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Short comminication

Optimization of continuous hydrogen fermentation of food waste as a function of solids retention time independent of hydraulic retention time

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Abstract

Four anaerobic sequencing batch reactors (ASBRs) were used for hydrogen fermentation and fed with food waste (4.4 ± 0.2% volatile solids (VS) containing 27 g carbohydrate-COD/L). The aim of this study was to investigate the effects of solids retention time (SRT) in the range 24–160 h and hydraulic retention time (HRT) in the range 24–42 h. Achieving high SRT independent of HRT with internal sludge retention contributed to higher H_2 production than in previous studies using continuous stirred-tank reactor systems. The maximum H_2 production rate of 2.73 L H_2/(L d) was estimated at an SRT of 126 h and HRT of 30 h, while the maximum H_2 yield of 80.9 mL H_2/g VS (1.12 mol H_2/mol $hexose_{added}$) occurred at an SRT of 126 h and HRT of 33 h. Furthermore, hydrogen fermentation facilitated organic acid conversion, alcohol conversion, and volatile suspended solid removal with efficiencies ranging from 29.6 to 46.3%, 4.1 to 14.6%, and 54.9 to 75.8%, respectively, which were comparable to conventional acidogenic fermentation without H_2 production.

Keywords: Hydrogen fermentation; Food waste; Solids retention time (SRT); Hydraulic retention time (HRT); Anaerobic sequencing batch reactor (ASBR)

1. Introduction

Inexpensive feedstock containing sufficient organic material is essential for making H_2 fermentation feasible [1]. Organic solid waste is a major environmental burden due to growing environmental awareness and public health concerns. It has the potential to be a plentiful and negative-value feedstock for H_2 production. In recent years, successful continuous H_2 production from various types of organic solid waste has been reported [2–7]. However, the design parameters for a continuous flow organic solid waste reactor have yet to be clearly defined.

The solids retention time (SRT) and hydraulic retention time (HRT) are important design parameters in biological processes. The SRT determines the substrate uptake efficiency, microbial population, and metabolic pathway. In H_2 fermentation, it is generally assumed that a high SRT causes the growth of H_2 consumers, including methanogens, and competitors for substrates, such as non-H_2-producing acidogens [8]. Therefore, an SRT in the range of 8–12 h is considered the general operational condition for continuous H_2 production from glucose or sucrose [9]. On the other hand, a low SRT may reduce substrate uptake efficiency, active biomass retention, and therefore, the overall process efficiency [10]. Furthermore, in the case of complex substrates such as organic solid waste, a higher SRT may be required due to the slowly degradable organic compounds [3,7,11]. However, little is known about the effects of SRT on H_2 fermentation of organic solid waste independent of HRT, because most previous studies used continuous stirred-tank reactor (CSTR) systems [2–6]. HRT determines the economics of the process, independent of SRT. For a given volume of waste, a lower HRT means a smaller reactor and therefore decreased cost. If the optimum level of SRT could be provided at a low HRT, it would enhance the productivity and technical feasibility of the H_2 production process.

This aim of this study was to investigate the effects of SRT on the continuous H_2 fermentation of organic solid waste, independent of HRT. Food waste, which accounts for 26.8% of the municipal solid waste in South Korea [12] amounting to about 12,977 tonnes/day—was used at the feedstock. Four anaerobic sequencing batch reactors (ASBRs) were operated

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for 84–130 days, with the SRT and HRT controlled in the ranges of 24–160 h and 24–42 h, respectively. The possibility of using H_2 fermentation as an organic solid waste treatment process was also evaluated.

2. Material and methods

2.1. Seed sludge and feedstock

Seed sludge was obtained from an anaerobic digester at Daejeon municipal wastewater treatment plant in South Korea. The digester was operated at 35 °C at an HRT (SRT) of 25 days, and fed a mixture of primary and secondary sludge. The pH, alkalinity, and volatile suspended solids (VSS) concentrations of the sludge were 7.6, 2.83 g $CaCO_3$/L, and 5.5 g/L, respectively. The sludge was heat-treated at 90 °C for 10 min to deactivate any bioactivity of H_2 consumers.

Food waste was obtained from a cafeteria at the Korea Advanced Institute of Science and Technology. Analysis conducted after the bones and clamshells were removed showed that on a total solids (TS) basis, it was composed mainly of grains (36.3 ± 1.8%), vegetables (45.8 ± 2.7%), meat (12.2 ± 2.3%), and fish (4.6 ± 0.5%). After grinding in a garbage disposal unit (Waste King Gourmet model 1001; Anaheim Manufacturing), we found that about 96.4% of the dried ground particles could pass through US sieve #8 (2.38 mm). The concentration of volatile solids (VS) in the ground food waste was 16.1 ± 0.9%. We adjusted the pH to 12.5 using 6 M KOH (average 3.0 mmol OH^-/g of VS) and agitated it at 30 rpm for 24 h under anaerobic conditions to enhance the hydrolysis of particulate organics and reduce the potential propagation of H_2 consumers [13–15]. Then, we added enough tap water to maintain the carbohydrate concentration at 27.0 g chemical oxygen demand (COD)/L (average VS 4.4%) [16,17]. We added iron in the form of $FeCl_2{}^{\bullet}4H_2O$ to maintain a level of 10 mg Fe/L [18]. The resulting feedstock characteristics were as follows: TS 4.6 ± 0.3%, VS 4.4 ± 0.2%, VSS 20.6 ± 1.5 g/L, total COD 44.2 ± 2.3 g/L, soluble COD 21.9 ± 1.3 g/L, soluble carbohydrate 12.6 ± 1.0 g COD/L, total Kjeldahl nitrogen 1.1 g N/L, total organic acid 3.6 ± 0.5 g COD/L, total alcohol 0.4 ± 0.1 g COD/L, pH 11.8 ± 0.3, and alkalinity 4.8 ± 0.3 g $CaCO_3$/L.

2.2. Reactor operation

We constructed four identical ASBRs each with a working volume of 4.5 L (liquid depth of 200 mm and inner diameter of 170 mm), operated in a room where the temperature was maintained at 35 ± 1 °C. Each ASBR was connected to a water displacement unit filled with acidified-saturated salt solution to measure biogas production. Two of the four reactors were inoculated with 1.35 L of the heat-treated sludge, and filled with the feedstock to the working volume. The headspace of the reactors was flushed with N_2 gas for 1 min, and then the reactors were agitated at 200 rpm. When cumulative H_2 production was equivalent to 0.5 mol H_2/mol $hexose_{added}$, the reactors were put into sequencing batch feed mode, going through three 8-h batches per day of feeding, reaction, and drawing phases. The feeding and drawing were controlled by an automatic pump. As the volume of biogas in the water displacement unit was maintained larger than the drawn volume, the gas phase of the reactors was kept anaerobic. The HRT (reactor volume divided by influent flow rate) was maintained at 24 h in reactor 1 and at 30 h in reactor 2. The reactors were agitated continuously at 200 rpm without settling before the drawing phase to maintain the SRT equal to the HRT. The pH of the mixed liquor was maintained at a level greater than 5.3 ± 0.1 by adding 3 M KOH [18]. After a start-up period, the mixed liquor from reactors 1 and 2 was used to seed reactors 3 and 4 with designated HRTs of 36 and 42 h, respectively. We operated all four reactors for at least 20 days, and then conducted further runs with increasing SRTs up to 120–160 h independent of the HRT. In these cases, a settling phase was introduced between the reaction phase and the drawing phase to allow separation of the liquids and solids. We stopped the agitation and pH control during the settling and drawing phases. As there was no waste sludge, the SRT is defined as

$$\theta_c = \theta \frac{X}{X_e} \quad (1)$$

where θ_c is the SRT, θ the HRT, X the VSS in the mixed liquor, and X_e is the VSS in the effluent. As the concentrated solids often floated during the settling phase due to internal gassing, a higher operating SRT than HRT was maintained by adjusting the settling time and the drawing level by changing the relative height of the drawing port with respect to the depth of mixed liquor. The settling time and the drawing level were readjusted three times per week. In most cases, the target SRT was reached within 7 days with a margin of error of ±20%. Table 1 summarizes the phase cycle times and the drawing level for each operating condition. In all cases, the operating period was greater than 20 days, and steady (±10%) H_2 production was maintained for at least 3 consecutive days before measuring the performance data.

2.3. Analytical methods

The measured biogas production was corrected to standard temperature (0 °C) and pressure (760 mmHg) (STP). The H_2, CH_4, N_2, and CO_2 contents of the biogas were determined using a gas chromatograph, while the organic acids and aliphatic alcohols were measured by high-performance liquid chromatography [17]. The solids, COD, VSS, Kjeldahl nitrogen, ammonia, and alkalinity were quantified according to standard methods [19]. Total and soluble carbohydrates were determined using the phenol–sulfuric acid method [20].

3. Results

3.1. Production of hydrogen

Production of H_2 reached steady-state (±10%) within 22 days in reactor 1 (24 h HRT) and reactor 2 (30 h HRT). Reactor 3 (36 h HRT) and reactor 4 (42 h HRT), which had been seeded with the mixed liquor from the other two reactors, also showed stable H_2 production within 10 days. When the SRT was the same as the HRT, the maximum H_2 production (0.91 L H_2/(L d) or 25.8 mL H_2/g VS_{added}) was observed at an HRT of 30 h (35 g VS/(L d) organic loading rate). However, the maximum yield was lower than the maximum H_2 production potential of the same food waste (60.1 mL H_2/g VS_{added}) using non-acclimated inoculum in a previous batch test [16]. Furthermore, the H_2 production based on $hexose_{added}$ was 0.36 mol H_2/mol $hexose_{added}$, which was lower than the typical reported

Table 1
ASBR operating conditions

HRT (h)	SRT (h)	Cycle time (min)				Drawing level[a]
		Filling	Reaction	Settling	Drawing	
24	24	5	470	0	5	0.65
24	50	5	380	90	5	0.65
24	70	5	400	70	5	0.42
24	100	5	380	90	5	0.42
24	120	5	350	120	5	0.42
30	30	5	470	0	5	0.65
30	60	5	380	90	5	0.65
30	90	5	400	70	5	0.42
30	160	5	380	90	5	0.20
36	36	5	470	0	5	0.65
36	70	5	420	50	5	0.65
36	120	5	400	70	5	0.42
36	160	5	380	90	5	0.20
42	42	5	470	0	5	0.65
42	75	5	400	70	5	0.65
42	100	5	380	90	5	0.42
42	120	5	350	120	5	0.42

[a] Relative height of the drawing port with respect to the depth of mixed liquor.