Anaerobic digestion of food wastes for biogas production

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Abstract: Five types of food wastes were investigated as feedstock for a potential centralized anaerobic digester system in the area of Sacramento, California to produce biogas energy. The wastes were from a soup processing plant, a cafeteria, a commercial kitchen, a fish farm, and grease trap collection service. Digestibilities of the food wastes, individually and in mixtures, were conducted at mesophilic (35℃) and thermophilic (50℃) temperatures and two foods to microorganism ratios (F/M) of 0.5 and 1.0 for 28 days. A continuously fed mesophilic single-stage anaerobic digester was evaluated using a mixture of the five food wastes at organic loading rates of 0.5 to 1.0 g VS/L/d. In the batch digestion tests, fish and grease trap wastes required longer time to complete the digestion and had higher biogas yields than the other wastes. The continuously-fed digester required the addition of sodium hydroxide to maintain pH at proper levels in the digester. Alkalinity of about 2,500 mg $CaCO_3$/L and pH above 7 was maintained by adding 0.2 g NaOH/g VS. The results of this study indicated that it was necessary to use the chemicals, such as NaOH, to control the pH of the single-stage anaerobic digester treating the food waste. For commercial applications, the chemical cost and proper management of additional salt in the digester effluent need to be carefully considered.

Keywords: anaerobic digestion, bioconversion, biogas, continuous digestion, food waste

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1 Introduction

Food waste is the third-largest component of municipal solid waste generated from the United States. According to a report by U.S. Environmental Protection Agency[1], approximately 32 million tons of food waste was generated annually. Less than three percent of the food waste was separated and treated, primarily through composting, and the rest was disposed of in landfills. Due to increasing needs for renewable energy generation and diversion of organic residuals from land fills to reduce the greenhouse gas emissions and other environmental impact, treatment of food waste using anaerobic digestion technologies has become a more attractive method for food waste management.

Anaerobic digestion is a controlled biological degradation process and allows efficient capturing and utilization of biogas (approximately 60% methane and 40% carbon dioxide) for energy generation. The digestate from anaerobic digesters contains many nutrients and can thus be used as plant fertilizer and soil amendment. Anaerobic digestion of different types of food waste has been studied extensively. Cho et al. conducted batch digestion tests of food wastes at 37℃ and 28 days retention time[2]. The methane yields were 0.48, 0.29, 0.28, and 0.47 L/g VS for cooked meat, boiled rice, fresh cabbage and mixed food wastes, respectively. Heo et al. evaluated the biodegradability of a traditional Korean food waste consisting of boiled rice (10%–15%), vegetables (65%–70%), and meat and eggs (15%–20%) and showed a methane yield of 0.49 L/g VS at 35℃ after 40 days retention time[3]. Zhang et al. analyzed the

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nutrient content of food waste from a restaurant, showing that the food waste contained appropriate nutrients for anaerobic microorganisms, as well as reported a methane yield of 0.44 L/g VS of food waste in batch digestion test under thermophilic conditions (50℃) after 28 days[4]. Anaerobic digestion of food waste is achievable; however different types of food waste result in varying degrees of methane yields, and thus the effects of mixing various types of food waste and their proportions should be determined on a case by case basis.

The objective of this study was to determine the digestibility of five food wastes individually and as a mixture under mesophilic and thermophilic conditions. The five food wastes were selected based on a previous survey results that indicated that these were the largest food waste streams in Sacramento, CA. The City of Sacramento was interested in developing a centralized anaerobic digester for these food waste streams. The digestibility was evaluated in terms of biogas yield, methane yield and volatile solids reduction. The second objective was to evaluate the performance and operating requirements of a single stage, mixed digester for treating the mixture of five food wastes.

2 Materials and methods

2.1 Collection and characterization of food wastes and anaerobic inoculum

The five food wastes were collected from July to October 2006. Food waste from a soup processing plant was collected after it was dewatered during the pressing stage. The waste was sampled on three consecutive days by manually collecting and placing the waste into one-gallon zipped-locked plastic bags. The soup processing plant was reported to be processing beef, potatoes, clams, and mushrooms on the first day, chicken, corn, pasta, ham, and other vegetables on the second day; and mushroom, ham, pasta, and other vegetables on the third day. For analysis, the three collections were mixed in equal proportions. Food waste from a cafeteria was sampled at a composting facility where the food waste was delivered on two non-consecutive days. For each sampling event, the waste was dumped from trucks onto a tipping floor. Samples were collected by shovel and placed into a five-gallon bucket. For analysis, the two collections were mixed in equal proportions. Food waste from the salad preparation line (pre-consumer) of a commercial kitchen was collected in a five-gallon bucket on one day. The waste consisted of melon rinds, bell peppers, cucumbers, onions, and various meats. The waste was processed through a meat grinder to obtain a homogenous mixture. Fish waste from a fish farm consisted of five Sturgeon heads and fish viscera. The fish waste was collected in a five-gallon bucket. The fish heads were difficult to cut and/or grind, therefore the flesh and gills were first stripped, and mixed with the fish viscera in a meat grinder. Grease trap waste was provided by a grease collecting company. Two grease trap samples were collected from two fast-food restaurants. The samples were shipped to the laboratory in one-gallon plastic jars in coolers. For analysis, the two samples were mixed in equal proportions. All the food waste samples were kept frozen at –20℃ until used.

Mesophilic anaerobic inoculum were collected from a working mesophilic anaerobic digester at wastewater treatment plant in Davis, CA. Thermophilic culture was collected from thermophilic anaerobic digesters at East Bay Municipal Utility District (EBMUD) in Oakland, CA. All the five food wastes and anaerobic inoculum were analyzed for total solids (TS), volatile solids (VS), and fixed solids (FS) in duplicate prior to any digestion tests. For the batch tests, the entire content of the reactor was measured for TS, VS, and FS at the end of the digestion period. Initial and final TS, VS, and FS were used to determine solid reduction during the digestion period. All the analyses were performed according to the standard methods[5]. Samples of the five waste streams were also sent to A&L Laboratories (Modesto, CA) for analysis of nutrients (N, P, K, S, Mg, Ca, Na), metals (Fe, Al, Mn, Cu, Zn), chloride, crude protein, crude fat, fiber, total carbohydrates, ash, organic matter, and carbon to nitrogen ratio (C/N).

2.2 Batch digestion tests

2.2.1 Experimental design and set-up

Mesophilic and thermophilic batch digestion experiments were conducted at (35±2)℃ and (50±2)℃ respectively. Each of the batch reactors had a total and effective volume of 1,130 and 500 mL, respectively. The reactors were loaded with 1.5 g VS of each food waste to obtain an organic loading of 3.0 g VS/L. To achieve food to microorganism ratios (F/M) of 0.5 and 1.0, 3.0 g VS and 1.5 g VS of inoculum was added to each reactor, respectively. Tap water was used to bring the working volume up to 500 mL working volume. All the reactors were tightly closed with rubber septa and screw caps. The head spaces of the reactors were purged with argon gas for five minutes to assure anaerobic conditions. In each of the experiments, blank reactors with only inoculum and tap water were also prepared to correct for the biogas produced from the inoculum only. All treatments were conducted in duplicate. All the reactors were manually mixed once a day for 30 s prior to measuring biogas volume.

2.2.2 Measurements and calculations

Daily biogas production was calculated using the headspace pressure of the reactor. Headspace pressure was measured using a pressure gauge (WAL-Me *β*-und Regelsysteme GmbH type 3150, Germany) with accuracy of 0.1%. After measuring the headspace pressure, the biogas in the headspace was released under water to prevent gas exchange between the headspace and ambient air. Then the pressure in the headspace was measured again as the initial condition for the next measurement. Daily pressure differences were converted into biogas volume using the following equation:

$$V_{\text{i,Biogas}} = \frac{(P_{i,\text{initial}} - P_{i\text{-1,final}}) \cdot V_{\text{head}} \cdot C}{R \cdot T}$$

Where, $V_{i,\text{Biogas}}$ is daily biogas volume in day i, L; $P_{i,\text{initial}}$ is absolute pressure before release in day i, Pa; $P_{i\text{-1,final}}$ is absolute pressure after release in day i-1, Pa; V_{head} is volume of the reactor head space, L; C is molar volume, 22.41 L/mol; R is universal gas constant, 8.314 L kPa K^{-1} mol^{-1}; T is absolute reactors temperature, K.

Methane (CH_4) and carbon dioxide (CO_2) concentrations in the biogas were measured using Gas Chromatography (GC) (Agilent GC 6890N, USA) equipped with a Thermal Conductivity Detector (TCD). Argon was used as the carrier gas at a flow rate of 30.1 mL/min. The injector, oven and detector temperatures were 120℃, 100℃ and 120℃, respectively. A biogas standard (Scott Specialty Gases, USA) containing 30.1% (v/v) CH_4, 30% H_2 and 40% CO_2 was used to calibrate the GC. Methane and carbon dioxide content of the biogas was measured every day for the first five days, and then every three days for the remaining 22 days as the change in biogas content became negligible. The Average Methane Content (AMC) over the digestion period was calculated by using the following equation. Biogas Production (DBP) and Methane Content (MP) for each day, *i*, were determined through interpolation using the measured data.

$$AMC = \frac{\sum_{i=1}^{n} BP_i \times MC_i}{\sum_{i=1}^{n} BP_i}$$

Where, AMC is average methane content, %; BP_i is biogas production in day I, L; MC_i is methane content in day i, %; N is number of observations.

2.3 Continuous digestion tests

2.3.1 Experimental design and set-up

A cylindrical shaped continuously digester was used in this study. The digester had an inner diameter and height of 20.3 and 61.7 cm, respectively. The total and working volumes were 20 L and 18 L, respectively. Because the batch digestion results indicated that the grease trap waste and the fish processing waste were better digested at the mesophilic temperature, it was decided to test the continuous digester in an environmental chamber maintained at (35±2)℃. There were two ports on the digester; one above the liquid level and one near the bottom. A peristaltic pump (Cole Parmer, Vernon Hills, IL) was used to draw biogas from the digester headspace at the upper port and charge it back through the bottom port on a periodic basis, and effectively mixing the digester contents. An inclined screen was installed in the digester to guide solids toward the bottom outlet. After daily feeding, the digester was mixed for two minutes every hour at a biogas recirculation rate of 2 L/min. In addition, on a daily basis, the digester was also mixed for two minutes before withdrawing effluent.

A food waste mixture was created based on the assumption of building a centralized food waste digester treating about 60 wet tons per day. For this determination, actual daily waste production amounts of fish farm and soup processing plant were used, while grease trap waste was limited to 20% of the total mixture VS (consideration based on results of the batch digestion study), and waste from cafeteria and commercial kitchen made up the remaining portion of the determination. Table 1 summarizes the amount and volatile solids fraction of the individual waste streams in the mixture. The total wet amount and total dry amount in the mixture were calculated as 18.2 and 60.8 tons/d, respectively.

Table 错误！文档中没有指定样式的文字。 **Amount and VS fraction of individual waste streams in the mixture**

Waste stream	Amount in mixture/ tons VS/d	VS fraction in mixture/%
Soup processing	2.3	13.6
Cafeteria	7.3	42.3
Commercial kitchen	4.1	23.8
Fish farm	0.1	0.6
Grease	3.4	19.7
Total	17.2	100

The food waste mixture was digested in a continuous single-stage completely mixed digester, seeded with the mesophilic anaerobic digestion sludge taken the Davis Wastewater treatment plant (Davis, CA). After the digester was seeded, it was flushed with argon to ensure anaerobic conditions, and then allowed to stabilize for two days before feeding commenced. The Hydraulic Retention Time (HRT) of the digester was set to 20 days, which is typical for mesophilic wastewater digesters. The digester was fed once a day manually. For each feed, 900 mL of effluent was removed through a valve at the bottom of digester, and an equal amount of freshly prepared feed was added through the valve at the top of the digester.

The daily feed was prepared by mixing five food waste streams and tap water for the desired mixture ratio and Organic Loading Rate (OLR). The starting OLR to the digester was 0.5 g VS/(L·d). After observing a steady decrease in digester pH, feeding was stopped until pH rose back to about 7. Feeding was resumed at 0.5 g VS/(L·d), however it was necessary to add 0.2 g NaOH/g VS fed in order to maintain an alkalinity level of 2,500 mg $CaCO_3$/L. After reaching steady state conditions, performance data of digesters was collected. The OLR was then increased to 1.0 g VS/(L·d) with the same feed mixture and NaOH addition. After the data collection, the digester was stopped because of the expiration of the project.

2.3.2 Measurements and calculations

Daily biogas production from the digester was measured using a wet tip gas meter (Rebel Point Wet Tip Gas Meter Company, Nashville, TN). On a daily basis the pH of the effluent was measured with an Accumet pH meter (Fisher Scientific, USA). After reaching a steady biogas yield, the biogas was sampled using gas sampling tubes, which were situated upstream of the wet gas tip meter. Biogas was analyzed for H_2, CH_4 and CO_2 contents using a Gas Chromatography (GC) on three consecutive days during steady state. Samples of the digester influent and effluent were also analyzed for TS, VS and FS in triplicate using the standard methods [5] to calculate solids reduction.

3 Results and discussion

3.1 Characterization of the food wastes and anaerobic inoculum

The solids analysis results for the five food wastes are shown in Table 2. The food wastes from the soup processing plant and cafeteria have similar TS and VS contents, whereas the commercial kitchen waste had lower TS and VS contents, possibly because the commercial kitchen waste stream contained food with higher moisture contents such as fruits. The fish waste had the highest VS content and the lowest moisture content among the five waste streams. All waste streams had VS/TS greater than 90%.

The component results of the food wastes are provided in Table 3. The carbon to nitrogen ratios (C/N) were highly variable, ranging from 3 to 23. Fish waste had the lowest C/N of 3 likely due to higher protein content, which was 83.1 mg/g. The characterization results suggest that mixing the food wastes is necessary in order to provide a nutrient balanced feedstock for anaerobic digestion.

Table 1 Average moisture (MC) and solids contents of five food waste streams and anaerobic inoculum (standard deviation in parentheses, *n*=3)

Food wastes	TS/%	VS/%	FS/%	MC/%	VS/TS/%
Soup processing	21.48	20.97	0.51	78.52	97.63
	-1.20	-1.04	-0.26	-1.20	-0.91
Cafeteria	23.45	21.82	1.62	76.55	93.05
	-0.38	-0.29	-0.09	-0.38	-0.11
Commercial kitchen	9.69	8.86	0.83	90.31	91.43
	-0.14	-0.15	-0.01	-0.14	-0.65
Fish farm	55.81	54.83	0.98	44.19	98.24
	-1.00	-1.72	-0.01	-1.00	-1.69
Grease	29.40	28.97	0.44	70.60	98.54
	-0.20	-2.04	-0.01	-0.20	-0.13
Anaerobic inoculums	TS/g • L^{-1}	VS/g • L^{-1}	FS/g • L^{-1}	MC/%	VS/TS/%
Mesophilic inoculum for batch digestion	12.55	6.40	6.15	98.74	50.96
	-0.01	-0.02	-0.01	-0.01	-0.12
Thermophilic inoculum for batch digestion	22.96	13.60	9.36	97.70	59.24
	-0.07	-0.04	-0.04	-0.01	-0.03

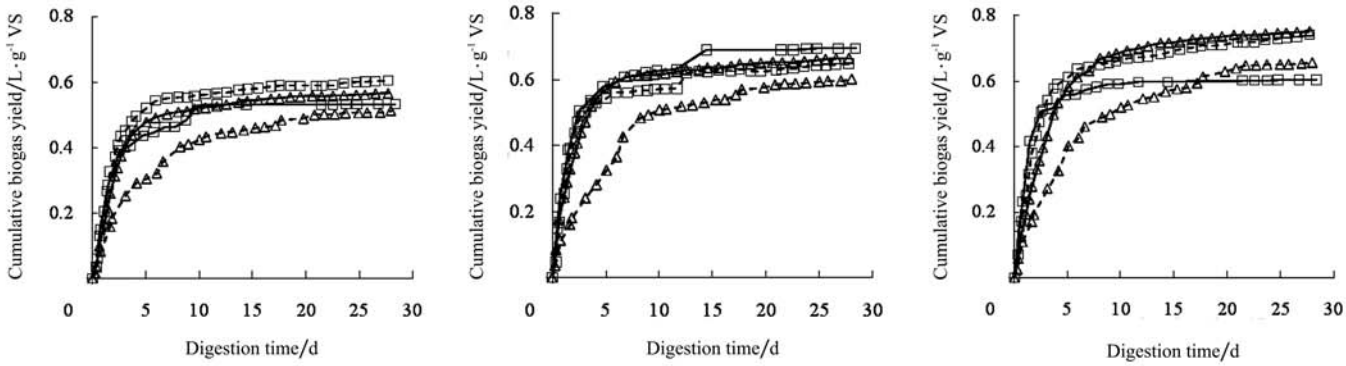
Table 2 Characteristics of five selected food waste streams

Element	Unit	Soup processing	Cafeteria	Commercial kitchen	Fish farm	Grease trap	Soup processing	Cafeteria	Commercial kitchen	Fish farm	Grease trap
		Wet weight basis					Dry Weight Basis				
Fe	μg/g	195	114	31	40	196	908	486	320	72	667
Al	μg/g	18	83	13	5	52	84	354	134	9	177
Mn	μg/g	5	7	2	1	2	23	30	21	2	7
Cu	μg/g	2	2	1	5	5	9	9	10	9	17
Zn	μg/g	9	15	7	11	6	42	64	72	20	20
Cl	mg/g	0.25	0.29	0.26	0.29	0.19	1.32	1.28	2.22	0.57	0.36
N	mg/g	5.8	5.1	5.5	13.3	2.1	31.4	22.9	46.3	26.1	4.2
P	mg/g	4.0	0.7	0.7	0.8	0.2	21.6	3.2	5.9	1.6	0.4
K	mg/g	0.6	1.7	2.5	0.7	0.1	3.2	7.7	21	1.4	0.2
S	mg/g	0.4	0.5	0.4	1.0	0.3	2.2	2.3	3.4	2.0	0.6
Mg	mg/g	0.1	0.3	0.4	0.1	0.1	0.5	1.4	3.4	0.2	0.2
Ca	mg/g	0.5	0.8	0.4	0.5	0.6	2.7	3.6	3.4	1.0	1.2
Na	mg/g	0.2	1.3	0.7	0.9	0.2	1.1	5.9	5.9	1.8	0.4
Carbohydrate	mg/g	145.4	164.8	65.9	277	369.1	785.3	743.1	554.5	542.7	736.4
Protein	mg/g	36.3	31.9	34.4	83.1	13.1	195.8	143.7	289.1	162.9	26.2
Crude Fat	mg/g	1.7	15.5	14.1	145.9	115.6	9.2	69.9	118.6	285.8	230.6
Fiber	mg/g	15.3	21.3	18.8	15.4	5.2	82.7	96	158.1	30.2	10.4
C:N	--	18	23	11	3	9	18	23	11	3	9

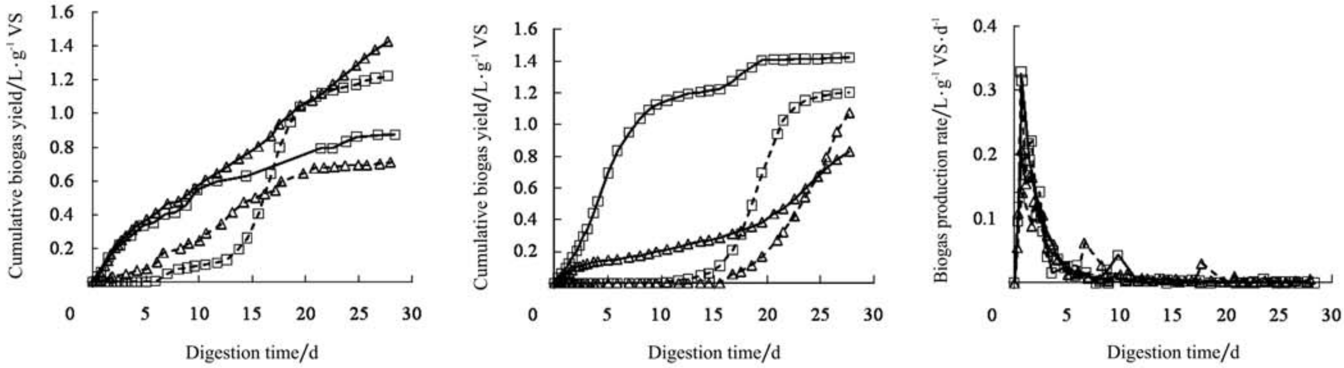
3.2 Results of batch digestion experiments

3.2.1 Batch digestion of individual food wastes

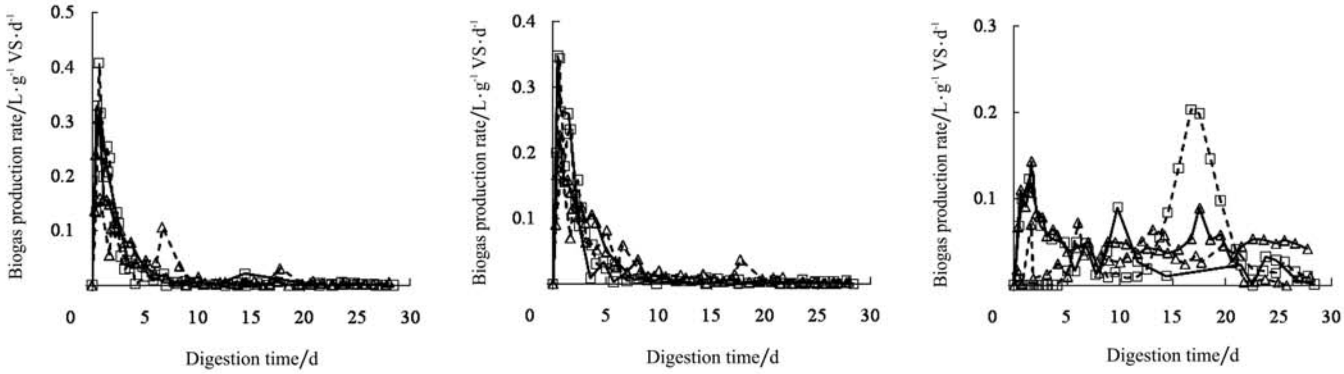
Cumulative biogas yields and biogas production rates for the individual food waste under mesophilic and thermophilic conditions for the two F/Ms of 0.5 and 1.0 are graphed in Figure 1. In all reactors, by the end of the 28 days of digestion biogas production was minimal. The soup processing, cafeteria, and commercial kitchen streams behaved similarly under both F/Ms (Figures 1a, 1b and 1c, respectively). For the soup processing, cafeteria and commercial kitchen streams, the final biogas yields were (0.53±0.13), (0.69±0.01), and (0.60±0.04) L/g VS with F/M of 0.5, respectively, and under mesophilic F/M of 1.0 were (0.57±0.05), (0.66±0.07), and (0.75±0.03) L/g VS, respectively. Under thermophilic conditions, the final biogas yields were (0.60±0.08), (0.65±0.07), and (0.74±0.10) L/g VS, respectively at F/M of 0.5, and (0.51±0.02), (0.60±0.06), and (0.66±0.07) L/g VS, respectively at F/M of 1.0. There was no significant difference between the three food wastes under the different digestion conditions. The results can be used to predict the biogas production potential of these three food waste streams under continuous conditions.



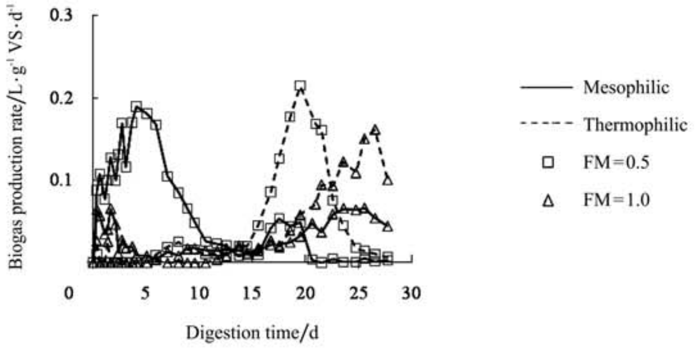
a. Soup processing b. Cafeteria c. Commercial kitchen



d. Fish farm e. Grease trap and biogas production rates of batch anaerobic digestion of wastes from f. Soup processing



g. Cafeteria h. Commercial kitchen i. Fish farm



j. Grease trap

Figure 1 Cumulative biogas yields of batch anaerobic digestion of wastes

For the soup processing, cafeteria, and commercial kitchen streams, most of the biogas was produced within the first five days of digestion. The time to reach 90% of their final biogas productions were within nine days under mesophilic F/M 0.5 and 1.0 and thermophilic F/M 0.5. The biogas production rate under thermophilic F/M 1.0 treatment was slower compared to the other treatments and took longer time of 15 days to reach 90% of their final biogas productions. This may be due to microbial inhibition from solubilized fats and grease from the meat products. Such a trend was evident for the soup processing, cafeteria, and commercial kitchen wastes.

Fish waste exhibited variable behavior under different treatment conditions (Figures 1d and 1i). Under mesophilic conditions, biogas production steadily increased up to day 12. After 12 days, treatments at F/M 1.0 showed continued rise in biogas and reached a biogas yield of (1.4±0.17) L/g VS, while at F/M 0.5 biogas production diminished after 12 days and reached a final biogas yield of (0.87±0.10) L/g VS. Since the biogas yield curve had an increasing trend, the biogas production potential of fish farm waste may be higher than the result shown in this study. Under the thermophilic conditions, seven day lag was observed in the batch digestion of fish waste, indicating inhibition to the microorganisms. After the initial lag phase, biogas production at F/M 0.5 sharply increased, reaching a final biogas yield of (1.2±0.05) L/g VS. This indicated the possible recovery of the methanogens that may be consuming the short chain acids. At F/M 1.0, biogas production also increased, however achieving a lower biogas yield of (0.71±0.01) L/g VS. The initial inhibition of the microorganisms in this study might be due to the high fat (146 mg/g) and protein content (83 mg/g) in the fish waste (Table 3). Carucci et al. stated that high lipid content of precooked food waste led to strong inhibition on unacclimated inoculums, but inhibition of methanogens could be overcome by a long acclimation periods of 70 days[6]. The results of this study showed that microbial inhibition was more under thermophilic conditions than under mesophilic conditions. Mshandete et al. studied batch anaerobic digestion of fish waste at 27℃ and different F/M ratio from 0.05 to 1.6 and for 29 days. The highest methane yield they obtained was 0.39 L/g VS, which was close to 0.5 L/g VS from this study under mesophilic temperature and F/M 0.5 for 28 days[8]. The difference may occur because of the different digestion temperatures.

Since the grease trap waste also had relatively high fat content, it was expected to behave similarly as the fish waste (Figure 1e and 1j). Under the mesophilic conditions and at F/M 0.5, biogas production readily increased in the first 10 days of digestion, reaching a final biogas yield of (1.42±0.05) L/g VS after 28 days. Whereas at F/M 1.0, biogas production exhibited a lag phase in the first 14 days of digestion; thereafter biogas production steadily increased reaching a final biogas yield of only (0.83±0.38) L/g VS, therefore showing incomplete digestion at the end of 28 days. The biogas yield was expected to keep increasing and eventually reach the same level of biogas yield at F/M 0.5 of (1.42± 0.05) L/g VS. The methane yield from mesophilic digestion at F/M 0.5 was calculated to be 0.97 L/g VS which was comparable to another study using grease trap waste as feedstock[9]. Davidsson et al[9] reported a methane yield of 0.84 L/g VS when grease trap waste was digested at mesophilic temperature and F/M of 0.38 for 16 days. From Figure 1e, cumulative biogas yield curve of mesophilic and F/M 0.5 at the 16th day was very close to Davidsson’s observation. Under thermophilic conditions, the initial lag phase was more severe than that experienced under mesophilic conditions. This might be due to higher temperature and/or higher loading rate resulting in faster biodegradation of fat and accumulation of VFAs in the digester. Consequently the methanogenic population was expected to take a longer time to recover. After 12 to 14 days of negligible biogas production, biogas production rose sharply for both F/Ms, and resulted in the final biogas yield of (1.2±0.04) L/g VS and (1.1±0.05) L/g VS for F/M of 0.5 and 1.0 were, respectively. Although the final biogas yields obtained under theromophilic conditions were similar to those obtained under mesophilic conditions at F/M of 0.5, the strong initial inhibition appeared under thermophilic conditions raised concerns. It appears that mesophilic conditions are better suited.

The digestion results of the grease trap and fish waste indicated that high F/M and temperatures could have an initial negative impact on the microbial population. However, after one to two weeks, the microbial populations acclimated to the prevailing conditions and biogas production commenced, usually with a sharp rise in production. These findings agreed with a report showing the negative impacts of oleic and stearic acids (long chain fatty acids commonly found in animal and vegetable fats) in thermophilic anaerobic digestion tests with cattle manure[7]. Thus the results from the mesophilic, F/M of 0.5 tests better predicts the potential biogas production of these food wastes.

Statistical analysis on cumulative biogas yields under different digestion conditions of each waste streams was performed in SAS-JMP 8 software using Tukey's HSD test with $\alpha = 0.05$. The results showed that for soup processing and cafeteria wastes, there were no significant difference between different reaction temperature and F/M. For commercial kitchen waste, the mesophilic F/M 1.0 and thermophilic F/M 0.5 were within the same statistical group and higher than the other two conditions. Thermophilic F/M 1.0 was lower than the above two but higher than mesophilic F/M 0.5. For fish farm waste, mesophilic F/M 1.0 and thermophilic F/M 0.5 were within the same group which was higher than the other group containing mesophilic F/M 0.5 and thermophilic F/M 1.0. Mesophilic F/M 0.5 was significantly higher than thermophilic F/M 0.5 and 1.0 for grease trap waste, and the lowest biogas yield for this waste stream was mesophilic F/M 1.0.

The methane contents of biogas of the five food waste streams under different F/M and temperature conditions are shown in Figure 2. For the soup processing, cafeteria, and commercial kitchen streams, the average methane contents were 52%, 52%, and 57% (Figure 2 a – c). For the fish waste under mesophilic and thermophilic conditions, the average methane contents were 64% and 62%, respectively (Figure 2d). For the grease trap waste, the average methane contents were 67% and 73% for mesophilic and thermophilic conditions, respectively (Figure 2e).

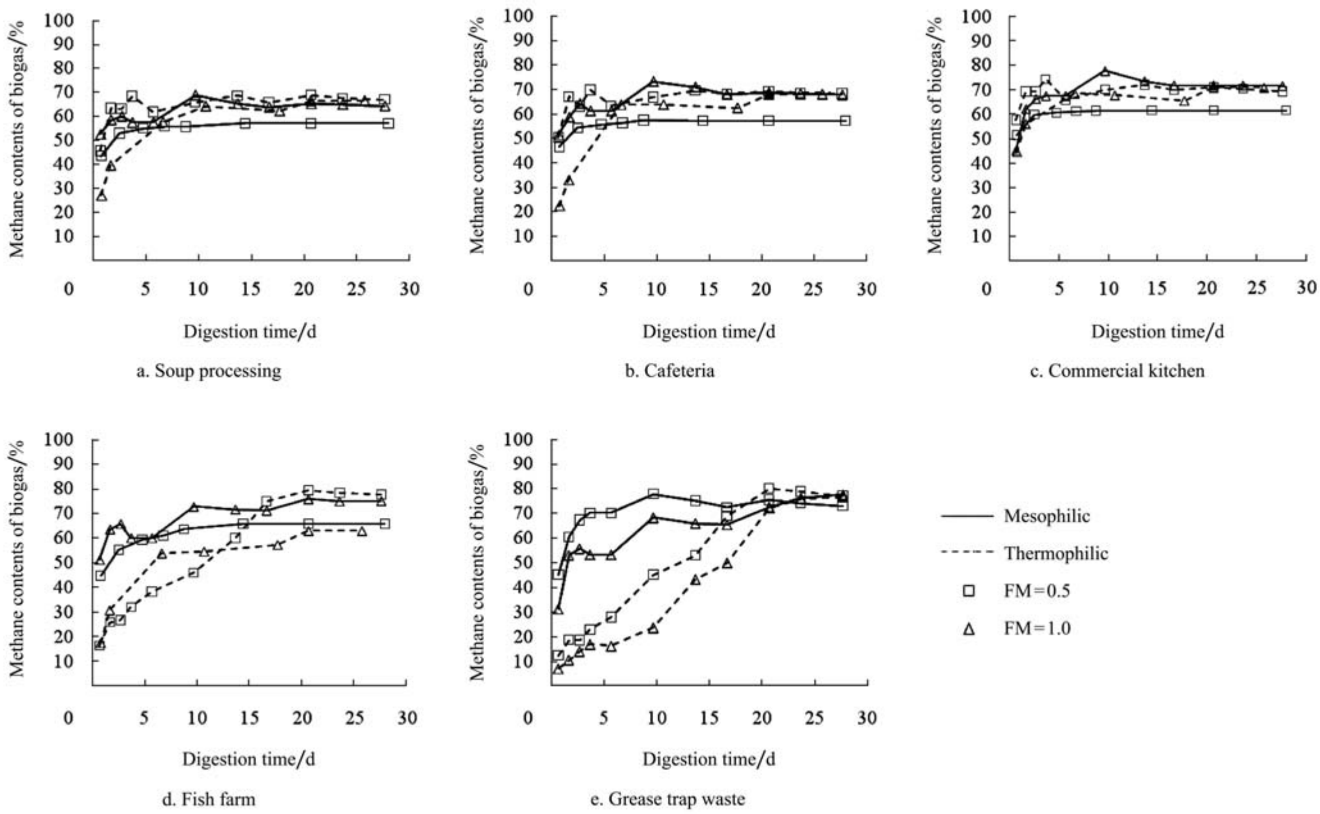


Figure 2 Methane contents of biogas produced from batch digestion of food wastes from (a) (b) (c) (d) (e)

The pH and VS in the batch digesters were measured at the end of the digestion period (28 days). Table 4 summarizes the results from the individual batch reactors under mesophilic and thermophilic conditions, respectively. Volatile solids reduction was corrected for the amount of VS reduced in the control digesters. VS reductions under mesophilic and thermophilic conditions were in the range of 73%–99% and 63%–95%, respectively, which is typical for anaerobic digestion of food waste[4,10].

Table 3 Batch anaerobic digestion results of individual food wastes after 28 days of digestion under mesophilic conditions and thermophilic conditions (standard deviation in parentheses, *n*=3)

Conditions	Parameter	Soup processing		Cafeteria		Commercial kitchen		Fish farm		Grease trap	
	F/M	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0
Mesophilic	Biogas yield/L・g^{-1} VS	0.53 (0.13)	0.57 (0.05)	0.69 (0.01)	0.66 (0.07)	0.60 (0.04)	0.75 (0.03)	0.87 (0.1)	1.33 (0.17)	1.42 (0.05)	0.83 (0.38)
	Methane yield/L・g^{-1} VS	0.25	0.32	0.32	0.36	0.34	0.45	0.51	0.92	0.97	0.55
	Biogas energy content/kJ・L^{-1}	16.80	20.05	16.47	19.67	17.51	21.46	21.09	24.67	24.33	23.62
	Methane content/%	47	56	46	55	49	60	59	69	68	66
	pH at the end of digestion	8.3	6.9	8.2	6.9	8.2	7.1	7.5	7.0	7.1	6.9
	VS reduction/%	80 (4.0)	88 (7.5)	87 (2.0)	80 (20)	83 (0.5)	97 (4.8)	81 (4.0)	82 (2.0)	99 (13.8)	73 (2.0)
Thermophilic	Biogas yield/L・g^{-1} VS	0.60 (0.08)	0.51 (0.02)	0.65 (0.07)	0.60 (0.06)	0.74 (0.1)	0.66 (0.17)	1.24 (0.05)	0.71 (0.01)	1.20 (0.04)	1.10 (0.05)
	Methane yield/L・g^{-1}VS	0.35	0.25	0.38	0.29	0.47	0.37	0.86	0.38	0.89	0.78
	Biogas energy content/kJ・L^{-1}	20.75	17.18	20.75	17.18	22.54	20.01	24.67	19.30	26.45	25.41
	Methane content/%	58	48	58	48	63	56	69	54	74	71
	pH at the end of digestion	7.7	7.3	7.7	7.3	7.7	7.4	7.9	7.4	7.8	7.3
	VS reduction/%	79 (3.9)	91 (3.4)	87 (13.2)	88 (1.2)	81 (6.8)	88 (1.0)	84 (6.4)	95 (1.5)	79 (17.8)	63 (32.7)

3.2.2 Batch digestion of mixed food wastes

For the five food waste mixture, the daily biogas production rates and cumulative biogas yields for the different treatments under mesophilic and thermophilic conditions are shown in Figure 3. Under mesophilic conditions biogas production rose steadily in the first seven days. The 90% of the total biogas yield was achieved within 11 days of digestion. After 28 days retention, the biogas yields for F/M 0.5 and F/M 1.0 were (0.95±0.01) L/g VS and (0.80±0.02) L/g VS, respectively. The higher biogas yield at F/M 0.5 is consistent with the results of the batch test from the individual digestion tests.

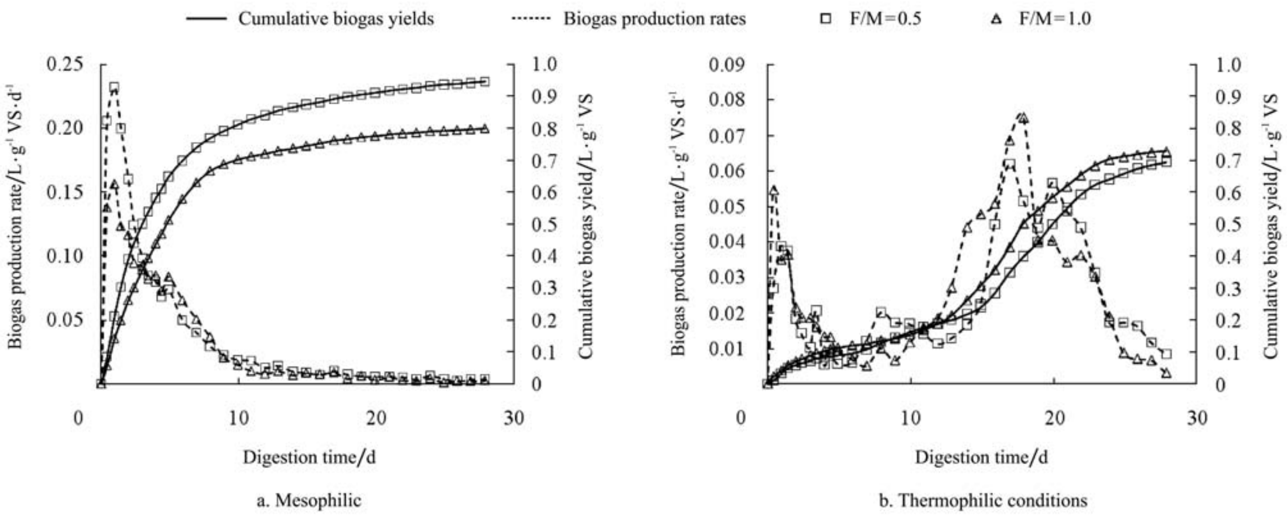


Figure 3 Cumulative biogas yields and biogas production rates from batch anaerobic digestion of mixed food wastes under (a) and (b)

For both F/Ms the biogas production rate was lower under thermophilic conditions compared to mesophilic conditions. This might be due to the negative effects of digesting the high fat content wastes (fish and grease trap) at thermophilic conditions. After 14 days of digestion biogas production rose sharply and 80% of the total biogas yield was achieved after 22 days. After 28 days, the biogas yields under thermophilic conditions at F/M 0.5 and F/M 1.0 were (0.69±0.08) L/g VS and (0.73±0.03) L/g VS, respectively, which were lower than the biogas yields under mesophilic conditions. The Tukey's HSD test with $\alpha = 0.05$ of batch digestion of mixed food wastes showed that mesophilic F/M 1.0, thermophilic F/M 0.5 and 1.0 were at the same level, which was lower than mesophilic F/M 0.5.

The methane content of the biogas from the mixed food waste stream under mesophilic and thermophilic conditions is shown in Figure 4. The average methane content of the biogas from the mesophilic reactors at F/M 0.5 and 1.0 were 62% and 59%, respectively. For thermophilic conditions, the methane content was low in the first seven days of digestion, and thereafter rapidly increased over 70% within 10 days. Therefore the average methane content of the biogas from the thermophilic reactors at F/M 0.5 and F/M 1.0 over the digestion period was 64% and 60%, respectively. This methane content trend correlates to the biogas yield curves (Figure 3b), demonstrating some inhibition under thermophilic conditions.

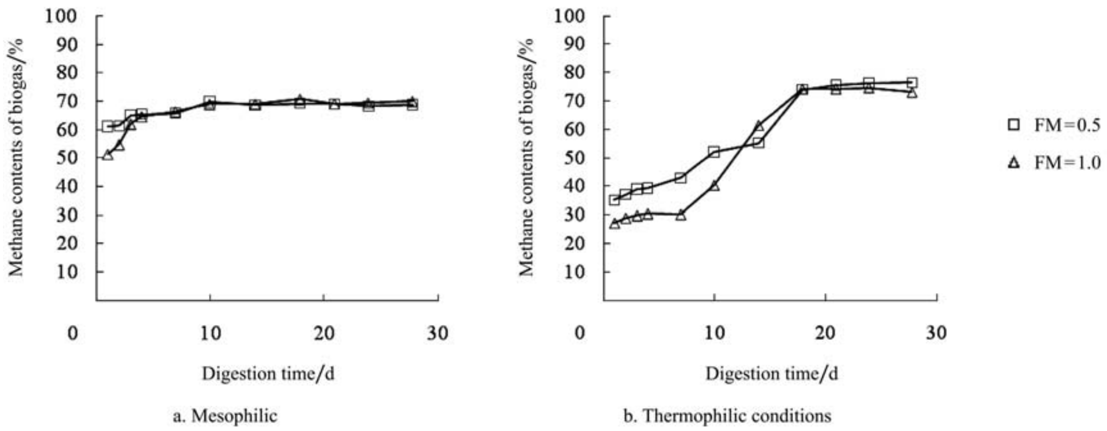


Figure 4 Methane content of the biogas produced from batch anaerobic digestion of mixed food wastes under (a) and (b)

Effluent pH and VS reduction at the end of the digestion period were measured and shown in Table 5 for mesophilic and thermophilic conditions. Volatile solids reduction was corrected for the amount of VS reduced in the control digesters.

Table 5 Biogas and methane yields of the mixed food waste streams after 28 days of mesophilic and thermophilic digestion (standard deviation in parentheses, *n*=3)

Parameter	Mesophilic		Thermophilic	
F/M	0.5	1.0	0.5	1.0
Biogas yield/L · g^{-1} VS	0.95 (0.01)	0.80 (0.02)	0.69 (0.08)	0.73 (0.03)
Methane yield/L · g^{-1} VS	0.59	0.47	0.44	0.44
Biogas energy content/kJ · L^{-1}	22.17	21.09	22.88	21.46
Methane content/%	62	59	64	60
pH at the end of digestion	7.2	7.0	7.8	7.4
VS Reduction/%	74 (7.6)	88 (2.5)	81 (2.0)	78 (29)

3.3 Results of continuous digestion experiments

Following the successful batch digestion of the mixed food waste under mesophilic conditions, continuous digestion test was conducted in a mesophilic single-stage continuous digester using the same food waste mixture (Table 1). HRT of the continuous digester was set to 20 days. The digester was initially fed at an OLR of 0.5 g VS/L/day. After the first nine days of continuous digestion the digester effluent pH began to gradually decrease from 7.0 to 6.4, indicating an accumulation of volatile fatty acids (VFAs) and likely inhibition of the methanogens[11]. To help the methanogens recover feeding to the system was stopped in an attempt to mitigate further accumulation of VFAs and increase digester pH.

After 10 days the digester had recovered, as indicated by digester pH 7.1. When operating a commercial digester, it would not be economically feasible to have frequent downtimes of 10 days or more. Another approach to prevent digestion failure due to accumulation of VFAs and low pH is to buffer the system with chemicals that can maintain digester alkalinity. Prior to resuming the continuous reactor, the digester alkalinity was adjusted to 2,500 mg/L $CaCO_3$ equivalent by adding NaOH, and the digester pH raised to about 8.5 (Figure 5). In order to maintain digester pH above 7.0 and alkalinity of 2,500 mg/L $CaCO_3$, 0.2 g NaOH was added per gram of the VS of the feed mixture (i.e. NaOH addition was 20% of feed by VS). Digester feeding resumed at 0.5 g VS/L/d with NaOH. Actual digester alkalinity was shown to be stable at about 2,300 mg/L $CaCO_3$.

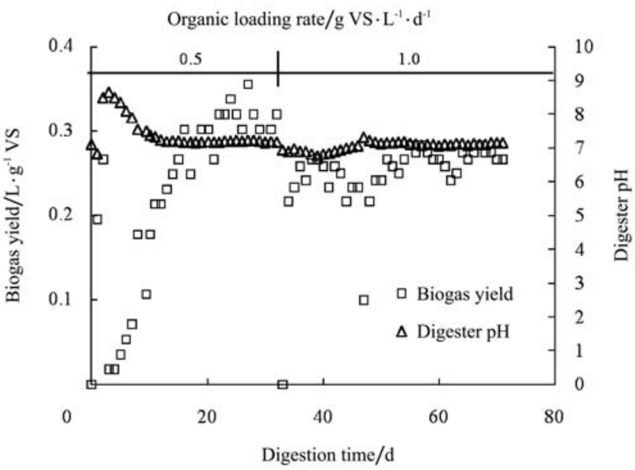


Figure 5 Biogas yield and digester pH for continuous anaerobic digestion of mixed food wastes under mesophilic conditions

The addition of NaOH allowed feeding to continue without failure as evidenced by the steady increase in biogas yield and digester pH being maintained above 7.0. From the 23rd to 32nd day of continuous digestion at an OLR of 0.5 g VS/L/day, biogas production was steady at (0.32±0.02) L/g VS and pH was stable at 7.2. During the last three days of continuous digestion at 0.5 g VS/L/day the methane content was 75.5% and volatile solids removal was 84%. The methane yield was calculated to be (0.24±0.04) L/g VS and the energy content of the biogas was 26.8 kJ/L. The OLR was increased to 1.0 g VS/L/day.

From the 61st to 70th day of digestion at 1.0 g VS/L/day, the biogas yield was steady at (0.27±0.01) L/g VS. Methane content of the biogas decreased to 68.1%, although the pH was stable at 7.13. Methane yield was (0.18±0.03) L/g VS and the energy content of the biogas was 24.3 kJ/L. However, VS reduction was measured to be 46%, indicating the possibility of microbial inhibition on the microorganisms. The results from the continuous digester are summarized in Table 6. The continuous digester was stopped because of the expiration of the project. However, the results of this project showed that it was necessary to add chemicals (NaOH) for controlling the digester pH when the food waste is digested in a single stage mixed digester. For commercial applications, the cost of chemicals and the proper management of salt (sodium) in the digester effluent need to be considered. Alternatively, to avoid or minimize the chemical use, co-digestion of food waste with other nutrient rich materials, such as animal manure and meat based products, will be desirable. In a study on the mesophilic continuous digestion of a mixture of industrial waste (including grease trap waste), pig manure, slaughter house waste, and restaurant waste (discarded vegetable and fruit products), Murto et al. was able to operate the digester at an OLR of 2.6 g VS/L/day with a 36 day HRT, and obtain the biogas and methane yields of 1.0 and 0.68 L/g VS, respectively[12].

Table 6 Measured parameters for the digester effluent and biogas at steady state from continuous digestion of food waste mixture (standard deviations are in parentheses, *n*=3)

Parameter	Organic Loading Rate (g VS/L/d)	
	0.5	1.0
Biogas production rate(L/L/d)	0.16(0.01)	0.27(0.01)
Biogas yield/L·g^{-1} VS	0.32(0.02)	0.27(0.01)
Methane content of biogas/%	75.5(3.0)	68.1(2.2)
Methane production rate(L/L/d)	0.24(0.04)	0.18(0.03)
Methane yield/L·g^{-1} VS	0.24(0.05)	0.18(0.03)
pH	7.2(0.1)	7.1(0.1)
VS reduction/%	84(7)	46(7)

4 Conclusions

Five different waste streams were successfully digested both individually and as a mixture in this study. Fish and grease trap wastes showed inhibition to the microorganisms during the initial period of batch digestion under thermophilic conditions, causing a one to two week lag phase in biogas production. Continuous digestion of the mixed food waste under mesophilic conditions was successful; however the addition of NaOH was necessary to control the pH value of the digester in order to operate the digester at the OLR of 0.5 and 1.0 gVS/L/day. For commercial applications, the cost of chemicals and the proper management of salt (sodium) in the digester effluent need to be considered. Alternatively, to avoid or minimize the chemical use, co-digestion of food waste with other nutrient rich materials, such as animal manure and meat based products, will be desirable.

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