Waste Management xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

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

The influence of the total solid content on the stability of dry-thermophilic anaerobic digestion of rice straw and pig manure

Shohei Riya [a,*], Kazuhiro Suzuki [a], Lingyu Meng [a], Sheng Zhou [b], Akihiko Terada [a], Masaaki Hosomi [a]

[a] Graduate School of Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Naka-cho, Koganei, Tokyo 184-8588, Japan
[b] Eco-environmental Protection Research Institute, Shanghai Academy of Agricultural Sciences, 1000 Jinqi Road, Fengxian, Shanghai 201403, China

ARTICLE INFO

Article history:
Received 6 September 2017
Revised 18 January 2018
Accepted 14 February 2018
Available online xxxx

Keywords:
Dry anaerobic digestion
Total solid
Moisture
Stability
Semi batch

ABSTRACT

Dry anaerobic digestion is a promising technology for the recycling of agricultural waste to produce energy and fertilizer. Adding water to the substrate enables better handling and avoid inhibition caused by high total solid (TS) content in the reactor; however, it also increases leachate and operational costs. To assess the extent to which the amount of water added can be reduced, it was examined how the TS content in the reactor influenced the production of biogas. A semi-batch dry thermophilic anaerobic digester was fed with substrate (rice straw and pig manure) at a constant organic loading rate, and varied the TS contents (27%, 32%, 37%, and 42%) of the substrate by adding different amounts of water (representing 0–36% of the total substrate). During incubation, the TS content in the reactor gradually increased from 18% to 31%. Biogas production was stable and high (564 ± 13–580 ± 36 N m^3 t^{-1} VS), and there was no accumulation of volatile fatty acids when the TS content of the reactor was between 18% and 27%. However, the rate decreased sharply and propionate and acetate were also produced when the TS content of the reactor exceeded 28%. By applying a simple TS balance model, it was found that stable biogas production could be achieved at a substrate TS content of 32%, at which reactor TS content reached 23% at steady-state condition.

1. Introduction

Anaerobic digestion is the process by which various microorganisms decompose organic matter in the absence of oxygen, producing biogas, which comprises methane (CH_4) and carbon dioxide (CO_2), and an organic residue called digestate as end products. Anaerobic digestion is currently used to treat organic waste and to produce renewable energy (Li et al., 2011a). The process has traditionally been called 'liquid' or 'wet' anaerobic digestion, as the sludge generally has a total solids (TS) content of less than 10%. Wet anaerobic digestion, which involves adding water to substrates with a high TS content (Ge et al., 2016), is typically used to treat sewage sludge and industrial or agricultural wastewater (Chen et al., 2008). In contrast, dry anaerobic digestion involves the digestion of substrates with a TS content greater than 15%, such as rice straw, municipal solid waste, or woody biomass (Ge et al., 2016; Li et al., 2011a). Dry anaerobic digestion has some advantages over liquid anaerobic digestion; for example, the volume of the reactor is smaller, less energy is used for heating, and the material needs less handling (Guendouz et al., 2008).

The greatest advantage however of dry anaerobic digestion is that the sludge produced has a low water content, meaning that a smaller volume of liquid digestate is produced than in liquid anaerobic digestion. Pig manure is a nitrogen-rich agricultural waste that can be used as fertilizer. Japanese pig farmers however, have no agricultural land on which to apply the digestate from liquid anaerobic digestion of this manure, so dry anaerobic digestion may help them to manage pig manure. It has been reported however that the high ammonium concentrations in pig manure may inhibit anaerobic digestion (Rajagopal et al., 2013). Stop of CH_4 production after 50 days during dry-thermophilic anaerobic digestion of pig manure was also observed in our previous study (Riya et al., 2016). However, when pig manure was mixed with rice straw at a carbon and nitrogen ratio (C/N ratio) of 30 in the dry-thermophilic anaerobic digestion, there was high and stable CH_4 production (Riya et al., 2016), suggesting that the rice straw diluted the ammonium concentration, with the result that there was less inhibition of the dry-thermophilic anaerobic digestion process (Riya et al., 2016). Thus, co-digestion of manure with rice straw may be an effective method for dry-thermophilic anaerobic digestion of pig manure.

After dry anaerobic digestion, the digestate needs to be composted for both drying and sanitization (ten Brummeler, 2000).

* Corresponding author.
E-mail address: sriya@cc.tuat.ac.jp (S. Riya).

https://doi.org/10.1016/j.wasman.2018.02.033
0956-053X/

If the digestate is aerated during the composting process, the organic matter will be oxidized, heat is produced, excess moisture evaporates, and the digestate is sanitized. Obviously, the TS content of the digestate determines the amount of energy that is required for aeration. In our previous study, water was added to the substrate in order to decrease the substrate TS content to 27% to facilitate easy mixing during dry anaerobic digestion (Riya et al., 2016). However, the aeration costs would be lower and there would be less liquid digestate if the waste was digested in dry anaerobic conditions without adding water.

A previous study reported that CH_4 production decreased during dry anaerobic digestion as the TS content increased. Tests showed that, when cardboard was digested anaerobically with a TS content of between 10% and 35%, the CH_4 yield decreased at TS contents greater than 30% (Abbassi-Guendouz et al., 2012). The reduction of CH_4 productivity at higher TS contents has been thought to reflect a limitation of substrate diffusion, i.e. water in the substrate acts as a medium to diffuse nutrients and microorganisms; therefore, a higher TS content level limits their movement. Recently, García-Bernet et al. (2011) evaluated the water distribution in digestate from dry anaerobic digestion, and found that only 50% of the water in the digestate was free water, and available as a medium for nutrient transport and microbial activity. Increases in the TS content therefore would influence the digestion of rice straw and pig manure mixtures, so it would be useful to determine at what TS content the performance of anaerobic digestion decreases.

While other researchers have studied how the TS content influences dry anaerobic digestion, most of these earlier studies were carried out in batch mode. In real situations, the substrate moisture levels vary from day to day, and changes in moisture in the reactor will control the digestion performance. Information about how the performance changes under different moisture levels is therefore needed so that effective continuous operation systems can be developed. In general, stability of, and biogas yields from, continuous dry anaerobic digestion are influenced by the organic loading rate (OLR) (Cho et al., 2013; Ganesh et al., 2013; Mumme et al., 2010; Nguyen et al., 2017). For example, CH_4 production and the accumulation of VFAs in an upflow anaerobic solid-state reactor loaded with maize silage and barley straw decreased continually when the OLR was increased from 7.1 to 17 kg VS m^{-3} day^{-1} (Mumme et al., 2010). Accumulation of VFAs, intermediate products of anaerobic digestion, indicates inhibition of the reaction because of over loading. Benbelkacem et al. (2015) evaluated how the TS content in the reactor influenced dry anaerobic digestion, and found that the VFA concentrations increased as the TS contents in the reactor increased. They however, controlled the TS content of the substrate by changing the amount of substrate added without changing the hydraulic retention time (HRT), so that the OLR increased when the substrate TS content increased. In situations like this, biogas production or changes in the metabolites in the reactor resulted from interactions between the OLR and the TS contents. To date, however, the influence of changes in the TS content alone on the stability of continuous dry anaerobic digestion has not been examined.

The aim of this study was therefore to identify a suitable substrate TS content for dry thermophilic anaerobic co-digestion of rice straw and pig manure. The experiment was conducted to (i) determine the range of TS contents in the reactor at which there would be stable biogas production, (ii) ascertain the reactor TS content that inhibits biogas production, and (iii) identify the optimum substrate TS content for stable biogas production as well as less water addition to the substrate as possible using simple TS balance model. A semi-batch dry thermophilic anaerobic co-digestion system for rice straw and pig manure was constructed. The TS content in the reactor was progressively increased by reducing the water content in the substrate; the solid retention time (SRT) was also increased so that the OLR was constant throughout the experiment, which then allowed us to identify the optimal TS content thresholds in the reactor without any influence from the OLR. From the results, the optimal TS content for dry thermophilic anaerobic digestion of rice straw and pig manure was recommended.

2. Materials and methods

2.1. Feedstock and inoculum

Forage rice straw (*Oryza sativa* L. cv. Takanari), and a mixture of pig urine and dung, were used as a feedstock. The forage rice straw had been harvested from a rice field in Ibaraki Prefecture, Japan, in 2012. The forage rice straw was cut into 10-cm lengths before feeding. Stable biogas production was proved in dry-thermophilic anaerobic co-digestion of the 10-cm length rice straw and pig manure in the same reactor used in this study (Riya et al., 2016). Pig urine and dung were from a pig farm in Ibaraki Prefecture, Japan. The urine and dung were mixed at a ratio of 1.9:3.5 by weight to simulate the composition of pig manure (Haga et al., 2004). Inoculum was obtained from a lab-scale dry-thermophilic anaerobic digester fed with rice straw and pig manure. Properties of the inoculum, pig dung, pig urine, and forage rice straw are shown in Table 1.

2.2. Semi-batch dry-thermophilic anaerobic digestion

Semi-batch dry-thermophilic anaerobic co-digestion was performed in a 20-L stainless steel, cylindrical digester (Fig. S1 of supplementary material). There were two ports on the lid of the digester; one was used for sampling the gas, and the other was connected to a flow meter that measured the cumulative biogas production (Fig. S1a). The space between the digester and the lid was packed with silicon seat to ensure that the digester remained sealed during the incubation (Fig. S1b). The volume of sludge

Table 1
Properties of inoculum, pig dung, pig urine, and forage rice straw.

	Inoculum	Dung	Urine	Rice straw
TS (%)	17.6	25.5	4.6	92.3
VS (%)	7.9	16.0	1.3	58.2
TC (g kg^{-1} wet)	63.0	11.8	1.1	35.6
TN (mg kg^{-1} wet)	4476	7682	5341	4861
NH_4^+ (mg kg^{-1} wet)	1345	2004	3035	N.D.[a]
pH	8.8	8.4	7.8	N.D.
Carbohydrate (% of VS)	N.D.	73.7	6.34	93.2
Protein (% of VS)	N.D.	20.2	61.6	4.35
Lipid (% of VS)	N.D.	6.1	32.1	2.5

[a] Not determined.

Please cite this article in press as: Riya, S., et al. The influence of the total solid content on the stability of dry-thermophilic anaerobic digestion of rice straw and pig manure. Waste Management (2018), https://doi.org/10.1016/j.wasman.2018.02.033