ARTICLE IN PRESS

Waste Management xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

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

Comparative evaluation of anaerobic digestion for sewage sludge and various organic wastes with simple modeling

Taira Hidaka *, Feng Wang, Jun Tsumori

Recycling Research Team, Materials and Resources Research Group, Public Works Research Institute, 1-6, Minamihara, Tsukuba, Ibaraki 305 8516, Japan

ARTICLE INFO

Article history:
Received 20 August 2014
Accepted 20 April 2015
Available online xxxx

Keywords:
Anaerobic digestion
Sewage sludge
Organic waste
Digested sludge
Mathematical model

ABSTRACT

Anaerobic co-digestion of sewage sludge and other organic wastes, such as kitchen garbage, food waste, and agricultural waste, at a wastewater treatment plant (WWTP) is a promising method for both energy and material recovery. Substrate characteristics and the anaerobic digestion performance of sewage sludge and various organic wastes were compared using experiments and modeling. Co-digestion improved the value of digested sewage sludge as a fertilizer. The relationship between total and soluble elemental concentrations was correlated with the periodic table: most Na and K (alkali metals) were soluble, and around 20–40% of Mg and around 10–20% of Ca (alkaline earth metals) were soluble. The ratio of biodegradable chemical oxygen demand of organic wastes was 65–90%. The methane conversion ratio and methane production rate under mesophilic conditions were evaluated using a simplified mathematical model. There was reasonably close agreement between the model simulations and the experimental results in terms of methane production and nitrogen concentration. These results provide valuable information and indicate that the model can be used as a pre-evaluation tool to facilitate the introduction of co-digestion at WWTPs.

1. Introduction

Anaerobic digestion of organic wastes with high moisture content, such as sewage sludge, kitchen garbage, food waste, and agricultural waste, is a promising method for both energy and material recovery. A wastewater treatment plant (WWTP) that can accept many kinds of organic waste for co-digestion could become a regional energy hub if the anaerobic digester produces more methane than the digestion of sewage sludge alone (Cabbai et al., 2013; Navaneethan et al., 2011; Di Maria et al., 2014). In 2011, the Sewerage and Wastewater Management Department of the Ministry of Land, Infrastructure, Transport and Tourism, Japan (2013) initiated the nationwide project called Breakthrough by Dynamic Approach in Sewage High Technology (B-DASH Project) for the development of innovative technologies in sewage treatment. Demonstration experiments were performed, including the co-digestion of sewage sludge and regional organic waste (NILIM, 2013a,b).

However, it is likely that the characteristics of sewage sludge and regional organic waste are different in each WWTP. The properties of substrates such as total solids (TS), volatile solids (VS), chemical oxygen demand (COD), proteins, lipids, and nutrient and trace elements can provide basic information for understanding anaerobic co-digestion characteristics. Co-digestion could potentially cause reaction inhibition by such as ammonia, metals and organics (Chen et al., 2008), increase loading to the water treatment process, and worsen the quality of effluent water from WWTPs. Some trace elements are required for methanogenesis, and some elements are important components of fertilizer. Basic information and a simple pre-evaluation tool for co-digestion are required to promote these technologies.

Batch experiments are widely used to investigate methane conversion performance. Alzate et al. (2012) used batch experiments to compare anaerobic digestion of microalgae with substrate-to-inoculum (*S*/*I*) ratios of 0.5, 1, and 3 (gVS/gVS), and reported that the methane production was higher at lower *S*/*I* ratios. The *S*/*I* ratios used in batch experiments are often higher than 0.5. Furthermore, the biodegradation profile in batch experiments affects the methane production quantity in continuous operation, especially in the case of a shorter hydraulic retention time (HRT). Assuming a first-order reaction and a continuously stirred tank reactor (Astals et al., 2013), theoretically not all of the degradable substrate is degraded, whereas almost all of the substrate is ultimately degraded in batch experiments. The sum of the methane conversion ratio multiplied by the feeding quantity is commonly used to design co-digestion systems, but this summation cannot accurately estimate the total methane production quantity in continuous operations.

* Corresponding author. Tel.: +81 29 879 6765; fax: +81 29 879 6797.
E-mail address: hidaka@pwri.go.jp (T. Hidaka).

http://dx.doi.org/10.1016/j.wasman.2015.04.026
0956-053X/

Mathematical models have been used to evaluate methane fermentation performance, combining operational parameters such as HRT, and substrate characteristics that differ among WWTPs. The International Water Association anaerobic digestion model No. 1 (ADM1) (Batstone et al., 2002) is an example of an effective general model that can be applied to many kinds of organic substrates. However, characterization of the biodegradability of substrates is required before using the ADM1. Yasui et al. (2008) and Astals et al. (2013) evaluated the sewage sludge from different WWTPs using anaerobic respirometry and mathematical modeling, but did not include other types of organic waste. Mottet et al. (2010) analyzed the thermophilic anaerobic biodegradability of waste activated sludge (WAS) from different WWTPs. Girault et al. (2012) proposed a COD fraction characterization method for the ADM1, but only two types of organic waste (pig slurry and WAS) were evaluated. Souza et al. (2013) proposed a simplified COD fractioning criterion for the ADM1, but it applied only to raw and pre-treated WAS. The ADM1 could be too complicated for use by designers and operational managers on site. Donoso-Bravo et al. (2009) proposed a two-population, three-reaction model, which was used to evaluate the thermophilic anaerobic digestion of sewage sludge (Donoso-Bravo et al., 2012). However, this simplified model did not include the self-degradation of microorganisms, which is important in batch experiments.

Although extensive research on co-digestion using experiments and modeling has been reported (Derbal et al., 2009; Esposito et al., 2011), there have been few comparative evaluations using a wide range of organic wastes together with sewage sludge. In the present study, the substrate characteristics and anaerobic digestion performance of various organic wastes were compared using experiments and simplified mathematical modeling. The primary purpose was to provide municipal employees and designers on site with basic information and a simple pre-evaluation method to facilitate the introduction of co-digestion at WWTPs.

2. Materials and methods

2.1. Anaerobic digestion characteristics of various organic wastes

Various organic wastes were compared in the present study. Glucose (GL) was used as a substrate to investigate the activity of the digested sludge. Mixed sewage sludge (MS), which is a mixture of primary sludge and WAS, was obtained from WWTP-A. Separated primary sludge (PS) from WWTP-B was obtained using an effective separation system demonstrated by the B-DASH Project (NILIM, 2013a), instead of a traditional primary sedimentation system. Kitchen garbage (KG), which was a mixture of PS and raw KG, was obtained from the B-DASH Project (NILIM, 2013a). Cow manure (CM) and swine manure (SM) were obtained from an agricultural research institute. Cabbage (CB), potato (PT), and carrot (CR) were evaluated as representatives of waste leaf and root vegetables. All parts of the vegetables, including edible parts and peels, were crushed together and used for the experiments. As part of the B-DASH Project, imperfect vegetables from markets were planned to be co-digested with sewage sludge.

Digested sludge adapted to various organic wastes was cultivated as inoculum sludge for the batch experiments. Two semi-continuous complete mix reactors, Reactor 1 and Reactor 2, each with a working volume of 100 L, were operated under mesophilic (35 °C) and thermophilic (55 °C) conditions, respectively. When the present study started, Reactor 1 and Reactor 2 had been operated for three months with MS. At the beginning of the present study, 3 L of the mesophilic digested sludge from the B-DASH Project demonstration anaerobic digester (NILIM, 2013b) was added to each reactor as an inoculum sludge adapted to MS and other waste biomass. A mixture of MS, PS, CM, and SM with average VS of around 37 g/L was fed to Reactor 1 and Reactor 2. The temperature was controlled using a hot water bath. The reactors were fed three times a week (on Monday, Wednesday, and Friday). The HRT was set at 120 d, and it was gradually decreased to 47 d, which corresponds to an organic loading rate (OLR) of around 0.8 kg VS/(m^3 d). The main purpose was to cultivate inoculum sludge adapted to various organic wastes for the following batch experiments. Therefore, the HRT was set to be longer than the HRT of conventional anaerobic digesters (JSWA, 2003).

Four series of batch experiments (B1, B2, B3, and B4) were performed using a commercially available experimental kit with 600 mL-vessels stirred at around 100 rpm (AMPTS II; Bioprocess Control AB, Sweden) (Table 1). Four hundred mL of the digested sludge and substrate were added to each vial. No microelements were added. The *S*/*I* ratios were set lower than for typical batch experiments, to determine rate constants under similar conditions to continuous operation. Before sealing, the vials were flushed with nitrogen gas. The produced biogas was passed through an alkali liquid (3 M NaOH) to remove CO_2, and the quantity of produced methane gas was monitored using the gas meter (AMPTS II). Before starting each batch experiment, substrate feeding was suspended for about one week in Reactor 1 and Reactor 2 to reduce the background methane production.

The digested sludge cultivated in Reactor 1 and Reactor 2 was used for B1 and B3 (mesophilic), and B2 and B4 (thermophilic), respectively. The substrate addition ratio was designed using the

Table 1
Batch experimental conditions.

Mesophilic	Thermophilic	Substrate	S/I [a]
B1	B2		
B1-1	B2-1	Blank	–
B1-2	B2-2	GL	0.1
B1-3	B2-3	GL	0.2
B1-4	B2-4	MS	0.1
B1-5	B2-5	MS	0.2
B1-6	B2-6	KG	0.1
B1-7	B2-7	KG	0.2
B1-8	B2-8	KG	0.4

Mesophilic	Thermophilic	Substrate	S/I [a]
B3	B4		
B3-1	B4-1	Blank	–
B3-2	B4-2	GL	0.1
B3-3	B4-3	GL	0.2
B3-4	B4-4	PS	0.1
B3-5	B4-5	PS	0.2
B3-6	B4-6	CM	0.1
B3-7	B4-7	CM	0.2
B3-8	B4-8	CM	0.4
B3-9	B4-9	SM	0.1
B3-10	B4-10	SM	0.2
B3-11	B4-11	SM	0.4
B3-12	B4-12	CB	0.2
B3-13	B4-13	PT	0.2
B3-14	B4-14	CR	0.2

[a] substrate/inoculum (digested sludge) ratio on VS base