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Hydrogen and methane production by co-digestion of waste activated sludge and food waste in the two-stage fermentation process: Substrate conversion and energy yield

Xinyuan Liu, Ruying Li *, Min Ji, Li Han

School of Environmental Science and Engineering, Tianjin University, Weijin Road 92, Tianjin 300072, China

HIGHLIGHTS

- H_2 and CH_4 were produced by co-digestion of food waste and waste activated sludge.
- The highest H_2 and CH_4 yields were achieved at the food waste proportion of 85%.
- The highest energy yield of 14.0 kJ/g-VS was achieved at food waste of 85%.
- Substrates conversion in each fermentation stage was investigated.
- Co-digestion had higher VS removal efficiency than single substrate fermentation.

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ABSTRACT

Batch experiments were conducted to produce hydrogen and methane from waste activated sludge and food waste by two-stage mesophilic fermentation. Hydrogen and methane production, energy yield, soluble organic matters, volatile solid removal efficiency and carbon footprint were investigated during two-stage digestion at various food waste proportions. The highest energy yield reached 14.0 kJ/g-VS at the food waste proportion of 85%, with hydrogen and methane yields of 106.4 ml-H_2/g-VS and 353.5 ml-CH_4/g-VS respectively. The dominant VFA composition was butyrate for co-digestion and sole food waste fermentation, whereas acetate was dominate in VFA for sole waste activated sludge fermentation. The VS removal efficiencies of co-digestion were 10–77% higher than that of waste activated sludge fermentation. Only 0.1–3.2% of the COD in feedstock was converted into hydrogen, and 14.1–40.9% to methane, with the highest value of 40.9% in methane achieved at food waste proportion of 85%.

1. Introduction

With the rapid development of wastewater treatment facilities, large amount of waste activated sludge is produced in China (Guo et al., 2008). Waste activated sludge contains great amount of water, microorganisms, and various organic and inorganic matters. The treatment and disposal of waste activated sludge is thus a significant environmental problem for wastewater treatment plants. On the other hand, the waste activated sludge is also an important biomass resource. Anaerobic digestion can effectively convert the bioenergy of sewage sludge to the methane fuel. However, conventional sludge digestion process does not collect hydrogen, which is an important intermediate product during anaerobic fermentation. Hydrogen is a clean and renewable energy, with an energy yield of 122 kJ/g, which was about 2.75 times higher than that of hydrocarbon fuel (Sreela-or et al., 2011). The two-stage fermentation process with hydrogen and methane production in respective reactor can increase the energy recovery efficiency (Lee and Chung, 2010; Xie et al., 2008).

However, hydrogen and methane yields of the two-stage fermentation from waste activated sludge were very low. It was reported that the hydrogen and methane yields were 3.8 ml/g-TS (Total solid) and 31.6 ml/g-TS respectively for waste activated sludge fermentation (Ting and Lee, 2007). Because of the low C/N ratio of waste activated sludge, other organic matters were generally used as the co-substrates to mix with waste activated sludge and adjust the nutrient balance in order to increase the biogas production. So far, the co-substrates utilized to adjust C/N ratio of waste activated sludge for two-stage fermentation included the meat-processing by-products (Luste and Luostarinen, 2010), cassava stillage (Wang et al., 2011), landfill leachate (Montusiewicz and Lebiocka, 2011) and food waste (Siddiqui et al., 2011) etc.

Food waste is a good co-substrate for waste activated sludge fermentation, with high C/N ratio and abundant organic matters,

* Corresponding author. Tel./fax: +86 22 27406057.
E-mail addresses: liuxinyuan11@163.com (X. Liu), liruying@tju.edu.cn (R. Li), jimin@tju.edu.cn (M. Ji), hanlitju@163.com (L. Han).

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which have been comprehensively demonstrated in single-stage fermentation processes to produce hydrogen (Sreela-or et al., 2011) or methane (Lahdheb et al., 2009). However, study on co-digestion of food waste and waste activated sludge for hydrogen and methane production by two-stage fermentation process is still at the embryonic stage. Most of the studies mainly focused on various methods to increase biogas production (Siddiqui et al., 2011; Zhu et al., 2011). Reports on substrates conversion mechanism corresponding to biogas production were still very limited. In this study, food waste was utilized as a co-substrate for waste activated sludge to produce hydrogen and methane in a two-stage fermentation process. Parameters of the fermentation process at various food waste proportions were analyzed, including hydrogen and methane yields, biogas energy yields, volatile solid (VS) removal efficiencies, volatile fatty acids (VFA), soluble carbohydrate, soluble protein, ammonium and carbon footprint.

2. Methods

2.1. Seed sludge

The hydrogen-producing seed sludge was the activated sludge obtained from the secondary sedimentation tank of Ji Zhuangzi wastewater treatment plant in Tianjin, China. The activated sludge was cultured for 7 days under anaerobic condition, and then heated at 100 °C for 30 min to enrich hydrogen-producing bacteria (Xie et al., 2008). The heat pretreated sludge was anaerobically cultured using glucose at pH5.5 for 7 days. The cultured sludge was centrifuged and washed by ultra-pure water for three times to remove the residual glucose. The washed sludge was heated again at 100 °C for 30 min and then used as hydrogen-producing seed sludge, which had the VS/TS of 51.8%. The methane-producing seed sludge was obtained from an anaerobic methane fermentation reactor, which had the VS/TS of 45.5%.

2.2. Substrates

Substrates in this study included waste activated sludge and food waste. The waste activated sludge with the VS/TS of 67.74% was collected from membrane bioreactor treating bath wastewater in the swimming pool of Tianjin University, China. The VS/TS of this sludge was much higher than those in municipal wastewater treatment plants in Tianjin, which suggests that it was suitable as substrate for anaerobic fermentation. The food waste was collected from the cafeteria of Tianjin University. The characteristics of substrates were shown in Table 1. Table 1 shows that the concentration of soluble organics was very low for waste activated sludge, in which the soluble chemical oxygen demand (SCOD) was less than 1% of total COD. The soluble carbohydrate and protein in food waste were much higher than those in waste activated sludge, providing more easily biodegradable organics for anaerobic fermentation.

Table 1
Characteristics of waste activated sludge and food waste in feedstock.

Parameters	Waste activated sludge	Food waste
pH	7.3–7.4	5.1–5.4
VS/TS (%)	67.74	92.44
Soluble carbohydrate (mg/g-TS)	0.1	185.3
Soluble protein (mg/g-TS)	0.8	12.0
Soluble COD (mg/g-TS)	6.5	625.0
Total COD (mg/g-TS)	965	1136
Ammonium (mg/g-TS)	0.2	1.7

2.3. Experimental conditions

Batch experiments were conducted using 300 ml serum bottles filled with 150 ml of substrates. The substrate concentration was 10 g-VS/l in each bottle, containing 10%, 20%, 30%, 40%, 54% and 85% of food waste, respectively. The sole waste activated sludge (0% of food waste) and sole food waste (100% of food waste) served as control. Batch experiments were conducted in duplicate at each proportion of food waste. The initial pH was 5.5 and the seed sludge for hydrogen production was 1.26 g dry weight. All the bottles were purged by nitrogen gas for 10 min and then sealed by rubber stoppers. The bottles were put in a shaker with rotating speed of 120 rpm and the temperature of 37 °C. The volume and components of the biogas produced were measured periodically. After hydrogen production ceased, the methane-producing seed sludge with the dry weight of 1.10 g was added into each bottle. The pH of the substrate was adjusted to 7.0 and then the K_2HPO_4/KH_2PO_4 buffer solution (pH 7.0) was added. All the bottles were purged by nitrogen gas for 10 min again before sealing and then put in the shaker again for methane fermentation at 37 °C. The cumulative hydrogen and methane gas volume were calculated by the equation described in the previous study (Liu et al., 2013).

2.4. Analytical methods

Production of biogas was measured by a glass syringe. Compositions of biogas were analyzed by a gas chromatograph (BEIFEN 3040, China) equipped with a thermal conductivity detector and a stainless steel packed column (TDX-01, 2 m). Argon was used as the carrier gas at a flow rate of 35 ml/min. The operation temperatures of the injection port, oven and detector were 100, 100 and 130 °C, respectively. VFA including acetate, propionate, butyrate, i-butyrate, valerate and i-valerate, and ethanol in the mixed liquor were analyzed by another gas chromatograph (SP6890, China) equipped with a flame ionization detector and a fused-silica capillary column (HP-FFAP, 0.53 mm × 10 m × 1 μm). Nitrogen was used as the carrier gas with a flow rate of 6 ml/min. The temperature of injection port and detector were 200 and 250 °C, respectively. The soluble carbohydrate was analyzed using anthrone–sulfuric acid method with glucose as standard (Gaudy, 1962), and the soluble protein was analyzed by Lowry method (Lowery et al., 1951). COD was measured by HACH method (HACH, USA). The samples for analysis of soluble carbohydrate and protein were filtrated by 0.45 μm membrane before detecting. TS, VS and ammonium were determined according to Standard Methods (APHA, 2005).

2.5. Kinetic analysis

The cumulative hydrogen volume in batch experiments followed the modified Gompertz equation (Lay et al., 1998).

$$H = P \cdot \exp\left\{-\exp\left[\frac{R_m \cdot e}{P}(\lambda - t) + 1\right]\right\} \quad (1)$$

where H represents the cumulative hydrogen production (ml), λ the lag phase time (h), P the hydrogen production potential (ml), R_m the maximum hydrogen production rate (ml/h), and e the constant 2.71828. The values of P, R_m and λ for each batch were determined by best fitting the hydrogen production data for Eq. (1) using Microsoft's software Excel 2003.

2.6. VS removal efficiencies calculation

The VS removal efficiencies were calculated by Eq. (2)–(4).