Waste Management 34 (2014) 2627–2633

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Anaerobic co-digestion of kitchen waste and fruit/vegetable waste: Lab-scale and pilot-scale studies

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ARTICLE INFO

Article history:
Received 24 January 2014
Accepted 1 August 2014
Available online 2 September 2014

Keywords:
Kitchen waste
Fruit/vegetable waste
Co-digestion
Pilot scale
Profit analysis

ABSTRACT

The anaerobic digestion performances of kitchen waste (KW) and fruit/vegetable waste (FVW) were investigated for establishing engineering digestion system. The study was conducted from lab-scale to pilot-scale, including batch, single-phase and two-phase experiments. The lab-scale experimental results showed that the ratio of FVW to KW at 5:8 presented higher methane productivity (0.725 L CH_4/g VS), and thereby was recommended. Two-phase digestion appeared to have higher treatment capacity and better buffer ability for high organic loading rate (OLR) (up to 5.0 g (VS) L^{-1} d^{-1}), compared with the low OLR of 3.5 g (VS) L^{-1} d^{-1} for single-phase system. For two-phase digestion, the pilot-scale system showed similar performances to those of lab-scale one, except slightly lower maximum OLR of 4.5 g (VS) L^{-1} d^{-1} was allowed. The pilot-scale system proved to be profitable with a net profit of 10.173 \$/ton as higher OLR ($\geqslant$3.0 g (VS) L^{-1} d^{-1}) was used.

1. Introduction

Recently, with great economic growth and rapid urbanization in China, the problem of huge municipal solid waste (MSW) disposal has been more serious in most megacities (Liu et al., 2012a). Statistically, approximate 16.4 × 10^7 tons of MSW was collected in China in the year of 2011 (National Bureau of Statistics of China, 2011), in which the organic ingredients including fruit/vegetable waste (FVW) and kitchen waste (KW) accounted for 50–60% (Liu et al., 2012b). Traditionally, most of these wastes generally have been treated by composting, landfill, and incineration together with other MSW. Unlike other solid waste, FVW and KW are characterized by high moisture content and rich biodegradable organic ingredients, which may potentially cause some negative issues in the traditional systems for MSW treatment. For example, the spread of odor during composting, the serious greenhouse gas and huge leachate discharge during landfill, and unsteady burning resulting in dioxin production during incineration (Hartmann and Ahring, 2006). By contrast, the anaerobic digestion can convert these wastes into biogas as energy and avoid the mentioned issues, which is rather meaningful to current energy crisis and environmental protection (De Baere, 2006; DiStefano and Belenky, 2009; El Hanandeh and El-Zein, 2010; Kafle et al., 2014).

Besides, the size of cities in China is extremely gigantic with extremely high population density. Thereby, food consumptions are relatively amassed in communities, canteens of universities or enterprises, and some restaurants. Correspondingly, the produced food waste can be largely and easily collected in these mentioned areas. Thus, a proper scale anaerobic digestion system can be potentially designed on the spot for treating these wastes and offer the biogas or electricity to canteens or restaurants, which will be a beneficial way to reduce logistic costs and pollution risks during the collection and transportation of food waste, meanwhile, the treatment difficulties of MSW also could be alleviated.

Technically, high volatile solids content is the common characteristic of FVW and KW, which caused the rapid hydrolysis during the digestion resulting in a severe acidification when the FVW and KW were digested separately. Consequently, the methanogenesis would be seriously inhibited (Ward et al., 2008; Jiang et al., 2012). This issue has been definitely limited the application of anaerobic digestion for treating food waste in industrial-scale. Currently, co-digestion for different organic substrates is generally accepted as an efficient way to balance the nutrients for anaerobic microorganisms and improves the digestion stability and methane production (Gomez et al., 2006; Cavinato et al., 2013). A few studies have proven that the co-digestion of FVW or KW with other organic substrates could achieve more stable digestion performances (Dinsdale et al., 2000; El-Mashad and Zhang, 2010; Kafle et al., 2012). Liu and Alkanok et al. reported that a number of

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http://dx.doi.org/10.1016/j.wasman.2014.08.005
0956-053X/

different substrates, which have similar compositions to FVW and KW, could be successfully co-digested (Liu et al., 2009; Alkanok et al., 2014). Therefore, it is possible to co-digest FVW with KW to achieve the more stable and applicable digestion.

Moreover, it was reported that the anaerobic digestion system of food waste was very difficult to run at higher organic loading rate (OLR) (Mata-Alvarez et al., 1992). It can be aborted completely as the OLR was increased to 3.0 g (VS) L^{-1} d^{-1} due to the serious accumulation of volatile fatty acids (VFA) (Lin et al., 2011). The methanogenic and non-methanogenic microorganisms are significantly different with respect to nutritional requirements, physiology, growth and metabolic characteristics, and sensitivity to environmental stress (Yu et al., 2012). In addition, the digestion failure risks from increasing OLR for FVW and KW digestion could be theoretically decreased by separating the acidification from methanogenesis. Thus, the two-phase digestion for FVW and KW may be potentially feasible to operate the digestion at high OLR.

In this study, the batch co-digestion of FVW and KW in lab-scale was carried out to investigate the digestion performances and clarify suitable FVW and KW mixture ratio for efficient co-digestion application. Co-digestion of two-phase and single-phase was also performed to investigate the enhancement potential of OLR. A pilot-scale anaerobic digestion system was built to verify the obtained results from lab-scale. Correspondingly, the operation costs and profits of this pilot-scale system were also evaluated.

2. Materials and methods

2.1. Feedstock and seeding sludge

FVW and KW were collected from the canteen in Beijing University of Chemistry Technology, Beijing. The indigestible compositions in FVW and KW, such as plastic and chopsticks were selected out before they were crushed and homogenized. The homogenized substrates were kept in a −20 °C fridge till for anaerobic digestion. Activated sludge for inoculum was taken from the anaerobic stream in the Xiaohongmen Wastewater Treatment Plant in Beijing. The main characteristics of substrates and seeding sludge are shown in Table 1.

2.2. Lab-scale co-digestion

2.2.1. Batch co-digestion

The batch digestion in lab-scale was carried out in 2-L conical flasks with working volume of 1.5 L at temperature of 35 ± 1 °C (Appels et al., 2008). The OLR of 16.5 g VS/L was employed in the digestion with FVW/KW ratio of 0:8, 2:8, 5:8, 8:8, and 8:0 (correspondingly labeled as A1–A5). The initial food (FVW and KW as feedstock) and microorganism (sludge as inoculum) weight for these batch reactors were 24.7 g (VS) and 9.7 g (VS), respectively, with food to microorganism ratio of 2.5. A reactor with the same amount of inoculums with A1–A5 was operated as blank (without feedstock). Shaking rate for digestion were controlled as 120 rev./min with shaking frequency of 24 times per day and 2 min for every shaking. During the digestion, the biogas production and methane content were monitored daily.

Table 1
Characteristics of feedstock and inoculum.

	KW	FVW	Seeding sludge
Water content (%)	77.83	92.06	94.57
TS[a] (wet basis, %)	22.17 ± 1.57[b]	7.94 ± 0.83	5.43 ± 0.30
VS[a] (wet basis, %)	17.87 ± 1.28	6.74 ± 0.65	2.29 ± 0.26
VS/TS (%)	80.60	84.89	42.17
pH	5.08 ± 0.07	5.28 ± 0.09	7.74 ± 0.06
Density (kg/L)	1.05 ± 0.04	1.09 ± 0.04	1.03 ± 0.02
Crude fat (dry basis, %)	33.82 ± 5.04	3.78 ± 0.88	2.73 ± 0.91
Crude fiber (dry basis, %)	6.93 ± 0.93	24.50 ± 2.72	N.D.[c]
Crude protein (dry basis, %)	16.88 ± 1.24	13.80 ± 1.74	19.12 ± 1.55
Soluble carbohydrate (dry basis, %)	21.60 ± 2.79	11.80 ± 1.64	N.D.
Total carbon (dry basis, %)	32.85	28.05	18.80
Total nitrogen (dry basis, %)	2.35	1.63	3.06
C/N[d]	13.98	17.21	6.14

[a] TS and VS are the abbreviations of total solids and volatile solids, respectively.
[b] The "±" in the table represent standard deviations.
[c] N.D. means not detected.
[d] C/N means the ratio of total carbon to total nitrogen.

2.2.2. Single-phase co-digestion

A10-L completely stirred tank reactor (CSTR) with working volume of 8.0 L was employed for anaerobic digestion in the mode of sequencing batch. This anaerobic digestion system was operated at temperature of 35 ± 1 °C and stirring rate of 120 rev./min with the frequency of 8 times per day, and each stirring was lasted for 5 min. The start-up OLR for the digestion was 0.5 g (VS) L^{-1} d^{-1}. Afterwards, the OLR was stepwise enhanced from 0.5 to 3.5 g (VS) L^{-1} d^{-1} during the following 129 days digestion. The hydraulic retention time (HRT) of 30 days was maintained in the whole digestion process. The employed FVW to KW ratio was based on the results from batch digestion. During the digestion, biogas production, methane content and effluent pH were also recorded daily. VFA in the effluent at the stable phase of each OLR were sampled and analyzed.

2.2.3. Two-phase co-digestion

The two-phase digestion was carried out in two CSTRs with working volume of 5.0 L and 8.0 L for acidification and methanogenesis, respectively. The start-up of acidification phase was at the OLR of 2.0 g (VS) L^{-1} d^{-1} for 10 days in batch. Afterwards, the OLR was gradually increased from 2.0 to 10.0 g (VS) L^{-1} d^{-1} with the HRT of 10 days for acidification phase. The effluent from the acidification phase was pumped to second phase for methanogenesis with the OLR of 1.0, 2.0, 3.0, 4.0 and 5.0 g (VS) L^{-1} d^{-1}, and the HRT of 20 days. The start-up for the methanogenic phase was completely same with the single-phase anaerobic digestion.

2.3. Pilot-scale co-digestion

A pilot-scale two-phase digestion system was established on campus at Beijing University of Chemistry Technology (BUCT), Beijing, to treat partial KW and VFW from canteen at BUCT for biogas production. The flow photo and diagram of the two-phase pilot-scale system are shown in Fig. 2. The working volume acidogenic phase and methanogenic stage phase were 2.0 m^3 and 4.0 m^3, respectively, with the daily treatment ability of 100–130 kg waste. The pilot-scale system was mainly integrated by the units of feedstock homogenization, pH adjustment, pumping, effluent reservoir, and biogas storage (see Fig. 2b). In order to make a comparison on the digestion performances between the lab-scale and pilot-scale system, the similar OLR was employed for digestion in the pilot-scale system. Other operation conditions for pilot-scale digestion including temperature, HRT and agitation were similar to those of lab-scale.

2.4. Analytical methods

Daily produced biogas in batch digestion was determined by water displacement method, and gas meters were used for the single-phase and two-phase digestion. Biogas content was analyzed using a gas chromatograph (GC) (Shimadzu, SP2100) equipped with a TDX-01 stainless steel column and a thermal conductivity detector. VFAs were analyzed by another GC (Shimadzu,