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Evaluation of bioenergy recovery processes treating organic residues from ethanol fermentation process

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ABSTRACT

This study evaluates a two-stage bioprocess for recovering bioenergy in the forms of hydrogen and methane while treating organic residues of ethanol fermentation from tapioca starch. A maximum hydrogen production rate of 0.77 mmol H_2/g VSS/h can be achieved at volumetric loading rate (VLR) of 56 kg COD/m^3/day. Batch results indicate that controlling conditions at $S_0/X_0 = 12$ with $X_0 = 4000$ mg VSS/L and pH 5.5–6 are important for efficient hydrogen production from fermentation residues. Hydrogen-producing bacteria enriched in the hydrogen bioreactor are likely utilizing lactate and acetate for biohydrogen production from ethanol-fermentation residues. Organic residues remained in the effluent of hydrogen bioreactor can be effectively converted to methane with a rate of 0.37 mmol CH_4/g VSS/h at VLR of 8 kg COD/m^3/day. Approximately 90% of COD in ethanol-fermentation residues can be removed and among that 2% and 85.1% of COD can be recovered in the forms of hydrogen and methane, respectively.

1. Introduction

The importance of renewable energy sources increases as the concerns of fossil fuel exhaustion and global climate change become serious. Considering the energy security and the global environment, there is an urgent need in developing a clean and renewable energy source. Bioenergy is considered an important form of renewable energy because of its sustainable feature, by growing energy crops from sunlight, carbon dioxide, and water. Currently, production of bio-ethanol and bio-diesel from different energy crops is technologically feasible, although its impacts on global economic and food security issues are debatable.

Hydrogen is a clean energy carrier, generating only water when it burns. However, for hydrogen production to meet sustainability requirements, it must be produced from renewable resources. One way to produce hydrogen renewably is through fermentative biohydrogen production from potential renewable materials such as carbohydrate-containing biomass and organic wastes (Das and Veziroglu, 2001; Hawkes et al., 2002; Li and Fang, 2007). Hydrogen production from anaerobic waste treatment potentially benefits both organic wastes reduction and renewable energy production at the same time (Water Environment Research Foundation, 1999), but it also creates challenges because the waste materials usually are composed of a variety of substrates that can be used by different species of microorganisms (Whang et al., 2006; Li and Fang, 2007; Li et al., 2010). Furthermore, wastewater compositions and characteristics are important for hydrogen fermentation. In general, simple sugars, such as sucrose and glucose, are easily converted to hydrogen and other metabolites through fermentation at high conversion efficiencies (Li and Fang, 2007; Lin et al., 2007). Fermentative biohydrogen has been studied for the organic fraction of municipal solid wastes (Lay et al., 1999; Okamoto et al., 2000), damaged wheat grains (Kalia et al., 1993), cellulose (Lay, 2001), municipal wastewater and sludge (Kim et al., 2004; Van Ginkel et al., 2005), distillery spent wash (Mohana et al., 2009), potato waste (Zhu et al., 2008), and food wastes (Han and Shin, 2004; Kim et al., 2004; Van Ginkel et al., 2005; Chu et al., 2008; Lee et al., 2008); but results suggest that hydrogen production is more efficient from carbohydrates than other materials (Li and Fang, 2007), indicating that high-carbohydrate wastewaters will be the most suitable ones for industrial production of hydrogen (Van Ginkel et al., 2005). Besides wastewater compositions and characteristics, another difficulty to the practical application of fermentative biohydrogen production is that conversion yields by known metabolic pathways appear to be limited to a maximum of 4 mol of hydrogen per mole of glucose, representing a maximum conversion efficiency of 33% (Gottschalk, 1986; Ljungdahl et al., 1989; Hallenbeck, 2009). This also indicates that the majority of the COD of waste streams remains untreated and that other processes,

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such as methanogenesis, would be more effective. Therefore, to be practical, means must be found to recover the remaining potential energy content (Hallenbeck, 2009).

In this study, we investigated a two-stage bioprocess for treating organic residues generated during ethanol fermentation from tapioca starch. Current technologies for ethanol fermentation from energy crops can attain a conversion efficiency of 75–80%, remaining about 20–25% of organic wastes as residues. The main objective of this study was to recover bioenergy in the form of hydrogen and methane while treating ethanol fermentation residues through the two-stage bioprocess. Two bioreactors were continuously operated at different organic loadings to evaluate their performance on reduction of organic wastes and production of hydrogen and methane. In this article, batch experiments on fermentative biohydrogen production were conducted to evaluate effects of substrate concentration and pH on hydrogen production. Furthermore, metabolism of fermentative biohydrogen from ethanol fermentation residues is also discussed. Finally, overall bioenergy recovery from the two-stage bioprocess treating organic residues of ethanol fermentation from tapioca starch is evaluated.

2. Methods

2.1. Operation of the two-stage bioprocess

Two bioreactors were operated in this study as a two-stage bioprocess. The first bioreactor, hydrogen fermentation bioreactor, was fed with organic residues obtained from an ethanol fermentation process using tapioca starch as substrate. Table 1 summarizes the wastewater characteristics of ethanol fermentation residues investigated in this study. As shown in Table 1, the residues contained a total COD of 67,700 mg/L, which consisted of volatile solid (1481 mg/L), carbohydrate (22,600 mg/L), organic nitrogen (4400 mg/L), organic acids and alcohols. The organic acids included lactate (5000 mg/L), acetate (1410 mg/L), and propionate (705 mg/L), while the alcohols included methanol (6000 mg/L) and ethanol (8658 mg/L). The second bioreactor, methane fermentation bioreactor, was fed with the effluent collected from the hydrogen fermentation bioreactor. The total volume of each bioreactor was 12 L with a working volume of 8 L and both bioreactors were equipped with a mechanic propeller for mixing. A complete-mix condition was achieved for the hydrogen fermentation bioreactor at an agitation speed of 160 rpm, while a gentle mixing was applied for the methane fermentation bioreactor at an agitation speed of 30 rpm in order to retain granular sludge in the bioreactor without washout. Both bioreactors were kept in a water-bath incubator in order to maintain an operational temperature at 35 °C. The influent feeds of both bioreactors were stored at 4 °C in a refrigerator and continuously fed into the bioreactors using a peristaltic pump. Oxidation–reduction potential (ORP) and pH were monitored for both bioreactors during operation. The pH values for hydrogen and methane fermentation bioreactors were controlled at 6 and 7, respectively, using a pH controller with addition of 5% H_3PO_4 and 2% NaOH throughout the experiments. The amount of biogases produced from both bioreactors was measured with a wet-gas flow meter (Shinagawa W-NK-0.5B, Tokyo, Japan). The seeding microorganisms for the hydrogen fermentation bioreactor was obtained from a pilot-scale hydrogen fermentor treating food wastes, while the seeding microorganisms for the methane fermentation bioreactor was from a pilot-scale upflow anaerobic sludge blanket (UASB) bioprocess also treating food wastes for methane production.

The operational conditions of the hydrogen and methane fermentation bioreactors are summarized in Table 2(A) and (B), respectively. Based on predetermined operational conditions for hydraulic retention time (HRT) and feed concentration, the volumetric loading rates (VLR) for the hydrogen fermentation bioreactor increased gradually from 25.2 to 117.6 kg COD/m^3/day, while for the methane fermentation bioreactor, the VLR varied between 2 and 19.8 kg COD/m^3/day.

2.2. Fermentative biohydrogen tests

The fermentative biohydrogen batch test conducted in this study was a modified version of biochemical methane potential

Table 1
Summary of wastewater characteristics of ethanol fermentation residues investigated in this study.

Parameter	Value	COD (%)
pH	4.0 ± 0.2	
Total COD (mg/L)	67,700	100
Soluble COD (mg/L)	63,800	94
TSS (mg/L)	1580	
TVS (mg/L)	1480	6
Total carbohydrate (mg/L)	22,600	37
Soluble carbohydrate (mg/L)	22,400	
Total organic nitrogen (mg-N/L)	4400	
Soluble organic nitrogen (mg-N/L)	4320	
Ammonium (mg-N/L)	1520	
Lactate (mg/L)	5000	8
Acetate (mg/L)	1410	2
Propionate (mg/L)	700	2
Methanol (mg/L)	6000	14
Ethanol (mg/L)	8660	28

Table 2
Operational parameters of the (A) hydrogen and (B) methane fermentation bioreactors.

Operational parameter	Reactor Unit	Hydrogen fermentation bioreactor Run 1	Run 2-1	Run 2-2	Run 3	Run 4
(A) Hydrogen fermentation bioreactor						
HRT	h	19.0	8.3		16.3	8.2
Substrate conc.	g COD/L	20	20		40	40
VLR	kg COD/m^3/day	25.2	57.6		59.0	117.6
F/M	kg COD/kg VSS/day	8.1	12.5	24.5	16.1	17.6

		Methane fermentation bioreactor Run 1-1	Run 1-2	Run 2	Run 3
(B) Methane fermentation bioreactor					
HRT	h	24	24	24	24
Substrate conc.	g COD/L	19.8	2	4	8
VLR	kg COD/m^3/day	19.8	2.0	4.0	8.0
F/M	kg COD/kg VSS/day	1.65	0.17	0.33	0.67