International Biodeterioration & Biodegradation 124 (2017) 155–161

Contents lists available at ScienceDirect

International Biodeterioration & Biodegradation

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

Relationship between the synergistic/antagonistic effect of anaerobic co-digestion and organic loading

Tian Xie, Sihuang Xie, Muttucumaru Sivakumar, Long D. Nghiem*

Strategic Water Infrastructure Laboratory, School of Civil Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia

ARTICLE INFO

Article history:
Received 11 February 2017
Received in revised form
28 March 2017
Accepted 28 March 2017
Available online 6 April 2017

Keywords:
Anaerobic co-digestion
Synergistic effects
Organic loading
Sewage sludge
Food waste
Energy recovery

ABSTRACT

Results from this study reveal a notable relationship between the synergistic/antagonistic performance of sewage sludge – food waste anaerobic co-digestion (AcoD) and organic loading. At the same sewage sludge content, biomethane potential assays show an increasing specific methane yield as the content of food waste increased to the optimum organic loading of 15 kg VS/m^3. Under these conditions, the specific methane yields experimentally measured in this study were considerably higher than those calculated by adding the specific methane individual co-substrates during mono-digestion. On the other hand, at above the optimum organic loading value, the antagonistic effect (i.e. lower specific methane yield compared to mono-digestion) was observed. The relationship between synergistic performance of AcoD and organic loading was also evidenced in the removal of volatile solids as well as chemical oxygen demand. Further analysis of the intermediate products show that methanogenesis was the rate limiting step during AcoD at a high organic loading value. As the organic loading increased, the digestion lag phase increased and the hydrolysis rate decreased.

1. Introduction

Sewage sludge is a solid by-product from municipal wastewater treatment. Because sewage sludge is rich in biodegradable organics and pathogenic agents, adequate treatment is necessary prior to disposal or any form of land applications (Semblante et al., 2014). Given the large amount of sewage sludge generated each day, sewage sludge management has become a major issue for the wastewater industry. Indeed, the treatment and disposal cost of sewage sludge accounts for up to 50% of the total operational budget of a typical wastewater treatment plant (WWTP) (Appels et al., 2008; Li et al., 2014).

Anaerobic digestion (AD) is the most widely used technology for sewage sludge treatment. AD is a multi-stage biological process to convert organic materials to biogas and stabilised biosolids in the absence of oxygen (Mata-Alvarez et al., 2014). Biogas contains 40–60% CH_4, 30–40% CO_2, and a trace amount of other gases such as H_2S and water vapour (Chynoweth et al., 2001; Wickham et al., 2016). Given its methane content, biogas is a valuable renewable fuel, which can be used by a combined heat and power engine to generate electricity to offset part of the energy demand at the WWTP and heat which can be used by the AD process itself (Shen et al., 2015). Stabilised biosolids are also valuable resources and can be used for agriculture production and soil reclamation (Armstrong et al., 2017).

The role of AD has become even more significant given the recent paradigm shift toward a circular economy in which sludge and organic wastes can be utilised as a renewable resource of energy and nutrients through anaerobic co-digestion (AcoD) (Mata-Alvarez et al., 2014; Nghiem et al., 2017). AcoD can utilise the infrastructure at existing WWTPs without a major capital investment (Nghiem et al., 2017). A significant increase in methane production can be achieved when the mixture of substrates has a balanced composition of carbon source, nutrients, and trace elements (Panpong et al., 2014b). The economic benefits from AcoD can be realised through gate fee revenue from organic wastes and bioenergy generation (Xie et al., 2016). In terms of environmental benefits, AcoD can divert the organic waste from the landfills and eliminate the greenhouse gas emissions at the same time (Nghiem et al., 2014; Xie et al., 2016). Other benefits include the dilution of toxic compounds, improve nutrition balance, and load increase of the biodegradable organic matter (Sosnowski et al., 2003).

A range of organic wastes is available for AcoD operation.

* Corresponding author.
E-mail address: longn@uow.edu.au (L.D. Nghiem).

http://dx.doi.org/10.1016/j.ibiod.2017.03.025

Among them, food waste is arguably the most abundant substrate that is also rich in energy (i.e. carbon) and nutrient content (Thi et al., 2016). In general, food waste consists of 10–30% readily biodegradable organic materials (Ratanatamskul and Manpetch, 2016; Zhang et al., 2007, 2016). Given the high organic content of food waste, AD has been identified as an ideal solution for energy recovery from food waste. In addition to the many benefits of AcoD discussed above, there have been several reports of the synergistic effect when sewage sludge is co-digested with organic-rich substrates, particularly food waste (Fernández et al., 2005; Khairuddin et al., 2015; Panpong et al., 2014a; Xie et al., 2017). This synergistic effect is defined as an increase methane yield compared to mono-digestion by per unit VS or COD input. However, data currently available in the literature are rather inconsistent. Antagonistic and neutral effects have also been observed during AcoD of sewage sludge and organic wastes. Silvestre et al. (2014) reported a decrease in methane production by more than 40% during thermophilic AcoD of sewage sludge and grease waste when the content of grease waste increased from 27 to 37% at the same organic loading. Their results demonstrate an antagonistic effect possibly due to fatty acid inhibition (Silvestre et al., 2014). In another study, Silvestre et al. (2015) did not observe any changes in the specific methane yield during mesophilic AcoD of sewage sludge and crude glycerol at more than 1% (v/v) co-substrate addition. Given the inconsistency in the literature regarding synergistic effect during AcoD, it is hypothesised here that organic loading can play a major role in governing the specific methane yield.

In practice, organic loading is a key parameter in the continuous operation of AcoD (Mata-Alvarez et al., 2014). In a batch process, organic loading can be defined as the ratio of either VS or COD content over volume. In a continuous process, the retention time is taken into account and the organic loading rate (OLR) can be used instead. Mono-digestion of sewage sludge at WWTPs is usually operated at an OLR of less than 1 kg VS/(m^3.d) (Nghiem et al., 2017). On the other hand, given the high organic content of the co-substrate (particularly food waste), AcoD is operated at a much higher OLR value of up to 4.6 kg VS/(m^3.d) (Nghiem et al., 2017; Zhang and Jahng, 2012), which may result in operational stability issues. Therefore, in terms of treatment efficiency and process stability, many efforts have been devoted to exploring the optimum organic loading for AcoD operation (Agyeman and Tao, 2014; Aramrueang et al., 2016; Li et al., 2015; Paudel et al., 2017).

The aim of this study is to explore the relationship between organic loading and the synergistic effects during AcoD of sewage sludge and food waste through BMP evaluation. The specific objectives include (i) evaluating the process performance and stability from total solids (TS), VS, and soluble COD removal, (ii) determining the hydrolysis rate constant (K_h) based on the reaction kinetics, (iii) appraising the biomethane yield and the synergistic effect at various organic loadings.

2. Materials and methods

2.1. Substrate characterization

Digestate and primary sludge samples were obtained from a full-scale WWTP in Wollongong and used as the inoculum and substrate respectively. Adult dog food from Optimum™ was used to simulate food waste. The Optimum dog food (beef & rice) contains mainly protein, carbohydrate, and fat. All substrates and inoculum were stored at 4 °C for less than 3 days prior to the BMP evaluation.

2.2. BMP assays

Food waste and sewage sludge were co-digested using a custom-built BMP system. The BMP system consisted of an array of 1000 mL volume fermentation glass bottles (Wiltronics Research Pty Ltd) and gas collection galleries as shown in Fig. 1 (Nghiem et al., 2014). Each bottle was submerged in a water bath (Model SWB20D, Ratek Instrument Pty Ltd) which constantly maintained the temperature at 35.0 ± 0.1 °C. Each setup of fermentation bottle consisted of a rubber stopper, S-shaped airlock, and soft tubes, which connect to a gas valve to the gas collection gallery and sampling valve for taking samples. The S-shaped airlock can maintain the substrates under an anaerobic condition by allowing the releasement of biogas produced in the fermentation bottle while preventing any intrusion of air into the system. The gas collector consists of a 1000 mL volume plastic cylinder and a plastic container, which both filled up with 1 M sodium hydroxide solution to ensure the gathered biomethane free from the disturbance of carbon dioxide and hydrogen sulphide.

Prior to the BMP evaluation, all the fermentation bottles were flushed with N_2 for 5 min before the immediate filling of co-substrates and inoculum as introduced in section 2.1. Organic loading was calculated based on the initial VS content in each BMP bottle (Table 1). All BMP experiments were conducted in duplicate.

Two BMP bottles were filled with only inoculum and used as the reference. Mono-digestion was simulated by filling the BMP bottles with inoculum and either sewage sludge or food waste. Co-digestion was simulated by filling the BMP bottles with inoculum, sewage sludge, and food waste. The active volume of all BMP bottles was 750 mL, which consisted of 450 mL of inoculum and a specified amount of substrate as noted in Table 1. When the substrate volume was less than 300 mL, Milli-Q water was added to obtain the total volume of 750 mL.

After filling with inoculum and substrates, the BMP bottles were flushed with N_2 again, sealed with rubber stopper instantly, and placed in the water bath, which was maintained at 35 °C. The gas valves were then opened to allow biogas from entering to the gas collection gallery. The BMP experiments were terminated when the daily methane production during three consecutive days was less than 10 mL. All BMP bottles were mixed manually twice a day.

The BMP protocol used in this study is broadly consistent with the standard procedure recommended by Holliger et al. (2016). However, it is noted that in this study, the inoculum to substrate (I/S) ratio was not constant to simulate varying organic loadings at a constant reactor volume.

2.3. First order kinetics

2.3.1. Biomethane production

Methane productivity was calculated and the cumulative methane yield was simulated with modified Gompertz model in Eq. (1):

$$M = Pexp\left\{-\exp\left[\frac{eR_{max}(\lambda - t)}{P} + 1\right]\right\} \quad (1)$$

where P is the maximum methane potential (mL); M is the cumulative methane production (mL); R_{max} is the maximum methane production rate (mL/d); λ is the lag phase (d); e is Euler's number (≈2.71828); and t is the time (d).

2.3.2. Hydrolysis process

K_h reflects the rate of the hydrolysis stage and depends highly on the addition of co-substrate, and operating conditions (Xie et al., 2017). It can be directly calculated using the net cumulative