sewage sludge collected by sludge treatment facility reached over 380,000 tonnes (Census and Statistics Department, 2018). The HKSAR Government is keen in maximising the utilisation of sludge, as well as minimising their volume before final disposal. In 2015, a treatment facility for dewatered sewage sludge, namely T•PARK, was commissioned. However, with the growing population and development of the city, sludge production will rise further in the near future.

1.3. Approach and scope

This is an experimental study. The majority of the works were conducted in laboratory with different experimental stages, from batch experiment to semi-continuous experiment. The performance of co-digestion under thermophilic condition at laboratory scale was evaluated based on the analysis of results obtained from experiments.

1.4. Objectives

In view of the problems arisen from food waste disposal and the production of sewage sludge, this study aims to examine the performance of co-digestion of food waste and sewage sludge under thermophilic conditions. Reactors with different food waste (FW) to feeding sewage sludge (FSS) ratio will be set up to compare the performance of mono-digestion and co-digestion of food waste and sewage sludge, whereby parameters will be tested to evaluate the performance of each of the set-up conditions. The following objectives will be accomplished upon the completion of this study: 1) to evaluate the performance of biogas production of co-digestion and mono-digestion under thermophilic condition; 2) to determine the yield of methane and the percentage of volatile solid reduction; and 3) to determine the effect of inhibitors of co-digestion.

2. Literature review

2.1. Anaerobic digestion of sewage sludge

The process of digestion of sewage sludge is anaerobic, during which oxygen is absent while organic matters are being digested, and biogas and digestates are produced. The four major stages in anaerobic digestion that lead to methane generation are hydrolysis, acidogenesis, acetogenesis and methanogenesis. The process is illustrated in Figure 1.

In hydrolysis, complex compounds such as carbohydrates, proteins and lipids are broken down into simpler, soluble organic acids, sugars and amino acid, during which some acetic acid, hydrogen and carbon dioxide are produced (Parkin and Owen, 1986). The process is followed by acidogenesis, where organic acids are further broken down into smaller organic acids such as propionic acid and butyric acid (Parkin and Owen, 1986). Subsequently, acetogenic bacteria is involved in the production of acetic acid, while hydrogen and carbon dioxide are also formed. At the same time, some acetic acid is also produced by hydrogen-consuming acetogenic bacteria from hydrogen (Parkin and Owen, 1986). At the final stage, over 70% of the methane are generated from acetic acid by aceticlastic methanogens during

methanogenesis, while the rest of the methane is converted from hydrogen and carbon dioxide by CO_2 -reducing methanogens.

Figure 1. Mechanism of the production of methane (Parkin and Owen, 1986).

2.2. Significant factors

There are a number of monitoring factors for the experiment to ensure the conditions are favourable for digestion to take place. Factors including temperature, pH, carbon-to-nitrogen ratio and presence of inhibitors will be examined.

2.2.1. Temperature

Temperature is one of the major factors in determining the performance of anaerobic digestion because heat provides kinematic energy for micro-organisms to undertake the reaction in breaking down organic matters. There are generally temperature settings for anaerobic digestion: mesophilic condition at 35°C and thermophilic condition at 55°C. Experiments in this study are to be carried out under thermophilic condition. Studies found that at higher temperature, more energy are provided for micro-organisms, and subsequently, digestion process is facilitated with higher reaction rate, resulting in a higher volatile solid reduction and an increased production of biogas (Gou et al., 2014).

2.2.2. pH

The optimum pH range for anaerobic digestion is 6.8 - 7.5. During anaerobic digestion as shown in Figure 1, organic acids are generated. The addition of FW is likely to further lower the pH in reactors due to the accumulation of volatile fatty acids (VFAs). If pH falls below the optimum range, the digestion will be inhibited and VFAs will be the final product of the digestion. Therefore, the pH of each reactor has to be monitored on the next day of feeding, and sodium bicarbonate in a concentration of 5 g/100 mL has to be added to increase the pH.

2.2.3. Carbon-to-nitrogen ratio

Carbon-to-nitrogen ratio (C:N) is also one of the factors that affect the process of anaerobic digestion as well as an indicator of how degradable a substrate is. The best condition is to adopt the optimum C:N of 20 - 30 (Iacovidou et al., 2012). If C:N is above 30, there is a deficiency of nitrogen such that insufficient nutrient is provided for the digestion and will cause instability; in contrast, if C:N is below 6, it is an indication of low carbon availability with a large amount of ammonia generation, which can lead to toxicity to micro-organisms (Iacovidou et al., 2012).

2.2.4. Inhibitors

The presence of inhibitors poses a major challenge in the co-digestion process of food waste and sewage sludge because they adversely affect the digestion process. Ammonium nitrogen, volatile fatty acid and metal ions are the main inhibitors that inhibit the reaction process.

2.3. Characteristics of FW

FW consists of a variety of food disposed from different areas in a city and therefore has a large variation in its composition. This may as well be due to seasonal changes in food consumption patterns, habits and dining culture. FW is characterised by large compositions of carbohydrates, lipids and proteins, making it highly degradable with high C:N due to the high proportion of carbon it contains. The proportion of each of the organic components differs considerably in different kinds of food. For example, vegetables are rich in carbohydrates, while nuts are rich in protein and lipids. Apart from its high organic contents, FW also has high water content and is rich in volatile solid (VS), which makes it easier to convert substrates into methane in the digestion process (Prabhu and Mutnuri, 2016). However, there are concerns regarding the lipid contents of FW, which may cause the accumulation of VFAs, leading to acidification of substrate. If the substrate is acidic and below the desirable range of pH values, the digestion process will be inhibited. Moreover, since FW has a relatively low content of nitrogen and phosphorus, digestion will be inhibited due to insufficient nutrients. With a suitable amount of sodium ion, Na^+ , the inhibition caused by ammonia can be avoided. However, the high salt content of FW with a high concentration of Na^+ is one of the inhibiting factors of the mono-digestion of FW (Dai et al., 2012).

Based on the food consumption pattern in Hong Kong, FW generally consists of 80% carbohydrates, 15% proteins and 5% lipids (Wang et al., 2015). Therefore, this distribution of organic matters in FW is adopted in this study and the FW is prepared accordingly for the experiment.

2.4. Characteristics of sewage sludge

When compared with FW, sewage sludge has lower C:N, ranging from 6 - 9 (Iacovidou et al., 2012) due to its lack of organic matters. The generation of ammonia, which poses a risk of inhibiting the digestion, is a major concern due to the low C:N. Sewage sludge also has a lower VS than FW, indicating it is less easily degradable than FW. Due to these factors, the digestion of sewage is comparatively less efficient than that of FW.

2.5. Benefits of co-digestion

With the constraints of mono-digestion of FW and sewage sludge discussed in Sections 2.3 and 2.4, it can be observed that the two substrates can overcome their limitations by adopting co-digestion, and thus the overall performance of digestion can be enhanced.

In the co-digestion of sewage sludge and FW, sewage sludge with low C:N provides nitrogen for the nutrient-deficient FW, while FW with high C:N improves the carbon content of sewage sludge. Therefore, a more balanced C:N can be achieved for an ideal digestion condition. Studies have also found that with the lower ratio of sewage sludge to FW, methane yield would be higher and volatile solid reduction (VSR) would also be increased (Dai et al., 2012). This phenomenon can be explained by the fact that FW is highly degradable, while sewage sludge is refractory to hydrolysis (Dai et al., 2012). In addition, the presence of FW in co-digestion improves the stability of the high ammonia digestion system, as well as dilutes toxicants in sewage sludge, and hence, increases the production of biogas (Dai et al., 2012). On the other hand, the addition of sewage sludge to FW helps dilute the high concentration of Na^+ in FW.

2.6. Difficulties of co-digestion

The major constraint in co-digestion is caused by FW, due to its high variability in nature. Micro-organisms in a digestion system are sensitive to the organic contents in FW and the performance of digestion depends on the composition of FW, which are carbohydrates, proteins and lipids. If the organic composition of FW changes, the system becomes unstable because micro-organisms have adapted to specific substrates and the reaction process will be affected (Iacovidou et al., 2012). Therefore, it is crucial to maintain the composition of FW added to the system.

3. Methodology

3.1. Overview

The experiment is divided into two main stages: batch experiment and semi-continuous experiment. The

activity and adaptation of methanogens under 55°C is monitored regularly in the first stage, while regular feeding is undertaken in the second stage to perform co-digestion and mono-digestion in reactors.

In order to investigate the performance of co-digestion, three sets of reactors are set up at FW to FSS ratio of 0:100, 50:50 and 100:0. Each set-up is duplicated, and therefore, six reactors are used in total. Although the volume of each reactor is over 500 mL, the actual working volume is set as 200 mL. The two substrates used in co-digestion are FSS and FW. FSS is a mixture of thickened primary sludge (TPS) and thickened secondary activated sludge (TSAS) collected from Tai Po Sewage Treatment Works (TPSTW). FSS was prepared by mixing TPS and TSAS at a ratio of 4.5:1 before the experiment. Solid retention time (SRT) of 20 days is adopted in this experiment. With the working volume of 200 mL and the feeding of substrates every four days, a total volume of 40 mL of digestate has to be discharged before each feeding.

3.2. Pre-experimental set-up

Digested sludge (DS) collected from TPSTW is used as inoculum, which is the micro-organism used for digestion, in the experiment. Since the sludge was stored at mesophilic condition at 35°C for digestion at Sewage Treatment Works, adaptation and activation of micro-organisms was required at thermophilic condition, i.e. 55°C before the commencement of the experiment. This was done by mixing DS and FSS at a ratio of 2:1, where 134 mL of DS and 66 mL of FSS are added to each reactor. The prepared inoculum was then kept in a water bath at a temperature of 55°C for two weeks. The activities and adaptation of inoculums were monitored by the measurement of biogas production as well as the methane yield.

3.3. Experimental set-up

Upon the completion of batch stage, reactors can be set up for the next stage. In the experiment, three types of reactors with different ratios of FW:FSS are set up. The set-up ratio of FW:FSS in reactor R1 and R2, R3 and R4, and R5 and R6 are 0:100, 50:50 and 100:0, respectively. FW and FSS are classified as feeding, while the digestate in the reactors from batch stage are used as inoculum. To prepare for the next stage, all digestate in each reactor after batch stage were mixed together before using as inoculum to ensure the unity of the performance of inoculum in each reactor. The ratio of inoculum to feeding in the working volume of 200 mL is 2:1.

FW with 80% carbohydrates, 15% proteins and 5% lipids was prepared with bread, steamed rice, cooked meat, lettuce and apples. The amount of FW added into each reactor depends on the total solid (TS) of FSS.

Since salt was present in FSS and the calculated TS of FSS with salt will affect accuracy of the TS required from

FW, the salt in FSS has to be removed before measuring the TS of FSS. The TS of desalted FSS was then obtained. Compared with the TS of un-desalted FSS of 23.56 g/L, the TS of desalted FSS was 13.5 g/L, which is unusually lower than expected. This may be due to the daily variation of water consumption, resulting in the variation in the amount of TS in sewage collected from TPSTW. To solve the problem, the above procedures were repeated using thickened FSS. The TS of the thickened and desalted FSS is 38.59 g/L, and the TS of FW was 23.85%. The total volume of the initial feeding is 66 mL and the amount of FW and FSS added for each reactor is summarised in Table 1.

Table 1. Amount of FW and FSS, and corresponding TS added to each reactor in batch stage.

Reactor	FW:FSS	Weight of FW added (g)	TS added from FW (g)	Volume of FSS added (mL)	TS added from FSS (g)
R1, R2	0:100	0	0	33	2.547
R3, R4	50:50	5.34	1.273	33	1.273
R5, R6	100:50	10.68	2.547	0	0

3.4. Operation of experiment

Semi-continuous feeding of FW and FSS into reactors is the main part of the experiment. 40 mL of feeding were added to the reactors. The total weight of FW and volume of FSS added to reactors in each feeding is summarised in Table 2. Water was added to FW so that the total volume of FW mixture fed into reactors was 20 mL for R3 and R4, and 40 mL for R5 and R6. After each feeding, oxygen was removed by purging nitrogen into reactors for one minute. Reactors were sealed with rubber septa and aluminium cap at the end of the process. The pH values of each reactor were also monitored to ensure an optimum pH range from 6.8 to 7.5. If pH drops below the optimum values, sodium bicarbonate was added for adjustment.

Table 2. Amount of FW and FSS, and corresponding TS added to each reactor in each feeding.

Reactor	FW:FSS	Weight of FW added (g)	TS added from FW (g)	Volume of FSS added (mL)	TS added from FSS (g)
R1, R2	0:100	0	0	40	1.543
R3, R4	50:50	3.24	0.771	20	0.771
R5, R6	100:50	6.47	1.543	0	0

4. Measurements and results

4.1. VSR

The efficiency in the reduction of VS is one of the important parameters in monitoring the performance of digestion in a reactor. VSR was obtained by comparing the difference between VS in each feed and the VS in effluent. The higher reduction in VSR is, the more organic matters

are removed during the digestion process. In general, the reduction of VS is the lowest in mono-digestion of FSS, with an average of 37.4%, while the reduction of VS is the highest in mono-digestion of FW, with an average of 80.4%. The average efficiency of VSR of co-digestion is 52.4%, in which the reduction efficiency is between mono-digestion of FSS and mono-digestion of FW. These results show that with the presence of FW in substrate, higher efficiency of VSR can be achieved because more organic matters are present in FW, making FW highly degradable. Therefore, mono-digestion of FW has the highest reduction in VS, while the co-digestion of FW and FSS has a higher VSR than mono-digestion of FSS.

4.2. Biogas and methane production rate

The volume of biogas produced in a cycle was measured on the day of feeding and the day after feeding. In Figure 2, biogas production rate was the highest for mono-digestion of FW at the first half of the experiment among all reactors, ranging from 595 mL/L/D to 1000 mL/L/D. However, gas production rate dropped significantly in the latter half of the experiment due to the presence of inhibitors, such as accumulation of VFAs. The gas production rate of co-digestion was the most steady, fluctuating between 580 mL/L/D and 680 mL/L/D, while that of mono-digestion of FSS attained the lowest value throughout the experiment, ranging between 250 mL/L/D and 480 mL/L/D. With the measurement on gas composition after the measurement on gas volume, the proportion of methane in biogas is approximately 40% - 50%. Therefore, a similar pattern was observed for methane production rate as in biogas production rate in Figure 2.

Figure 2. Gas production rate.

4.3. Biogas and methane yield

Biogas yield is defined as the volume of biogas produced per gram of VSR. This is an indication of the amount of energy recovery in the digestion process. Biogas yield is the most stable for co-digestion, ranging between 485 mL/g VSR and 749 mL/g VSR, while mono-digestion of FSS attained the highest yield at the first seven cycles from 485 mL/g VSR to 1083 mL/g VSR. The biogas yield

for mono-digestion of FW fluctuated between 250 mL/g VSR and 710 mL/g VSR and attained the lowest value at the end of the experiment.

Figure 3. Methane yield.

Figure 3 shows the theoretical and experimental methane yield of digestion. Performance gaps can be seen between the theoretical yield and the experimental yield because inhibitors are present in reactors, such as ammonium nitrogen in mono-digestion of FSS and VFAs in mono-digestion of FW. The performance gap is the smallest in co-digestion.

4.4. Concentration of total organic carbon (TOC)

The measurement of the concentration of TOC is the concentration of organic carbon in the effluent from reactors in each feeding cycle. The accumulation of VFAs contributes to the concentration of TOC. The concentration of TOC in reactors with mono-digestion of FSS and co-digestion of FW and FSS were approximately the same and remained steady, ranging between 300 mg/L and 880 mg/L, while that for the mono-digestion of FW remained steady at the first eight cycles at similar range as in other reactors, followed by a sharp increase in the concentration up to 4090 mg/L at the end of the experiment. This can explain the inhibition effect in R5 and R6, which has led to a sharp drop in methane production in the reactors at the later stage of the experiment.

4.5. Concentration of VFAs

VFAs are one of the most critical inhibitors in anaerobic digestion. In case of high accumulation of VFAs, pH value drops out of the optimum range, leading to an inhibition effect on digestion. The concentration of VFAs in mono-digestion of FSS and mono-digestion of FW and FSS remains relatively low at a concentration of 175 mg/L - 350mg/L, with heptanoic acid being dominant. On the other hand, the concentration of VFAs in mono-digestion of FW had a rapid increase from cycle nine onwards, reaching a concentration of over 20 times higher than all other reactors, with acetic acid being dominant, causing a serious inhibiting effect on digestion.

Table 3. Mass balance.

Reactor	Input COD (g)	Output COD (g)			Total output COD (g)	Coverage rate (%)
		COD _{gas} (g)	COD _{liquid} (g)	COD _{solid} (g)		
R1	1.81	0.535	0.0796	0.984	1.598	88
R2		0.514	0.0576	1.037	1.608	89
R3	1.77	0.816	0.0605	0.606	1.483	84
R4		0.825	0.0582	0.611	1.494	84
R5	1.66	0.723	0.236	0.417	1.375	83
R6		0.741	0.218	0.371	1.330	80

4.6. Concentration of ammonium nitrogen ($\text{NH}_4^+\text{-N}$)

$\text{NH}_4^+\text{-N}$ is an inhibitor that presents at a high concentration in FSS. The concentration of $\text{NH}_4^+\text{-N}$ is the highest for the mono-digestion of FSS, ranging between 800 mg/L and 1025 mg/L, while its concentration is the lowest in reactors undergoing mono-digestion of FW, ranging from 213 mg/L to 654 mg/L. The concentration of $\text{NH}_4^+\text{-N}$ in reactors undergoing co-digestion ranges between the concentrations of the other two types of reactors. Overall, there was a decreasing trend in the concentration of $\text{NH}_4^+\text{-N}$ as the experiment proceeded. The high concentration of $\text{NH}_4^+\text{-N}$ in mono-digestion of FSS can explain the phenomenon that reactors undergoing this kind of reaction always have the lowest gas production rate, when compared with co-digestion of FW and FSS and mono-digestion of FW. It is also found that the concentration of $\text{NH}_4^+\text{-N}$ can be lowered by the addition of FW into digestion, achieving co-digestion.

4.7. Mass balance

In checking the validity of the results, a mass balance on chemical oxygen demand (COD) was calculated and summarised in Table 3. In R1 and R2, the reactors undergoing mono-digestion of FSS, mass balance coverage of 88% - 89% was achieved. This is within the range of acceptable percentage of coverage of $100\% \pm 20\%$. However, for R3 and R4, the reactors undergoing co-digestion of FW and FSS, and R5 and R6, the reactors undergoing mono-digestion of FW, have seen a lower coverage rate in mass balance calculation of 80% - 84%. This is likely due to the fact that biogas produced is leaked from the reactors during measurement with the limited headspace of 300 mL, while the volume of gas produce could go beyond 400 mL.

5. Limitations

The major limitation of the experiment is the limited headspace volume in reactors, and the addition of sodium bicarbonate solution in adjusting the pH in R5 and R6

further reduced the headspace volume to accommodate the biogas produced. Therefore, it is suggested that experiment in a larger scale with larger reactors should be conducted in future when investigating co-digestion.

6. Conclusion

With the goal to improve the efficiency of biogas production from anaerobic digestion and to alleviate the problems arisen from the disposal of food waste, a trial scheme on co-digestion of food waste and sewage sludge has been commissioned in 2019. This study has investigated the performance of co-digestion under thermophilic condition. To conclude, co-digestion of FW and FSS can achieve more steady and efficient production of biogas such as methane, while the percentage of VSR was higher when compared to mono-digestion of FSS. The overall stability of the digestion system can be improved in co-digestion. However, it is recommended that future experiment should be carried out in a larger scale, as well as using different FW to FSS scale in digestion to gain a further investigation on co-digestion in treatment plants.

Notes on Contributor

Miss Jamie Ka Yan Li received her B.Eng. degree in Civil Engineering in The University of Hong Kong. She has undertaken a range of studies and experiments on the topic of thermophilic co-digestion of food waste and sewage sludge for her final year project. She is now a Graduate Engineer in MTR Corporation Limited.

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