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Techno-economic evaluation of a combined bioprocess for fermentative hydrogen production from food waste

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HIGHLIGHTS

- The techno-economic evaluation of H_2 production from food waste was performed.
- The H_2 price and labor cost have the highest impact on the net present value.
- The unit production cost of hydrogen obtained from this study was US\$1.02/m^3.
- The plant would shutdown with food waste feed less than 0.3 ton/day.

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ABSTRACT

In this study, the techno-economic evaluation of a combined bioprocess based on solid state fermentation for fermentative hydrogen production from food waste was carried out. The hydrogen production plant was assumed to be built in Hangzhou and designed for converting 3 ton food waste per day into hydrogen. The total capital cost (TCC) and the annual production cost (APC) were US\$583092 and US \$88298.1/year, respectively. The overall revenue after the tax was US\$146473.6/year. The return on investment (ROI), payback period (PBP) and internal rate of return (IRR) of the plant were 26.75%, 5 years and 24.07%, respectively. The results exhibited that the combined bioprocess for hydrogen production from food waste was feasible. This is an important study for attracting investment and industrialization interest for hydrogen production from food waste in the industrial scale.

1. Introduction

With the development of technology and economy, a number of environmental problems have gradually exposed, such as municipal solid waste pollution (Tawfik et al., 2011). The generation of municipal solid waste has increased more than four times over the past three decades (Sagnak et al., 2011). Food waste is one of the largest parts which accounts for one third of the municipal solid waste (Elbershbishy et al., 2011). So, disposal and utilization of food waste has become a major environmental problem, especially in the developing countries (Han et al., 2015a). Governments have to spend a large amount of money to reduce food waste pollution. For example, the Chinese government was going to invest 260 billion for the construction of garbage disposal facilities, including 10.9 billion in food waste disposal (Li et al., 2009).

Generally, landfill, incineration and composting are three basic technologies for municipal solid waste disposal. However, these methods are not suitable for treating food waste because of the space limitation, production of toxic gas and high energy consumption (Pleissner et al., 2013). Hangzhou, which is one of the major cities of China, is puzzled by food waste problem. In the past 7 years, the municipal solid waste of Hangzhou grew by an average of 10% per year (Zhang et al., 2013). According to the present growth rate, Hangzhou Tianzi Mountain Landfill will be used only for another five years (Xiao et al., 2013). People will have to face a fearful garbage situation if they cannot find a better way to solve the problem of landfill limitation (Banks et al., 2011). Thus, it is in urgent to seek a new solution for food waste disposal. As we know, the composition of food waste is complicated and changeful. In addition, it contains many valuable components which can be used for biofuels production (Van-Ginkel et al., 2005). In the past decade, many biotechnologies of biofuels production from food waste have been developed (Yun et al., 2000).

Hydrogen is regarded as a promising fuel in the future since it is renewable and non-pollution (Hwang et al., 2011). Dark fermentative hydrogen production has received increasing interest worldwide because it could convert organic waste/wastewater into

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hydrogen (Akinbomi and Taherzadeh, 2015; Kim and Lee, 2010). The dominant obstacles for industrial of dark fermentative hydrogen production are low hydrogen production rate and high cost (Xu et al., 2011). Utilization of food waste as substrate for dark fermentative hydrogen production could not only solve the food waste problem, but also generate the clean energy (Yasin et al., 2013; Zhou et al., 2013). However, nutrients stored in the food waste are in the form of macromolecules (such as starch and protein) which have to be degraded into utilizable forms (such as glucose and free amino nitrogen) before used by microorganisms for dark fermentative hydrogen production (Han et al., 2015b). Although some reported pretreatments are able to convert the macromolecules into micromolecules, various inhibitory products (such as furfural) could also be generated (Quemeneur et al., 2012).

In our previous study, we have successfully developed a novel combined bioprocess based on solid state fermentation for dark fermentative hydrogen production from food waste (Han et al., 2015c). Food waste is first used to produce glucoamylase and protease by *Aspergillus awamori* and *Aspergillus oryzae* via solid-state fermentation. The produced gluoamylase and protease are utilized to hydrolyze food waste to get the food waste hydrolysate rich in glucose and free amino nitrogen (FAN). Subsequently, the food waste hydrolysate is used as substrate for dark fermentative hydrogen production by heat pretreated sludge. Obviously, more hydrogen yield could be achieved using glucose solution (food waste hydrolysate) rather than direct food waste solid as substrate. Furthermore, other reported pretreatments could solubilize part of the starch contained in the food waste, while a large amount of starch remains in the solid phase. In our previous study, the starch conversion efficiency of the food waste could reach 82.8–87.2% by using enzymatic hydrolysis within 24 h. The proposed bioprocess could effectively accelerate the hydrolysis rate of food waste, improve raw material utilization and enhance hydrogen yield. In the light of the technical feasibility, this study aims to evaluate the economic feasibility of the proposed combined bioprocess for hydrogen production from food waste. Profitability of a plant to be built in Hangzhou for treating food waste is assessed.

2. Methods

The fermentative hydrogen production plant was assumed to be built in Hangzhou (China) and designed with a total capacity of converting 3 ton per day of food waste into hydrogen, hence a total of 1095 ton per year of food waste could be treated for 365 days in a year. The lifetime of the fermentative hydrogen production plant was set to be 15 years.

2.1. Description of the combined bioprocess for hydrogen production from food waste

The proposed bioprocess for hydrogen production from food waste was based on previous study (Han et al., 2015c) and the bioprocess flow was described in Fig. 1.

Food waste was first ground into smaller size and then blended with water to provide a liquid medium for mixing. *A. awamori* and *A. oryzae* were used for the production of glucoamylase and protease, respectively, via solid state fermentation. Solid state fermentation was carried out under static condition at 30 °C for 4 days. The produced enzymes were transferred into the bioreactor with the pretreated food waste for enzymatic hydrolysis. The temperature and agitation speed were controlled at 55 °C and 500 rpm, respectively. After 24 h, the micromolecular nutrients (glucose and FAN) could be released from food waste by the produced enzymes (glucoamylase and protease). The resulting mixture was centrifuged at 10,000 rpm for 30 min. The supernatant was subsequently filtered to get the food waste hydrolysate. Small amount of oil was also removed. The food waste hydrolysate was then used as substrate for hydrogen production by pretreated sludge.

The anaerobic sludge was obtained from a local municipal wastewater treatment plant and screened by a sieve (diameter: 2 mm) to eliminate large particular materials. Before used as inoculum for fermentation hydrogen production, heat pretreatment was performed in a water bath at temperature of 100 °C for 6 h to inhibit methanogenic activity. Fermentative hydrogen production by heat pretreated sludge was carried out in a fermentor with agitation speed of 300 rpm. The fermentor was sparged with 0.5 vvm N_2 for 30 min to achieve the anaerobic condition for fermentative hydrogen production. The pH of the fermentation was automatically maintained at 4.0–4.6 by adding 5 M $NaHCO_3$ and 0.005 M H_2SO_4. The experimental result showed that the overall yield of the hydrogen was 39.14 mL H_2/g food waste.

A purification system was used to separate the produced biogas (mainly hydrogen and carbon dioxide). The purification system included a low-pressure gas tank, a carbon dioxide compressor, an activated carbon filter, an absorbing type desiccator, a compression refrigerator and a storage tank. Hydrogen could be used in a fuel cell and combustor to generate electricity and heat energy, respectively. Meanwhile, carbon dioxide could be used for the food industries (Li et al., 2012).

2.2. Economic analysis

2.2.1. Total capital cost

Total capital cost (TCC) could be divided into two categories: fixed capital investment (FCI) and working capital cost (WCC). FCI consisted of the equipment purchase cost, and additional direct/indirect costs for building the plant. The free-on-board equipment quotations were provided by Shuangzi Machinery Factory in Zhejiang province, China. In addition to the purchase of bare equipment, additional direct/indirect costs (such as installation, piping and construction) were also considered. Therefore, the TCC could be calculated according to Eq. (1).

$$\text{TCC} = \text{Equipment purchase cost} + \text{Additional direct/indirect costs} + \text{WCC} \tag{1}$$

The distribution of the FCI components could be estimated according to Peters's study (2003). All costs were converted into US dollar for the ease of comparison. Fermentative hydrogen production from food waste was a waste recovery project which was supported by the Hangzhou government. So, the land cost would not be taken into account. This project could also attract great attentions by local property management companies due to the high benefits. The WCC for the plant was assumed to be 6.5% of the total FCI (Lam et al., 2013).

2.2.2. Annual production cost

The major components of the annual production cost (APC), which included raw materials (C_{RM}), utilities (C_U), operating labor (C_{OL}), maintenance and repair (C_{MR}), laboratory cost (C_{LC}) and other necessary costs (C_O), could be calculated according to Eq. (2).

$$\text{APC} = C_{RM} + C_U + C_{OL} + C_{MR} + C_{LC} + C_O \tag{2}$$

A waste recycling centre which was sponsored by the local government would be in charge of the collection and transportation of food waste. So, the cost of food waste could not be considered. The main C_{RM} was the chemical costs which were provided by a local chemical supplier (Hangzhou Chemistry Co., Ltd). C_U was the annual energy consumption which included the purification system for biogas separation. According to the mass and energy balance by computer simulation using Aspen Plus, the C_U could