Waste Management xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

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

Development of an efficient anaerobic co-digestion process for garbage, excreta, and septic tank sludge to create a resource recycling-oriented society

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ARTICLE INFO

Article history:
Received 5 July 2016
Revised 15 October 2016
Accepted 10 November 2016
Available online xxxx

Keywords:
Anaerobic co-digestion
Garbage
Excreta
Septic tank sludge
Biogas

ABSTRACT

In order to develop a resource recycling-oriented society, an efficient anaerobic co-digestion process for garbage, excreta and septic tank sludge was studied based on the quantity of each biomass waste type discharged in Ooki *machi*, Japan. The anaerobic digestion characteristics of garbage, excreta and 5-fold condensed septic tank sludge (hereafter called condensed sludge) were determined separately. In single-stage mesophilic digestion, the excreta with lower C/N ratios yielded lower biogas volumes and accumulated higher volumes of volatile fatty acid (VFA). On the other hand, garbage allowed for a significantly larger volatile total solid (VTS) digestion efficiency as well as biogas yield by thermophilic digestion. Thus, a two-stage anaerobic co-digestion process consisting of thermophilic liquefaction and mesophilic digestion phases was proposed. In the thermophilic liquefaction of mixed condensed sludge and household garbage (wet mass ratio of 2.2:1), a maximum VTS loading rate of 24 g/L/d was achieved. In the mesophilic digestion of mixed liquefied material and excreta (wet mass ratio of 1:1), biogas yield reached approximately 570 ml/g-VTS fed with a methane content of 55% at a VTS loading rate of 1.0 g/L/d. The performance of the two-stage process was evaluated by comparing it with a single-stage process in which biomass wastes were treated separately. Biogas production by the two-stage process was found to increase by approximately 22.9%. These results demonstrate the effectiveness of a two-stage anaerobic co-digestion process in enhancement of biogas production.

1. Introduction

Approximately 300 million tons of biomass wastes are generated in Japan each year. Excreta from humans and animals, and garbage produced by food industries and households, account for >20% and 5% of biomass waste, respectively (Liu et al., 2009; Tang et al., 2008). Sewage sludge and/or septic tank sludge are other types of biomass wastes. Sewage sludge is a product derived from the treatment of municipal wastewater; while septic tank sludge is the waste from septic tanks, which are cleaned out periodically to prevent septic disposal beds from clogging (Warman and Termeer, 2005). Currently in Japan, most of these biomass wastes are directly incinerated or composted. However, incineration is costly and energy inefficient, due to the high moisture content of these biomass wastes (Jiang et al., 2013; Zhang et al., 2007). In addition, dioxins are produced during the incineration process. To achieve complete combustion and avoid dioxin production, the incineration temperature should be maintained at over 800 °C, and the exhaust gas should be cooled to below 200 °C in a short time. However, it is difficult to achieve these conditions in small and medium-scale incinerators. Although composting is suited to treating some biomass wastes (e.g., livestock manure) to produce fertilizer, fertilizers are oversupplied in most regions of Japan. From a visit to Germany and Sweden in early 2000, it was found that a resource-recycling process had already been put to practical use there. Energy was recovered by the anaerobic digestion of biomass wastes (e.g., livestock manure, garbage, and vegetable waste), and the digested liquid was utilized as fertilizer. The benefits to environmental conservation gained by utilizing biomass wastes in local regions over incinerating them were realized.

The practice of using of anaerobic digestion for the treatment of these biomass wastes has gained importance and increased in recent years (Ikbal et al., 2003; Li et al., 2016; Kim et al., 2006; Nishio and Nakashimada, 2007) due to new regulations regarding

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http://dx.doi.org/10.1016/j.wasman.2016.11.021
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Please cite this article in press as: Sun, Z.-Y., et al. Development of an efficient anaerobic co-digestion process for garbage, excreta, and septic tank sludge to create a resource recycling-oriented society. Waste Management (2016), http://dx.doi.org/10.1016/j.wasman.2016.11.021

to the disposal of biomass wastes and the production of electricity from renewable energy sources. The government of Japan published the "Biomass Nippon Strategy" in 2002 to encourage a resource recycling-oriented society and to fulfill the commitments of the 1997 Kyoto protocol (MAFF, 2002). For example, Ooki *machi* (Fukuoka prefecture, Japan), which was among the first certified "biomass towns", had been entrusted to the cleaning center in Ohkawa City (Fukuoka prefecture, Japan) for garbage treatment. In addition, the excreta and septic tank sludge were dumped into the ocean. Since ocean dumping of wastes was prohibited in 2007, the construction of a recycling process was proposed, i.e. waste biomass could be treated by anaerobic digestion to produce biogas and the digested liquid could be used as fertilizer. Moreover, sorting and collection of garbage was also conducted by the town hall and the townspeople. Specifically, a draining bucket was used in each home, a relay bucket was used in one out of 10 households, and the relay buckets were collected by car. For biomass waste utilization, Wong et al. (2008) evaluated the potential for regional bioenergy recovery as electricity and heat from small-scale methane fermentation systems using biomass wastes generated in the Tokyo Bay region. Results showed that an additional 368,000–1,328,000 MW of electricity could be generated, and that 1300–3600 TJ of heat could be supplied to households, potentially reducing annual CO_2 emissions from fossil fuels by 307,000–798,000 t.

Different biomass wastes are characterized by different physicochemical properties, and the performance of anaerobic digestion and biogas production are affected by these properties depending on the type of biomass waste. The anaerobic digestion of garbage is very rapid due to its high biodegradable organic matter content (Brown and Li, 2013; Ikbal et al., 2003; Kübler et al., 2000), while excreta is known to have a poor biogas yield, and is therefore rarely used as the sole substrate for biogas production (Ahring et al., 2001; Møller et al., 2004; Zhang et al., 2013). In addition, in order to reduce transportation costs, anaerobic digestion systems for biomass wastes are normally operated close to population centers, where several biomass wastes can be treated simultaneously (i.e. co-digestion). Co-digestion is a proven and attractive strategy to enhance the digestion efficiency of different biomass wastes (Brown and Li, 2013; Zhang et al., 2013). Moreover, another merit of co-digestion is its efficient use of equipment and cost sharing between waste producers through the processing of multiple waste streams in a single facility. Sosnowski et al. (2003) reported that the digestion of sewage sludge along with food waste improves biogas productivity. However, as a vertically administrated system in Japan, anaerobic treatment of waste biomass other than sewage sludge (primary sludge + surplus sludge) was not carried out in sewage treatment plants at that time. Thus, a two-stage digestion process that included the liquefaction of thickened surplus sludge was studied based on the anaerobic digestion performance of both thickened surplus sludge and primary sludge. As a result, the maximum volatile total solid (VTS) loading rate (7.7 g/L/d) of the two-stage digestion process was approximately twice as high as that (4.0 g/L/d) of the conventional single-stage process. The VTS digestion efficiency also increased by up to 10% of the efficiency of the conventional process using the same VTS loading rate of 2–4 g/L/d (Kida and Ikbal, 1995). Other studies have indicated that combining manure with the organic fraction of municipal and industrial wastes is technologically feasible (Hartmann and Ahring, 2005; Callaghan et al., 2002; Zhang et al., 2013). Appropriate methods need to be considered to make the co-digestion of various biomass wastes more efficient (e.g., mass ratio and process conditions). In order to develop a feasible process, Liu et al. (2009) investigated the thermophilic anaerobic co-digestion of garbage, screened swine manure and dairy cattle manure with respect to the relative quantity of each biomass waste type discharged into two stock raising areas in the Kumamoto Prefecture in Japan. Their results revealed that co-digestion with garbage at a relatively low percentage (2.3–3.1%) significantly improved the digestion characteristics of swine manure and dairy cattle manure (Liu et al., 2009). Besides the thermophilic anaerobic digestion of garbage and two-stage digestion of sewage sludge as described above, thermophilic anaerobic digestion of wastewaters with high organic substance concentrations had also been conducted in authors' lab (Kida and Sonoda, 1993; Tokuda et al., 1998). Since ocean dumping of waste was prohibited in 2007, a joint study of the household garbage, excreta, and septic tank sludge generated in Ooki *machi* was proposed by a consulting company called BET JAPAN (Kumamoto City, Japan), and the development of an effective process in a short time was requested. In order to assist in the development of a sustainable resource recycling-oriented society, regional bioenergy recovery using the anaerobic co-digestion of local biomass wastes in Ooki *machi* was studied.

The aim of the present study was to improve the biogas evolution from biomass wastes with a hydraulic retention time (HRT) of 20 days, since an efficient process in a short time was requested, and the average HRTs for mesophilic and thermophilic anaerobic digestion were 30 and 20 days, respectively. First, the physicochemical characteristics and anaerobic digestion performance of household garbage, excreta and septic tank sludge were investigated. Excreta was subjected to mesophilic anaerobic digestion due to its higher NH_4^+ concentration, and the other two waste biomass types (household garbage and septic tank sludge) were treated separately by thermophilic anaerobic digestion. Then, thermophilic liquefaction of a household garbage and condensed sludge mixture was investigated due to their higher total solid (TS) concentration. On the basis of these results, a two-stage anaerobic co-digestion process consisting of thermophilic liquefaction and mesophilic digestion was proposed, considering the actual quantity of these biomass wastes generated in Ooki *machi*. Finally, the performance of the two-stage process was evaluated by comparing it the single-stage process in which biomass wastes are treated separately.

2. Materials and methods

2.1. Biomass wastes and seed sludge

2.1.1. Biomass wastes

Synthetic garbage was prepared by mixing various kinds of fruits (except apples), vegetables, meat, fish, eggs, and staple foods in a ratio of 30:36:5:5:4:20 (wet weight), as described in Ikbal et al. (2003). This synthetic garbage was mashed using a mixer (JC-MW1, Toshiba, Japan) and municipal tap water was added to obtain a final total solid (TS) concentration of approximately 10%. The mixture was then stored in an enclosed container at −20 °C for later use. Household garbage, excreta, and septic tank sludge were kindly provided by Ooki *machi*, Japan. The sorted household garbage was ground using the same mixer that was used on the synthetic garbage. The excreta were strained by the screener with 2 mm square holes. Since septic tank sludge has a high settleability, 5-fold condensed septic tank sludge (hereafter called condensed sludge) was obtained through static settling and used as feedstock for our treatment. Table 1 shows the characteristics of each biomass waste used. Ni^{2+} and Co^{2+} were added to the wastes to give final concentrations of 74 and 21 μg/g-VTS, respectively, and to enhance the methane fermentation rate (Kida and Sonoda, 1993; Kida et al., 2001).

2.1.2. Seed sludge

Mesophilic sludge from an anaerobic digester was provided by the Kumamoto Northern Sewage Treatment Plant (Kumamoto City,

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