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Characterization of food waste as feedstock for anaerobic digestion

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Abstract

Food waste collected in the City of San Francisco, California, was characterized for its potential for use as a feedstock for anaerobic digestion processes. The daily and weekly variations of food waste composition over a two-month period were measured. The anaerobic digestibility and biogas and methane yields of the food waste were evaluated using batch anaerobic digestion tests performed at 50 °C. The daily average moisture content (MC) and the ratio of volatile solids to total solids (VS/TS) determined from a week-long sampling were 70% and 83%, respectively, while the weekly average MC and VS/TS were 74% and 87%, respectively. The nutrient content analysis showed that the food waste contained well balanced nutrients for anaerobic microorganisms. The methane yield was determined to be 348 and 435 mL/g VS, respectively, after 10 and 28 days of digestion. The average methane content of biogas was 73%. The average VS destruction was 81% at the end of the 28-day digestion test. The results of this study indicate that the food waste is a highly desirable substrate for anaerobic digesters with regards to its high biodegradability and methane yield.

Keywords: Anaerobic digestion; Biodegradability; Biogas; Nutrients; Food waste

1. Introduction

Food waste is the single-largest component of the waste stream by weight in the United States – Americans throw away about 43.6 million tons of food each year (US EPA, 2002). The food waste includes uneaten food and food preparation leftovers from residences, commercial establishments such as restaurants, institutional sources like school cafeterias, and industrial sources like factory lunchrooms. According to a report published by California Integrated Waste Management Board (Carr, 2004), the amount of food waste generated in California was estimated in 1999 to be 5.6 million wet tons per year or 2.2 million dry tons per year. The food waste is, for the most part, disposed of in landfill. In light of rapidly rising costs associated with energy supply and waste disposal and increasing public concerns with environmental quality degradation, conversion of food wastes to energy is becoming a more economically viable practice. Food wastes can be highly variable depending on their sources. Some characteristics of food wastes that have been reported in the literature are shown in Table 1, indicating moisture content of 74–90%, volatile solids to total solids ratio (VS/TS) of 80–97%, and carbon to nitrogen ratio (C/N) of 14.7–36.4. The characteristic data of specific types of food leftovers can be found in the book authored by Miller and Clesceri (2003) and the paper by Steffen et al. (1998). Due to relatively high moisture content of food waste, bioconversion technologies, such as anaerobic digestion, are more suitable compared to thermochemical conversion technologies, such as combustion and gasification.

Anaerobic digestion has been widely applied for treatment of organic wastes that are easily biodegradable

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Table 1
Characteristics of food wastes reported in literature

Source	Characteristics			Country	Reference
	MC (%)	VS/TS (%)	C/N		
A dining hall	80	95	14.7	Korea	Han and Shin (2004)
University's cafeteria	80	94	NA[a]	Korea	Kwon and Lee (2004)
A dining hall	93	94	18.3	Korea	Shin et al. (2004)
A dining hall	84	96	NA	Korea	Kim et al. (2004)
Mixed municipal sources	90	80	NA	Germany	Nordberg and Edstrom (1997)
Mixed municipal sources	74	90–97	NA	Australia	Steffen et al. (1998)
Emanating from fruit and vegetable markets, household and juices centers	85	89	36.4	India	Rao and Singh (2004)

[a] NA – not available.

(Ten Braummeler, 1993). Many factors affect the design and performance of anaerobic digestion processes. Some of them are related to feedstock characteristics, reactor design and operation conditions (Hawkes, 1980; Fischer et al., 1986). The physical and chemical characteristics of the organic waste are important information for designing and operating anaerobic digesters, because they affect biogas production and process stability during anaerobic digestion. They include, but not limited to, moisture content, volatile solids content, nutrient contents, particle size, and biodegradability. The biodegradability of a feedstock is indicated by biogas or methane yield and percentage of solids (total solids or volatile solids) that are destroyed in the anaerobic digestion. The biogas or methane yield is measured by the amount of biogas or methane that can be produced per unit of volatile solids contained in the feedstock after subjecting it to anaerobic digestion for a sufficient amount of time under a given temperature. Cho and Park (1995) determined the methane yields of different food wastes at 37 °C and 28 days of digestion time. They were 482, 294, 277, and 472 mL/g VS for cooked meat, boiled rice, fresh cabbage and mixed food wastes, respectively, which correspond to 82%, 72%, 73% and 86% of the stoichiometric methane yield, respectively, based on elemental composition of raw materials. Heo et al. (2004) evaluated the biodegradability of a traditional Korean food consisted of boiled rice (10–15%), vegetables (65–70%), and meat and eggs (15–20%) and reported that after 40 days a methane yield of 489 mL/g VS could be obtained at 35 °C. Extensive literature search showed that little information is available on the biodegradability of mixed food waste under thermophilic conditions.

The objectives of this study were to characterize the food waste collected from commercial restaurants in San Francisco, CA, for assessing their potential as a feedstock for a thermophilic anaerobic digester and to determine the overall variability and consistency of this material over time. Currently, approximately 200 tons of food waste was collected each day by a waste management company and sent to a composting facility. This study was initiated to examine the feasibility of converting the food waste into biogas energy.

2. Methods

2.1. Characterization of food waste

The food waste was provided by a waste management company in northern California. It was collected from the City of San Francisco and was separated and processed at a transfer station. The food waste streams were sampled and analyzed with the procedures described as follows.

2.2. Food waste collection and analyses

The food waste was collected as source-separated food waste from five selected routes that covered 500 sources, which included 300 restaurants, 50 food markets (grocery stores), and 150 commercial sources (hotels and businesses). Each route was initially selected based on estimates of organic content by operation personnel of the waste management company. Since the food waste as collected from original sources (restaurants) contained considerable impurities, such as wood, metal, cardboard, glass and plastics, a screening and grinding operation previously developed by the waste management company was used to prepare the food waste for anaerobic digestion. The raw waste was screened to remove the coarse contaminants and then ground in a hammer mill for size reduction. Due to the confidentiality concerns from the waste management company, the details about the screening and grinding operation can not be disclosed here. At each sampling, the ground food waste samples were approximately 200 g (wet weight) were taken at 15-min intervals from the grinder discharge belt and later mixed into one large sample, stored over ice (at 0 °C), and delivered to the Bioenvironmental Engineering Research Laboratory at University of California, Davis for analyses.

To gain an understanding of the compositional variability of the food waste, daily and weekly sampling was performed. Samples were initially taken on five days (Monday through Friday) of one week and then were taken on every Tuesday for a period of eight weeks. Since the food waste was only collected on weekdays, no sampling was performed on the weekend. All collected food waste samples were analyzed for total solids (TS) and volatile solids (VS) contents according to the standard methods of American Public Health Association (APHA, 1998), and also contents of various nutrients and metals was measured by DANR Analytical Laboratory, UC Davis (http://danranlab.ucanr.org/). The methods used by DANR Laboratory are those described by Carlson (1978) for total Kjeldahl nitrogen (TKN), Switala (1999) and Wendt (1999) for ammonium-nitrogen (NH_4-N) and nitrate-nitrogen (NO_3-N) and Diamond (1994) for chloride (Cl) and Sah and Miller (1992) for other elements.

2.3. Anaerobic digestion tests

The biodegradability of food waste was determined using batch anaerobic digestion tests as described in Anaerobic Lab Work (1992). Digestion tests were performed on composite food waste samples prepared from the food waste samples collected from the weekly samplings. The composite samples were prepared by mixing all food waste samples and then taking representative samples from the mixture. The composite samples were digested in four 1-L batch digesters at two initial VS loadings (6.8 and 10.5 g VS/L), each in duplicate, and at a thermophilic temperature (50 ± 2 °C). The effective volume of each digester was 0.5 L. At the beginning of the digestion tests, in each digester, 150 mL of bacterial inocula was mixed with food waste at an amount determined from the initial VS loading and the VS content of the food waste. The inoculum was anaerobic sludge collected from a thermophilic anaerobic digester at a municipal wastewater treatment plant in Oakland, California. It had average TS and VS/TS values of 2.56% (w.b.) and 50.84%, respectively.

After the inoculum and food waste were added, each digester was filled up to 500 mL with tap water. The digesters were tightly closed with a rubber septa and a screw cap. To assure the anaerobic conditions, the head space was purged with helium gas for five minutes. Two blank digesters that contained inoculum only were also incubated at the same temperature to correct for the biogas produced from the inoculum. Each blank digester contained the same amount of inoculum and was filled up to 500 mL with tap water. All the digesters were incubated for a time period until little if any biogas was produced (see Fig. 3). Each digester was manually mixed once a day.

2.4. Biogas measurements

Daily methane production from each digester was measured by using a water displacement set up after the biogas passed through a Mariotte flask containing 5% NaOH solution (Anaerobic Lab Work, 1992). Biogas samples were taken periodically from the gas collection lines prior to the flask and analyzed for CH_4 and CO_2 using gas chromatography (Hewlett Packard 5890A, USA) equipped with a thermal conductivity detector. A 1.8 m × 0.32 mm Alltech carbospher column was used and helium was the carrier gas. Column head pressure was maintained at 350 kPa. The temperatures of oven, injector port and thermal conductivity detector were 100, 120 and 120 °C, respectively. A gas standard consisting of 60% (v/v) CH_4 and 40% of CO_2 was used for gas chromatography calibration. Each gas chromatography analysis was run in duplicates. The measured methane volume was adjusted to the volume at standard temperature (0 °C) and pressure (1 atm).

2.5. Statistical analysis

One way ANOVA was used to examine the significance of the daily and weekly differences of food wastes compositions. To compare the average concentrations, Fisher's least significant difference (Fisher's LSD) was calculated at $t = 0.01$ and $t = 0.05$. Student's t-test was used to compare the methane yield from the two initial VS loadings tested. Both statistical methods were performed using Excel software.

3. Results and discussion

3.1. Characteristics of food waste

The average MC, VS, and VS/TS of daily food waste samples are shown in Fig. 1 together with standard deviations as indicated by the Y error bars. All the values for MC and VS are reported on wet weight basis. The MC ranged from 66% to 73%. The statistical analysis showed no significant differences between the week days in MC, VS and VS/TS at $\alpha = 0.01$, which was chosen based on the practical relevance of this study. The P values from ANOVA analysis were 0.015, 0.179, and 0.116 for MC, VS, and VS/TS, respectively. The average MC over the week days was calculated to be 70%. Thus it can be concluded that the VS remained fairly constant at an average of 25%. The VS/TS was relatively high, favoring anaerobic conversion, and was rather constant, 84–87%, except for Monday's sample where 70% was measured.

The weekly variations in MC, VS and VS/TS of the food waste samples tested are shown in Fig. 2 with the standard deviations are indicated by the Y error bars. The averages of MC, VS and VS/TS were 74%, 23% and 87%, respectively, for all studied weeks. The statistical analysis showed significant differences in the weekly data of MC and VS but did not show significant differences in VS/TS data at $\alpha = 0.01$. The P values from ANOVA analysis were 0.00056, 0.000064, and 0.1857 for MC, VS, and VS/TS, respectively. There was a significant difference between each pair of weeks for MC and VS based on the calculated Fisher's LSD values (Table 2). The VS differences are caused by MC differences, which may be attributed to the weather changes during the time of sampling. The range of MC was 68–80%, showing that the food waste contained sufficient moisture for anaerobic digestion. The range of VS was 16–27%, showing the expected variation change of 17–30% based on the average VS, which could indicate similar change in the weekly biogas production of an anaerobic digester if it is

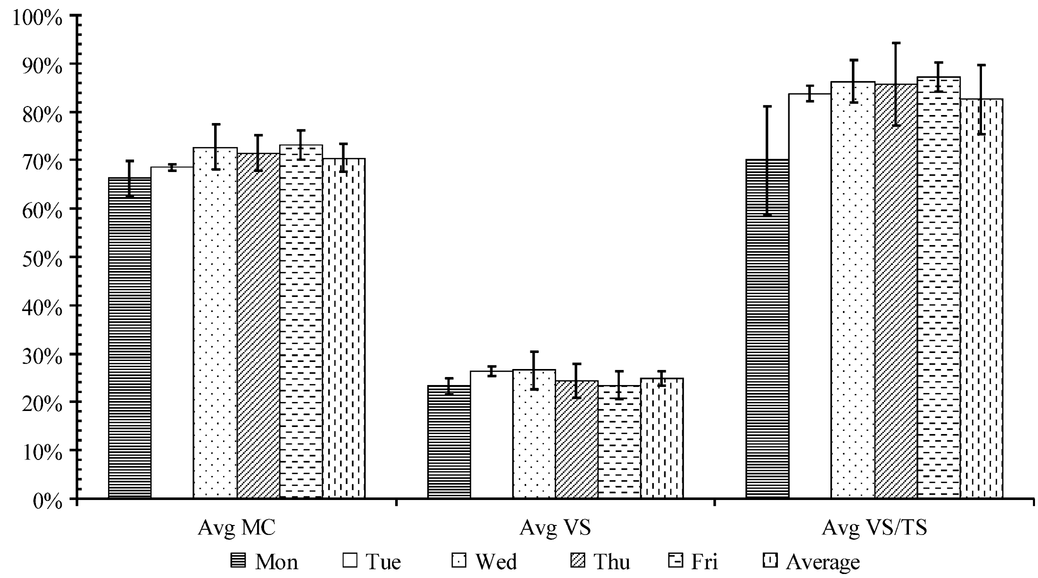

Fig. 1. Daily average MC, VS and VS/TS of food waste with the standard deviations as indicated by *Y* error bars. The values of MC and VS are on a wet weight basis.

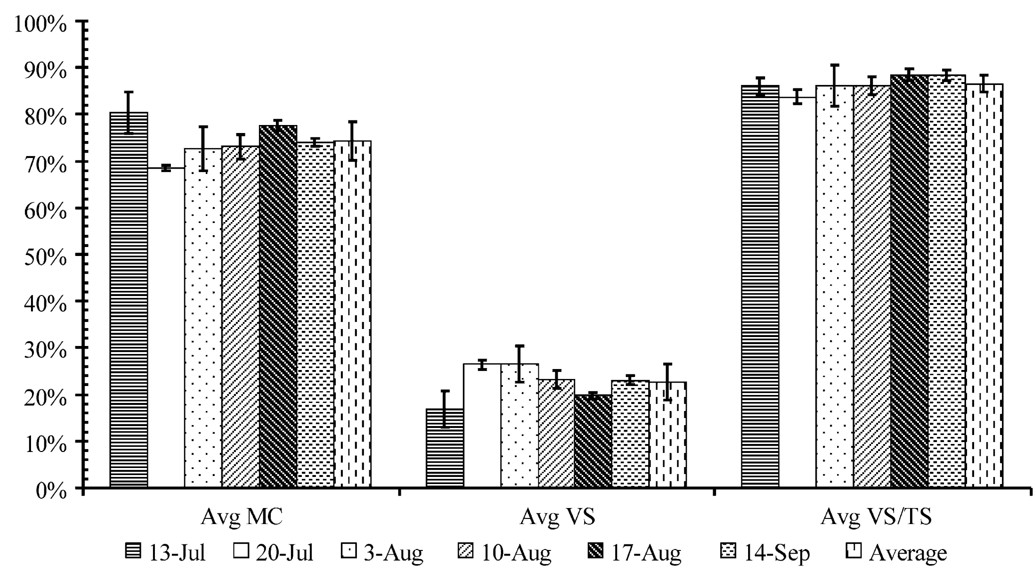

Fig. 2. Weekly average MC, VS and VS/TS of food waste. *Y* error bars show the standard deviations. The values of MC and VS are on a wet weight basis.

Table 2
Significance of MC and VS weekly averages pairs based on Fisher's LSD

	20-July	3-August	10-August	17-August	14-September
13-July	MC**/VS**	MC**/VS**	MC**/VS**	NS[a]	MC**/VS**
20-July		MC*	MC*/VS*	MC**/VS**	MC**/VS*
3-August			VS*	MC**/VS**	VS**
10-August				MC*/VS*	NS[a]
17-August					MC*/VS*

[a] Non-significant differences.
* Significant differences (Fisher's LSD was calculated at $t = 0.05$).
** Very significant differences (Fisher's LSD was calculated at $t = 0.01$).

operated on the food waste alone. The measured values of MC and VS/TS are in the range of the values reported in the literature for food waste (Table 1).

The contents of various nutrient elements in the food waste are shown in Table 3. Macro and micronutrients were balanced for anaerobic microorganisms. Since the

Table 3
Elemental composition of food waste examined in this study

Components	Unit	Average value (standard deviation)
Total solids (TS)	% (w.b.)	30.90 (0.07)
Volatile solids (VS)	% (w.b.)	26.35 (0.14)
Fixed solids (FS)	% (w.b.)	4.54 (0.21)
VS/TS	%	85.30 (0.65)
C (Total)	% (d.b.)	46.78 (1.15)
N (Total)	% (d.b.)	3.16 (0.22)
P (Total)	% (d.b.)	0.52 (0.08)
K	% (d.b.)	0.90 (0.11)
Ca (Total)	% (d.b.)	2.16 (0.29)
Mg (Total)	% (d.b.)	0.14 (0.01)
S (Total)	ppm[a]	2508 (87)
NH_4-N	ppm	973 (571)
NO_3-N	ppm	118 (80)
Al	ppm	1202 (396)
Fe (Total)	ppm	766 (402)
B (Total)	ppm	12 (1)
Zn (Total)	ppm	76 (22)
Mn (Total)	ppm	60 (30)
Cu (Total)	ppm	31 (1)
Cd	ppm	<1
Cr	ppm	3 (1)
Pb	ppm	4 (3)
Ni	ppm	2 (1)

[a] *Note*: Based on wet base.

total concentration of each of these nutrients will not change significantly during the digestion (Lusk, 1998), the digester effluents would provide the essential elements for plant growth if they are used as organic fertilizers. The C/N ratio of the food waste was 14.8 and sulfur (S), calcium (Ca) and magnesium (Mg) contents were, on wet weight basis, 0.25%, 2.16% and 0.14%, respectively. The ammonia concentration was 973 ppm. In addition, metals and other microelements were also found with aluminium (Al) and iron (Fe) being the predominant metals.

3.2. Anaerobic digestion tests

The characteristics of food waste used in the anaerobic digestion experiments are shown in Table 3, with data given as the average of duplicates. Standard deviations are shown in parentheses.

3.2.1. Methane production

The methane yield (mL/g VS) and methane production rate (mL/L.d) during the digestion of food waste are shown in Figs. 3 and 4, respectively. Methane production increased until day 16, and then remained almost constant at a low level until the end of experiments (28 days). The average methane yield from the digesters with 6.8 and 10.5 g VS/L initial loadings after 28 days of digestion was approximately 425 and 445 mL/g VS added, respectively, with their average being 435 mL/g VS. Essentially, there was no significant difference in the methane yield ($P = 0.303$) between the two different initial loadings. Approximately 80% of the methane yield was obtained after the first 10 days of diges-

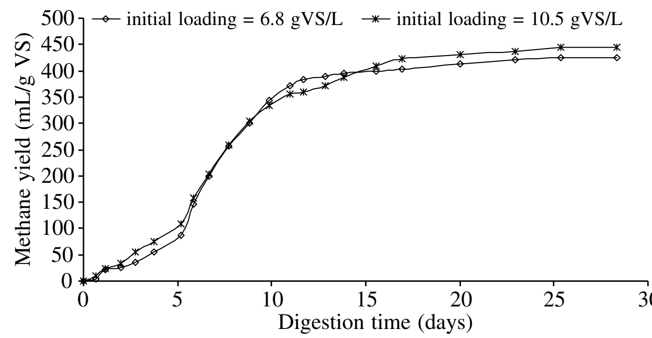

Fig. 3. Methane yield of food waste during anaerobic digestion at 50 °C at two different initial loadings (6.8 and 10.5 g VS/L).

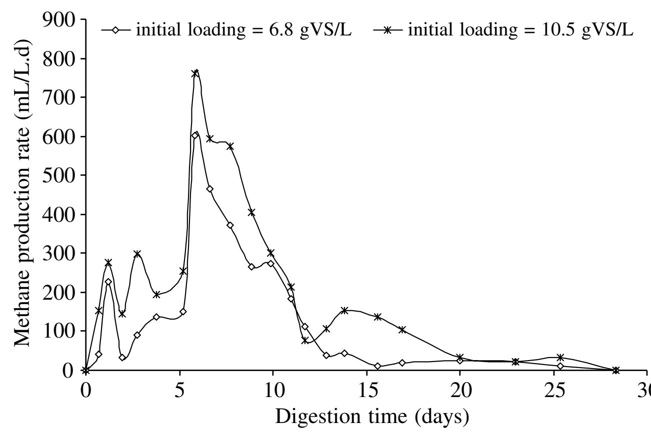

Fig. 4. Daily methane production during digestion of food waste at two different initial loadings (6.8 and 10.5 g VS/L).

tion. The methane yield obtained in this study was lower than the values reported by Cho and Park (1995), who obtained 472 mL/g VS at 37 °C and 25 days and Heo et al. (2004), who obtained 489 mL/g VS at 35 °C and 40 days. It should be mentioned that the VS/TS of the food waste tested by Cho and Park (1995) was 95%, which is higher than the VS/TS of the food waste tested in this study. Steffen et al. (1998) reported the biogas yield from food waste to be 480 mL/g VS but did not indicate the methane content of biogas and also did not provide the digestion conditions. If the same methane content of biogas of this study, 73%, were assumed, their methane yield would be 350 mL/g VS, which is lower than the yield obtained in this study.

As shown in Fig. 4, the methane production rate was relatively low during the first five days of digestion, increased to reach a peak at the sixth day of digestion, and then declined again. The maximum methane production rates of about 602 and 762 mL/L.d could be achieved for the digesters started at 6.8 g VS/L and 10.5 g VS/L initial loadings, respectively. However, during the increasing period (ca. day 2 to day 11), the average methane production rate per g of VS was almost the same for both starting initial loadings. This was deduced from plotting the data of methane yield (Y) against digestion time (X) and estimating the slopes of the straight lines which represent the average methane production rates for each gram of VS during that period. The equations obtained were

For 6.8 g VS/L initial loading, $Y = 31.032X$, $R^2 = 0.8858$.
For 10.5 g VS/L initial loading, $Y = 31.309X$, $R^2 = 0.9322$.

Thus the calculated average methane rates during that period were 31 and 31 mL/g VS.d at 6.8 and 10.5 g VS/L initial loadings, respectively. This may suggest that the anaerobic sludge used in the experiments had high methanogenic activity.

3.2.2. Biogas composition

The biogas composition during digestion of food waste at two initial loadings is shown in Fig. 5. Almost constant methane content was obtained under each initial loading. However, the biogas produced from the digesters of lower loading had higher methane content compared with the digesters that had higher initial loading. The average CH_4 and CO_2 contents that were measured to be 73% (v/v), and 27%, respectively. Thus, an average energy content of 27.2 MJ/m^3 could be estimated for the biogas produced from food waste based on 73% methane content and 37.3 MJ/m^3 energy content of methane. The average values and standard deviations of the biogas composition are shown in Table 4. The biogas yield from food waste was calculated to be 465.4 m^3 of biogas per ton of dry material. At the end of the digestion experiments, the VS destructions were 81% and the pH was 7.57.

The biogas composition obtained in this study is comparable to those obtained by Wang et al. (2005) who studied the anaerobic batch digestion at 35 °C of food waste using laboratory and pilot-scale hybrid solid–liquid anaerobic digesters. Their results showed that the methane contents of the biogas produced were 71% and 72%, respectively. The total VS destruction for food waste after digestion was 77% and 78% after 10 and 25 days of digestion, respectively.

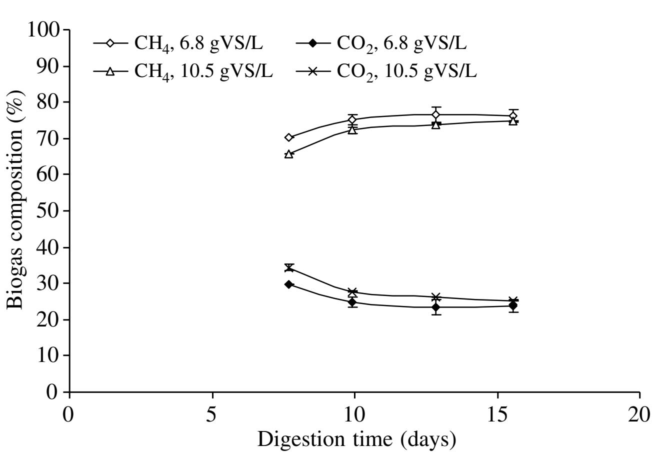

Fig. 5. Biogas composition during food waste digestion at two different initial loadings (6.8 and 10.5 g VS/L).

Table 4
Average biogas and methane yields and biogas composition for food waste

Parameter	Unit	Average value (standard deviation)
Average methane content	%	73.14 (3.64)
Average carbon dioxide content	%	26.86 (3.64)
VS destruction	%	80.57 (3.1)
Average pH at the end of digestion	–	7.57 (0.13)
Methane yield	L/g VS	0.44
	m^3/ton (d.w.)[a]	340.38
	m^3/ton (w.w.)[b]	105.18
Biogas yield	L/g VS	0.6
	m^3/ton (d.w.)	465.39
	m^3/ton (w.w.)	143.80

The numbers between brackets are standard deviations.
[a] d.w. – dry weight.
[b] w.w. – wet weight.

4. Conclusions

The daily average values of MC and VS/TS of the food waste collected over a one-week sampling period were 70% and 83%, respectively, and the weekly average values from the eight-week sampling period were 74% and 87%, respectively. There were no significant differences among the week days in MC, VS, and VS/TS. There were significant differences in MC and VS for the weekly data but there were no significant differences in VS/TS. The nutrient contents of food waste indicate that food waste contained the required nutrients for anaerobic microorganisms. On average, food waste had C/N of 14.8. The results of the anaerobic digestion tests showed that food waste had average methane yields of 435 mL/g VS after 28 days of digestion at 50 ± 2 °C. About 80% of the methane yield was obtained after the first 10 days of digestion, giving a methane yield of 348 mL/g VS. The methane accounted for 73% of the biogas produced. In conclusion, the food waste was a highly desirable feedstock for anaerobic digestion.

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