



CALIFORNIA  
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# Anaerobic Phased Solids Digester Pilot Demonstration Project

## Characterization of Food and Green Wastes As Feedstock for Anaerobic Digesters

CONTRACTOR REPORT

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## **Acronyms / Abbreviations**

AMPY	=	average accumulated methane production yield
APS	=	anaerobic phased solids
COD	=	chemical oxygen demand
FPW	=	food processing wastes
ft <sup>3</sup>	=	cubic foot
GW	=	green wastes
MC	=	moisture content
MFW	=	mixed food wastes
MPR	=	methane production rate
° C	=	degree Celsius
STP	=	standard temperature and pressure
TS	=	total solids
UC	=	University of California
VFA	=	volatile fatty acids
VS	=	volatile solids
HRT	=	hydraulic retention time

## **Abstract**

In order to select the proper operating conditions and assess the performance of an anaerobic digester, it is important to analyze the characteristics of an organic feedstock. In this study, food and green wastes were characterized daily and weekly, and digestability was tested. The green wastes were collected from the City of Vacaville, California, and surrounding areas over a period of four months (July to October) and passed through a mesh screen to remove large particles. Based on the analysis of bi-weekly samples, the green wastes had an average moisture content (MC) of 65% and an average volatile solids to total solids ratio (VS/TS) of 78%. The food wastes were collected from the City of San Francisco over a two-month period (July and August) and they were ground and passed through a mesh screen screening. The daily average MC and VS/TS determined from a week-long sampling were 70% and 83%, respectively, while the weekly average MC and VS/TS determined from sampling over an eight-week period were 74% and 87%, respectively. The results showed that the composition of both food and green wastes varied minimally on a daily and weekly basis. The nutrient content analysis showed that both green and food waste contained well balanced nutrients for anaerobic microorganisms.

The biodegradability and biogas and methane yields of food and green wastes were determined using batch anaerobic digestion tests performed at 50°C. After 10 and 28 days of digestion, food waste showed a methane yield of 338 and 435 mL/gVS respectively, and green waste showed 202 and 226 mL/gVS. The average VS destruction was 80.57% for food waste and 79.30% for green waste at the end of the 28-day digestion test. Moreover, biogas yields were 5078 and 2862.5 ft<sup>3</sup>/ton of food and green wastes with average methane contents of 73% and 55 %, respectively. Based on the sources of food and green wastes, it is expected that the biodegradability of food waste will be relatively consistent throughout the year but the biodegradability of green waste could have seasonable variation. The results of this study on the green waste would well represent the characteristics of green waste in the summer and early fall. Further study is needed for charactering the green waste generated in other seasons. These results support the UC Davis pilot digester project funded by California Energy Commission.

## **1. Introduction**

Many technologies are currently used for treatment of food and green wastes. To choose a certain technology for waste treatment, the characteristics of the feedstock should be considered. Anaerobic digestion is widely applied for treatment of organic wastes that are easily biodegradable and have relatively high moisture contents. Recently, it is also applied to materials of low moisture contents (Ten Braummeler, 1993).

From a pollution control standpoint, green (GW) and food (FW) wastes are not hazardous wastes but the large volume produced takes up valuable landfill space (Thassitou and Arvanitoyannis, 2001). The physical and chemical characteristics of the food and green wastes are important information for designing and operating anaerobic digesters for biogas generation. According to Kroyer (1995), there are some common characteristics of

food wastes: (1) large amounts of organic materials such as proteins, carbohydrate and lipids, (2) high concentrations of chemical oxygen demand (COD) and nitrogen, and (3) high variations in pH. The feedstock composition is one of major factors that affects biogas production and process stability during digestion. Biodegradability is an important design parameter for anaerobic digesters. It determines the maximum amount of methane that can be produced from a feedstock after subjecting it to anaerobic digestion for sufficient digestion time. It can also be a good indication of the degradation rate of particulate organic substrates. The rate and extent of digestion dramatically depends on the composition of the feedstock. According to Veeken and Hamelers (1999), wastes collected indoors are largely comprised of non-lignocellulosic food remainders while those collected outdoors are mainly composed of lignocellulosic plant materials. The former generally degrade easily and quickly.

Chao et al (1995) assessed the biochemical methane potentials of different food wastes at 37°C and 28 days of digestion time. The ultimate methane yields were 482, 294, 277, and 472 L/ kg VS for cooked meat, boiled rice, fresh cabbage and mixed food wastes (MFW). Based on elemental composition of these food wastes, the values of anaerobic biodegradability were, respectively, 82, 72, 73 and 86 % of the stoichiometric methane yield. Gunaseelan (2004) determined the biochemical methane potential of 54 fruits and vegetable wastes samples and eight standard biomass samples at 35°C and 100 days of digestion time. His data revealed that little, if any, methane was collected during the period from day 30 to day 100. The ultimate methane yields ranged from 180 to 732 and 190 to 410 L/kgVS for fruit and vegetable wastes, respectively. For sorghum, the methane yield ranged from 228 to 538 L/kgVS for roots and inflorescence with grains respectively while for Napier grass, the methane yield ranged from 342 to 419 L/kgVS for sheath and microcrystalline cellulose, respectively.

To study the performance of an anaerobic phased digester system (APS-Digester) and support the UC Davis pilot digester project funded by California Energy Commission, short and long-term characterization of the feedstock is required. The main objective of this study was to characterize the proposed feedstock, preprocessed green and food wastes, and to determine the overall variability and consistency of these materials over time. According to the requirement of APS-Digester system design, thermophilic temperature was used for anaerobic digestion tests. The extensive literature search showed that there is a scarcity of information concerning the biodegradability of food and green waste under thermophilic conditions.

## **2. Materials and Methods**

### **2.1. Characterization of Fresh and Green Wastes**

The food and green wastes studied in this project were provided by Norcal Waste Systems, Inc. who operates a composting facility in Dixon, CA and processes over 200 tons of food and green wastes daily. The food waste was collected from the City of San Francisco and was separated and processed at a transfer station. The green waste was collected from the City of Vacaville and surrounding areas and processed at the

composting facility. The food and green waste streams were sampled and analyzed with the procedures described as follows.

### **2.1.1. Food waste**

The food waste material is currently collected and processed in San Francisco before being sent to Norcal's Hay Road facility for composting or the East Bay Municipal Utility District (EBMUD) digesters for treatment and disposal. Collection and handling operations include the normal daily pickup of source-separated material from commercial routes within the city. Currently five routes each day have been included in this study. Each route was initially selected based on estimates of organic content by operations personnel. The material was dropped off at a transfer station in San Francisco where it was first pre-screened to remove the coarse contaminants (wood, metal, cardboard, glass, plastics, etc.). The larger material ("overs") passed over the screen and was conveyed to a truck for transport to a landfill facility. The material that passed through the screen ("unders") was sent to a grinder for final size reduction before loaded onto a truck and transported to the anaerobic digesters of EBMUD.

Initial comparison testing was conducted and resulted in nearly identical findings between the two sources, ground and un-ground. The un-ground material tested was collected from the under-drum conveyor as it fell onto the discharge belt. A scoop shovel was used to collect the material before it left the screen, and several small samples, collected periodically, were mixed in a 5-gallon bucket to form a single composite sample. The ground samples were pulled at periodic intervals (15 minutes) from the grinder discharge belt and placed in separate zip-lock bags, put on ice, and delivered to the Bioenvironmental Engineering Research Lab at UC Davis for testing.

In order to assess the ability of the APS-Digester to produce a relatively constant gas production, an understanding of the feedstock variability is required. Daily and weekly variations were studied. Samples were initially collected at 15 minute intervals, from each day of the week (Monday through Friday) and then one day (Tuesday) was selected as a representative day of the week, and samples were taken on that same day of the week for a period of 8 weeks.

### **2.1.2. Green Waste**

Samples of green waste were obtained from the composting facility of Norcal Waste Systems, Inc., in Dixon, CA. The green waste was collected from urban areas in and near Vacaville. The collected green waste was first processed through a screen of 4 in. openings to separate grasses and similar materials from the large materials. Samples were taken from the materials that passed the screened and transported to the laboratory at UC Davis for analysis. Bi-weekly samples were taken over a four-month period from July to October, 2004 with an attempt to determine the variation, as well as average values, in the characteristics of sieved green waste.

### 2.1.3 Analysis

The Total Solids (TS) and Volatile Solids (VS) contents were measured according to the standard methods. The nutrients contents were measured according the standard methods in DANR Analytical Laboratory (<http://danranlab.ucanr.org/>). Figure (1) shows the main components of a specific waste, moisture and total solids. The TS contains VS and ash (fixed solids, FS)

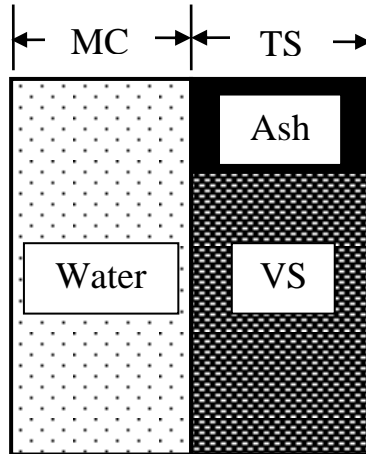


Figure 1. Main components of a specific waste: not in a scale

## 2.2. Anaerobic Digestion Tests

### 2.2.1. Equipment and Method

Batch digesters are the common systems used to assess the anaerobic biodegradability of different materials. These systems are simple both in design and operation and therefore very attractive (Lettinga, 2001). These systems start with a certain amount of digestate (i.e. inoculum), which should be taken directly from a running reactor and then the substrate to be digested is added with the inoculum at the beginning. Afterwards anaerobic conditions are maintained until the depletion of the available substrate (i.e. end of the digestion).

Batch anaerobic digestion tests were performed in duplicate using 1-L anaerobic reactors at thermophilic temperature ( $50^{\circ}\text{C} \pm 2$ ). The effective volume of each digester was 500 ml. In the beginning of the tests, 150 ml of inoculum (seed bacterial culture) were mixed with a certain amount of food or green waste. Two different initial loadings of food waste were studied: 6.8 and 10.5 gVS/L

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. 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 with tap water until 500 ml. All the digesters were incubated for a time period until little if any biogas was produced (Figures 5 and 7). Mixing was provided once a day.

### **2.2.2. Inoculum**

The thermophilic inoculum used in the digestion tests was anaerobic sludge collected from a thermophilic anaerobic digester at East Bay MUD in Oakland, California. The inoculum used in the food waste digestion experiments had average TS and VS/TS of 2.56% and 50.84%, respectively, while the inoculum used in green waste digestion had average TS and VS/TS of 3.40 % and 61.0 %, respectively. It should be mentioned that the lower TS and VS/TS for the first inoculum might be due to the storage of the sludge without feeding for about two weeks at 50 °C.

### **2.2.3. Gas Measurements**

Daily biogas production from each anaerobic digester was measured and biogas composition (CH<sub>4</sub> and CO<sub>2</sub> contents) was measured periodically (see Figures 4 and 5) using gas chromatography (GC). The measurements were duplicated for each digester. Biogas production was adjusted to standard temperature (0°C) and Pressure (STP) (1 atm).

## **3. Results and Discussion**

### **3.1. Characteristics of Food Wastes**

The average MC, VS, and VS/TS of daily samples of food waste are shown in Figure 2 together with standard deviations as indicated by the Y error bars. The MC of food waste ranged from 66% to 73%. Taking into consideration the standard deviation, it can be deduced that the MC is almost constant over five days of the week, with an average value of 70%. Similarly, VS remained fairly constant at an average of 25%. The VS/TS was relatively high, which favors anaerobic conversion. For all the samples VS/TS was rather constant, 84-87%, except for Monday's sample where an average ratio of 70% was measured.

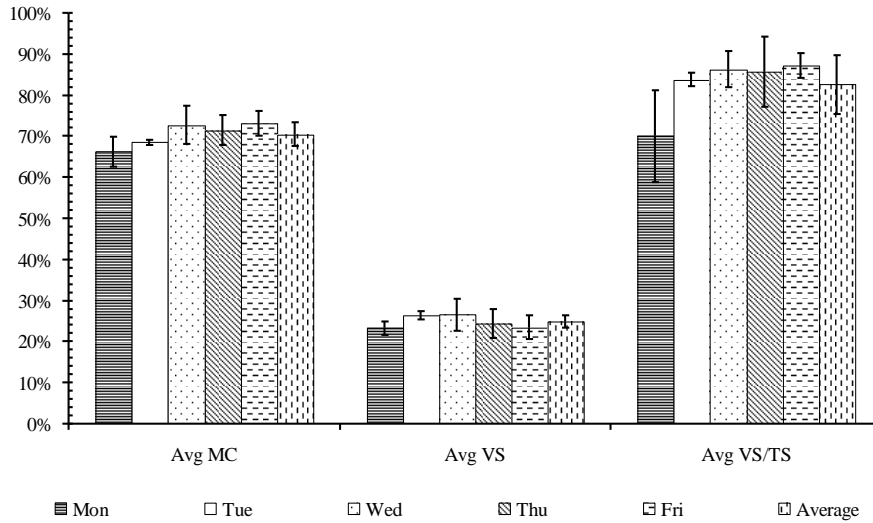


Figure 2. Daily average MC, VS (weight basis) and VS/TS of food wastes with the standard deviations as indicated by Y error bars.

Figure 3 shows the weekly variations in the average values of MC, VS and VS/TS of the samples tested. The standard deviations are indicated by the Y error bars. The MC, VS and VS/TS were almost constant (74%, 23% and 87% on average, respectively) for all studied weeks. The measured values of VS/TS are similar to the values reported for other countries (see Appendix). However, the MC of food waste samples collected in this study was higher than those reported. This could be due to many factors, including the weather conditions during sample collections.

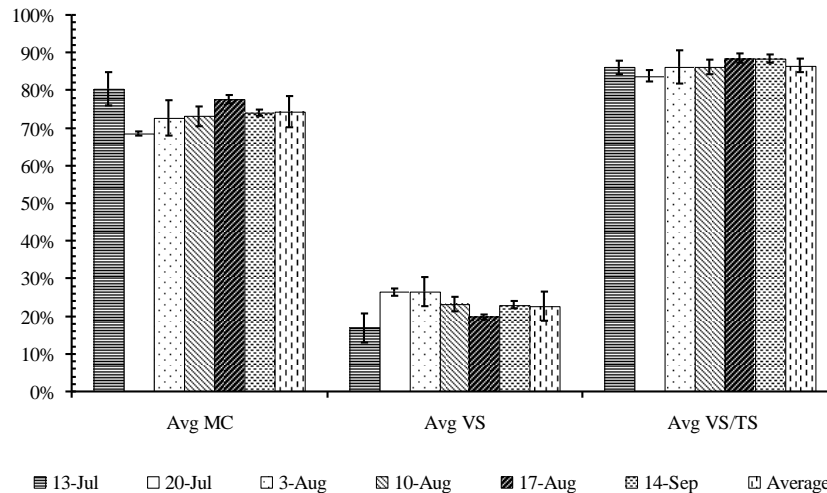


Figure 3. Weekly average MC, VS (wet weight basis) and VS/TS of food wastes. Y error bars show the standard deviations.

Table 1 shows the nutrient composition of both food and green wastes, revealing that well balanced macro and micro nutrients are available for anaerobic microorganisms. Since the total concentration of each of these nutrients will not change significantly

during the digestion, the digester effluents should provide the essential elements for plant growth if they are used as organic fertilizers.

Table 1. Elemental composition of food and green wastes

Components	Unit	Food wastes	Green wastes
C (Total)	% <sup>*</sup>	46.78	41.75
N (Total)	%	3.16	3.14
P (Total)	%	0.52	0.53
K	%	0.90	2.73
Ca (Total)	%	2.16	1.43
Mg (Total)	%	0.14	0.47
S (Total)	ppm <sup>**</sup>	2507.50	4215.00
NH <sub>4</sub> -N	ppm	972.50	600.00
NO <sub>3</sub> -N	ppm	117.50	35.00
Al	ppm	1202.00	1055.50
Fe (Total)	ppm	765.75	1500.00
B (Total)	ppm	11.25	49.50
Zn (Total)	ppm	76.00	125.00
Mn (Total)	ppm	59.75	107.00
Cu (Total)	ppm	31.13	22.50
Cd	ppm	<1	<1
Cr	ppm	2.50	2.00
Pb	ppm	3.50	2.00
Ni	ppm	2.00	7.50

\* % of dry matter

\*\* wet material

### 3.2. Characteristics of Green Wastes

Figure 4 shows the characteristics of green wastes from the last week of July until the last week of October 2004. As can be seen, more or less constant average MC was obtained during the study period except for the samples collected on 9/14/2004, which had relatively low moisture content. This may be due to the fact that the temperature was high causing much evaporation. For the first two samples (23<sup>rd</sup> of July and 14<sup>th</sup> of September) almost the same VS/TS was determined. Likewise, the last three samples had almost the same VS/TS. Over the whole period, the average values for MC, VS, and VS/TS were 64.9%, 26.8%, and 77.8%, respectively. As for food waste, these results are not completely in agreement with comparable studies from other countries (see Appendix). This may be due to variations in the components of this type of waste.

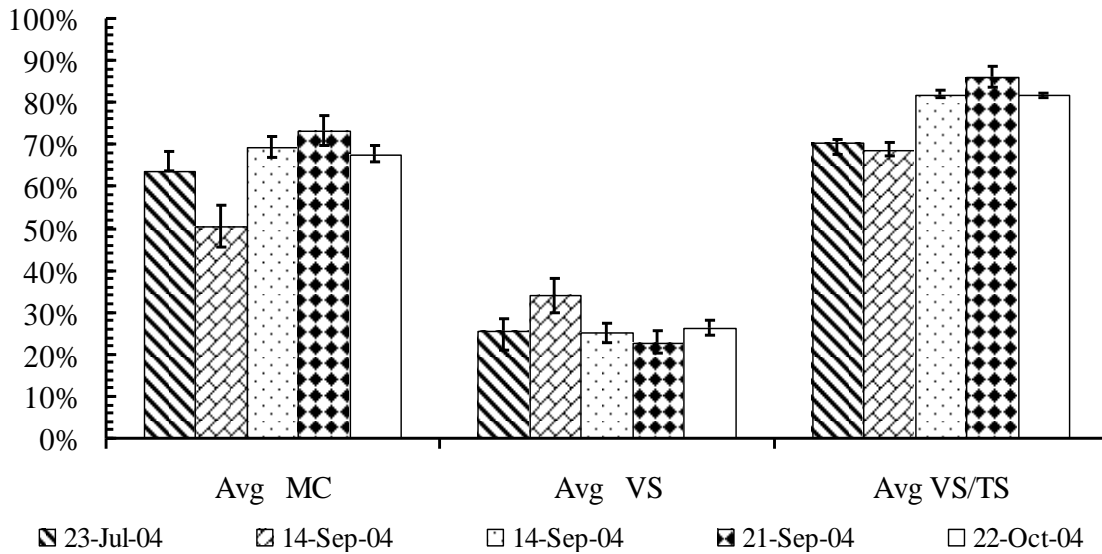


Figure 4. Weekly average MC, VS (wet weight basis) and VS/TS of green wastes. Y error bars show the standard deviations.

Similar to the food waste, green waste also has the essential nutrients needed by microorganisms (Table 1). Comparing the composition of food waste with that of green waste, it is clear that the two materials had very similar C/N ratios: 14.8 and 13.3 for food and green wastes, respectively. The green waste contained higher sulfur (S) content (4215 ppm) compared to food waste (2507 ppm). Calcium contents were 2.16% and 1.43% for food and green wastes, respectively. Magnesium concentration in the food waste was about one third of that of the green waste. The ammonia concentration of food wastes was about 1.5 times of that of green waste. In addition, both materials contained metals and other micro elements.

### 3.3. Anaerobic Digestion Tests

Table 2 shows the characteristics of food and green waste used in the digestion experiments. It should be mentioned that these data are the average of duplicates and triplicates for food wastes and green waste, respectively. Standard deviations are shown in parentheses.

Table 2. Characteristics of the feedstock used in the experiments with standard deviation between brackets.

Parameter	Food waste	Green waste
Total Solids (TS), %	30.90 (0.07)	24.70 (2.39)
Volatile Solids (VS), %	26.35 (0.14)	21.64 (2.21)
Fixed Solids (FS), %	4.54 (0.21)	3.06 (0.19)
VS/TS, %	85.30 (0.65)	87.57 (0.51)

### 3.3.1. Methane Production

The methane yield (mL/gVS) and methane production rate (mL/L.day) during the digestion of food wastes are shown in Figures 5 and 6, respectively. The average methane yield from the two digesters that had 6.8 gVS/L initial loading was about 425 mL/g VS. While for the two digesters that had 10.5 gVS/L initial loading, the methane yield was 445 mL/gVS. Essentially, there is no significant difference between the two different initial loadings. So, food waste yielded 435mL of methane per g VS on average after 28 days of digestion. About 80% of the methane yield was obtained after the first 10 days of digestion. As can be seen in Figure 5, methane production increased until day 16, and then remained almost constant at a low level until the end of experiments.

The methane yield obtained in this study is comparable to the values reported in the literature. A methane yield of 472 mL/g VS was reported by Cho et al (1995) during the digestion of municipal food waste at 37°C and 25 days. It should be mentioned that the VS/TS of their feedstock was 95%. They calculated that the stoichiometric methane yield was 546 mL/g VS, thus the measured biodegradability was 86%.

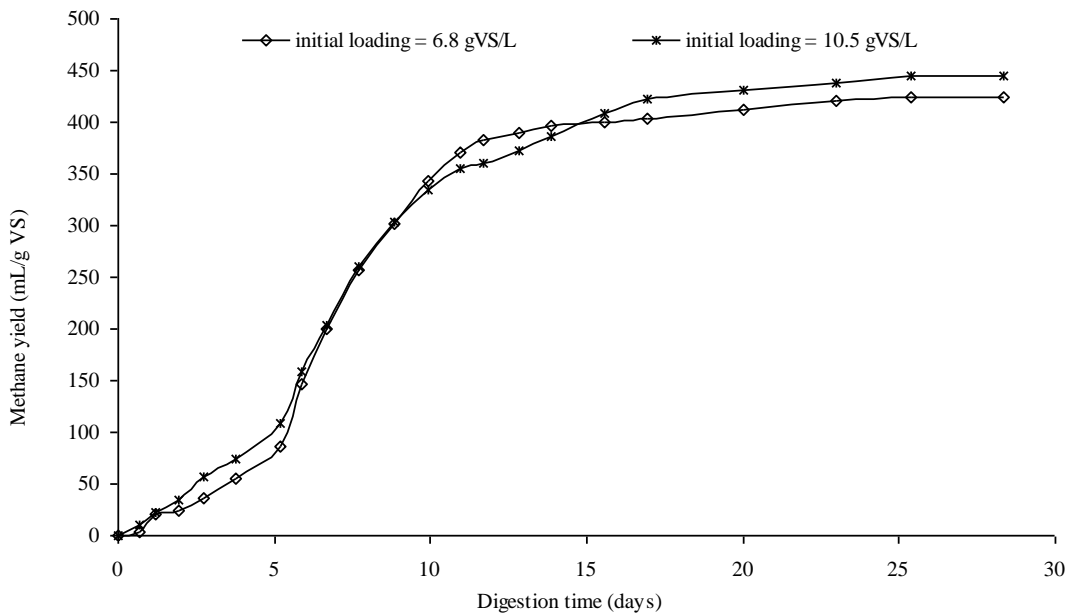


Figure 5. Methane yield of food waste during anaerobic digestion at 50°C.

Figure 6 shows that the methane production rate was low during the first five days of digestion, increased to reach a peak at the sixth day of digestion, and then declined again. Maximum methane production rates of about 602 and 762 mL/L per day could be achieved for the digesters started at 6.8 gVS/L and 10.5 gVS/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 conditions. 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 g of VS during that period. The equations obtained were: Y =

31.032 X with  $R^2 = 0.8858$  at 6.8 gVS/L initial loading and  $Y = 31.309X$  with  $R^2 = 0.9322$  at 10.5 gVS/L initial loading. Thus the calculated average methane rates during that period were 31 and 31 mL/gVS per day 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. Therefore, it can be concluded that under similar operational conditions, it is possible to operate a single batch reactor, treating food wastes, with an initial loading of up to 10.5 g VS/L without jeopardizing process stability and reduction of methane yield.

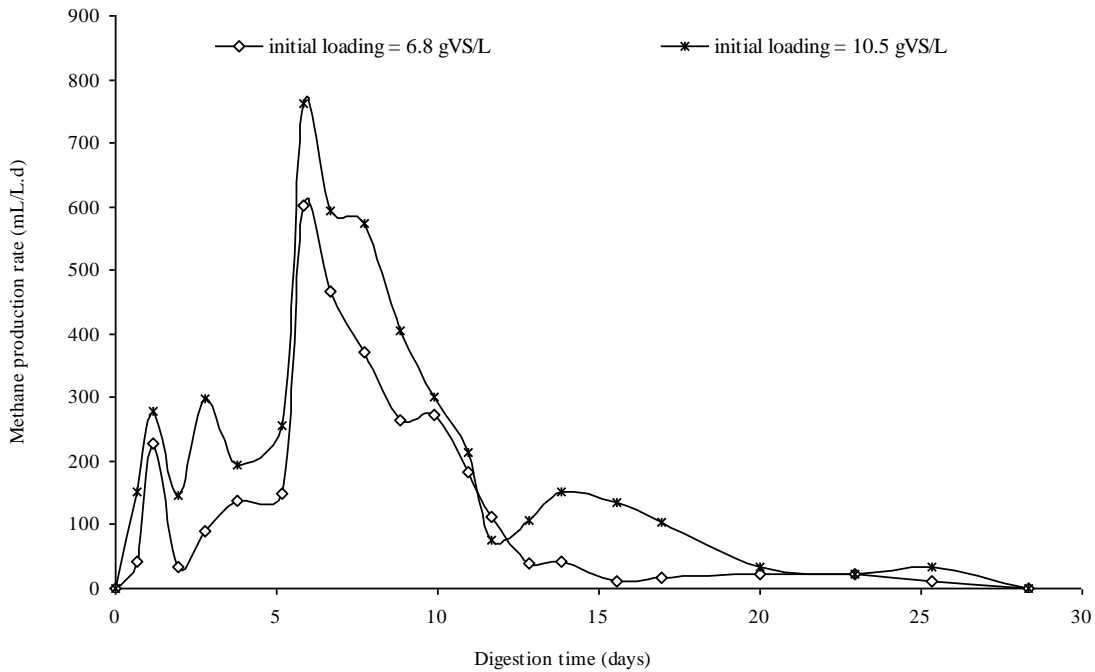


Figure 6. Daily methane production during digestion of food wastes

The methane yield (mL/g VS) of green waste during 28 days of digestion is shown in Figure 7. There was a short lag phase for about one day before biogas production commenced. A methane yield of about 226 ml/gVS was obtained after 28 days, out of which 90% was produced during the first 10 days.

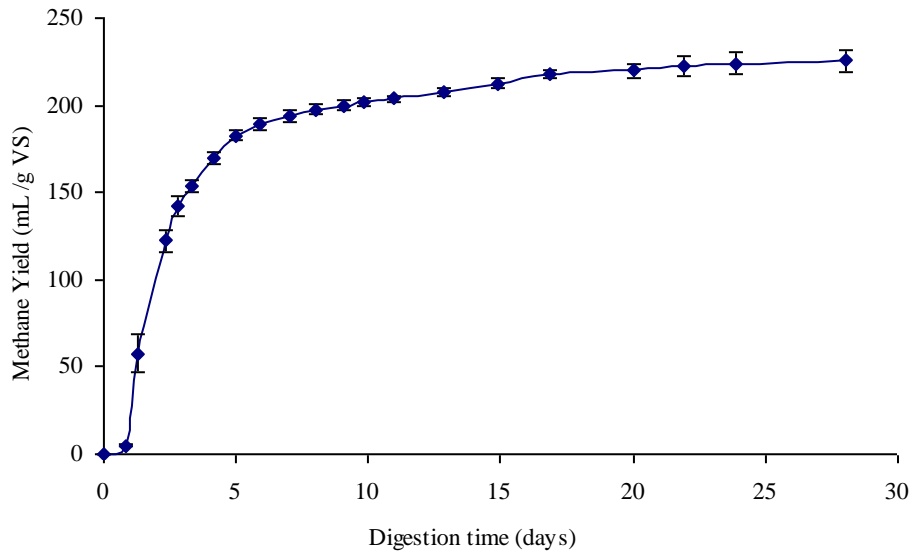


Figure 7. Methane yield during the digestion of green waste

Figure 8 shows the methane production rate (mL/L per day) from the digestion of green waste. Like food waste digestion, a peak methane production rate of 1567 (mL/L per day) was achieved after about two days of digestion. This may be due to the higher initial amount of volatile solids, or it may suggest that the green waste used in the experiments had elements (i.e. volatile fatty acids) that were very accessible to the methanogenic bacteria. According to Chanakya et al. (1999), significant fractions of most biomass feedstocks are readily biodegradable.

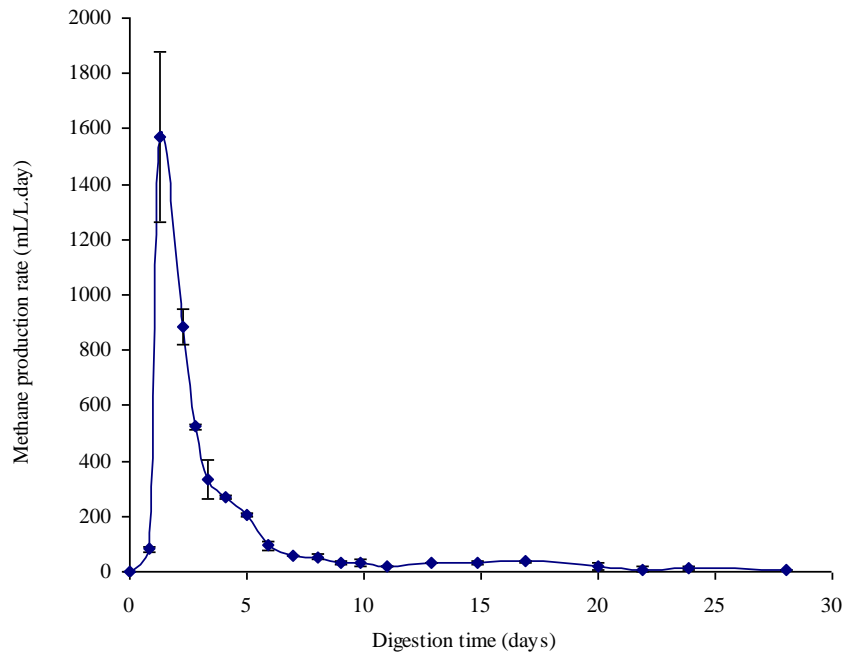


Figure 8. Daily methane production during digestion of green waste

### 3.3.2. Biogas Composition

The biogas composition during digestion of food wastes for the two reactors that had different initial loadings is shown in Figure 9. Almost constant methane content was obtained under each loading. Moreover, the biogas produced from the digesters of lower loading had higher methane content compared with the digesters that had higher loading. The average  $\text{CH}_4$  and  $\text{CO}_2$  contents during the whole experiment were 73.14% and 26.86% respectively. Thus, an average energy content of  $731.4 \text{ Btu/ft}^3$  could be estimated for the biogas produced from food waste. The average values of the biogas composition with standard deviation in parentheses are shown in Table 3.

The biogas composition obtained in this study is comparable to those obtained by other researchers. Wang et al. (2005) studied the anaerobic batch digestion at  $35^\circ\text{C}$  of food waste using lab and pilot-scale hybrid solid-liquid anaerobic digesters. The results showed that the methane contents of the biogases produced were 71% and 72%, respectively. The total VS destruction for food waste after digestion was 77% and 78% after 10 and 25 days, respectively.

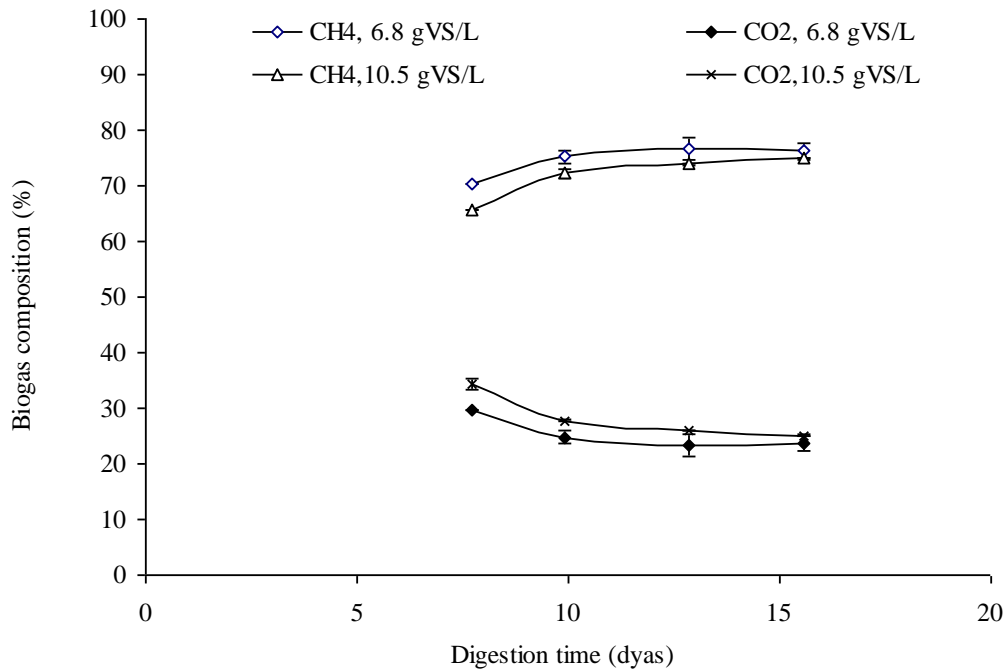


Figure 9. Biogas composition during food wastes digestion at two different initial loadings (6.8 and 10.5 gVS/L)

The biogas composition of green waste is shown in Figure 10. The methane content increased slightly during the first week of digestion and then remained relatively constant. An average methane content of 54.7 % was determined over the whole digestion time. Consequently, an average energy content of  $547 \text{ Btu/ft}^3$  could be estimated for the biogas produced from green waste.

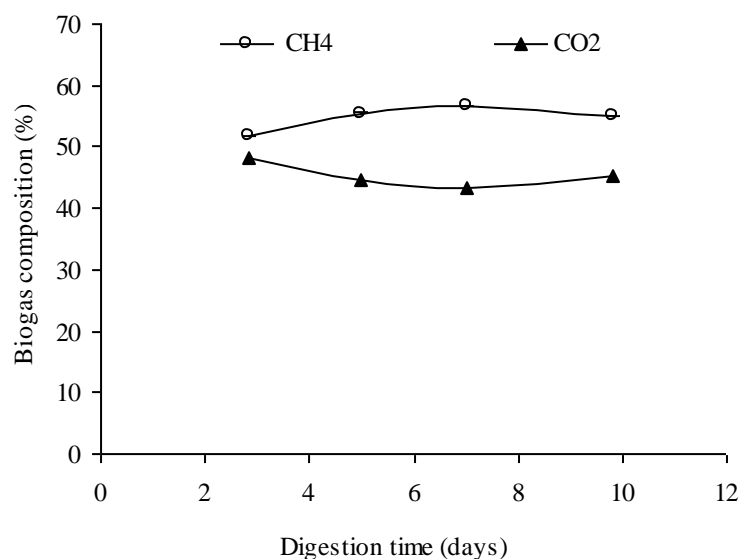


Figure 10. Biogas composition during green waste digestion

Based on these results the biogas and methane yields and biogas composition are summarized in Table 3. The biogas yields from food and green wastes were 5077.8 and 2862.5 ft<sup>3</sup> [biogas]/ton [w.w.], respectively. The data in Table 3 also show that, at the end of the digestion experiments, the VS destructions were 80.6% and 79.3% and the pH were 7.57 and 7.51 for food and green wastes, respectively.

Table 3. Average biogas and methane yields and biogas composition for food and green waste. The numbers between brackets are standard deviations

Parameter	Unit	Food wastes	Green waste
<b>Average methane content</b>	%	73.14 (3.64)	54.73 (2.13)
<b>Average carbon dioxide content</b>	%	26.86 (3.64)	45.33 (2.12)
<b>VS destruction (%)</b>		80.57 (3.1)	79.30 (1.7)
<b>Average pH at the end</b>		7.57 (0.13)	7.51 (0.0)
<b>Methane yield</b>	L/g VS	0.44	0.23
	ft <sup>3</sup> /lb VS	7.0	3.6
	ft <sup>3</sup> /ton[d.w.]	12019.2	6342.3
	ft <sup>3</sup> /ton[w.w.]	3713.9	1566.6
<b>Biogas yield</b>	L/g VS	0.6	0.4
	ft <sup>3</sup> /lb VS	9.6	6.6
	ft <sup>3</sup> /ton[d.w.]	16433.1	11588.3
	ft <sup>3</sup> /ton[w.w.]	5077.8	2862.5

w.w. wet weight.  
d.m. dry matter.

## Conclusions

The overall agreement between the daily and weekly samples, as shown by the narrow ranges of MC, VS, and VS/TS, indicates a reasonably consistent feedstock for both food and green waste. For food waste, the daily average values of MC and VS/TS from five samples taken over a one-week period were 70% and 83%, respectively, and the weekly average values from a eight-week sampling period were 74% and 87%, respectively. For green waste, the average values from six samples taken over a four-month period were 65% and 78%, respectively. The nutrient contents of food and green wastes assure the availability of nutrients required for anaerobic microorganisms. On average, food and green wastes had C/N of 14.8 and 13.3, respectively. The results of the anaerobic digestion tests showed that:

- Food and green wastes had average methane yields of 435 and 226 mL/gVS, respectively, after 28 days of digestion.
- More than 80% of the methane produced from both materials was produced in the first 10 days of digestion.
- The biogas produced from food and green wastes had methane content of 73% and 55%, respectively.

Based on the sources of food and green wastes, it is expected that the biodegradability of food waste will be relatively consistent throughout the year but the biodegradability of green waste could have seasonable variation. The results of this study on the green waste would well represent the characteristics of green waste in the summer and early fall. Further study is needed for charactering the green waste generated in other seasons.

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**Appendix:** Characteristics of green and food wastes reported in the literature

Waste	Source	Components	Characteristics			Country	Reference
			MC (%)	VS/TS	C/N		
Food wastes	A dining hall	Grains, vegetables and meat	79.5	0.95	14.7	Korea	Han and Shin (2004)
Food wastes	University's cafeteria	Mainly cooked meal residues	80.03	0.94		Korea	Kwon and Lee (2004)
Food wastes	A dining hall		93.2	0.94	18.3	Korea	Shin et al. (2004)
Food wastes	A dining hall		84.1	0.96		Korea	Kim et al. (2004)
Food and beverage industry	Food processing	Sludge, processing wastes (e.g. sugar, tobacco, beer production, meat and fish)	10	0.85		Netherlands	Faaij et al. (1997)
Swill	Food remains released at restaurants, hospitals, etc.		80	0.99		Netherlands	Faaij et al. (1997)
Food wastes	Emanating from fruit and vegetable markets, household and juices centers		85	0.89	36.4	India	Rao and Singh (2004)
Verge grass		Mowed grass released during maintenance of road sides	60	0.9		Netherlands	Faaij et al. (1997)
Household organic wastes		Remains of vegetables, fruit, plants and garden waste	60	0.8		Netherlands	Faaij et al. (1997)
Straw		Residues from cereal production	15	0.9		Netherlands	Faaij et al. (1997)
Green wastes	Gardens and parks		52.1	0.97		United Kingdom	Manios and Stentiford (2004)

