Techno-economic analysis of a novel bioprocess combining solid state fermentation and dark fermentation for H₂ production from food waste

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Abstract: The techno-economic analysis of a novel bioprocess combining solid state fermentation and dark fermentation for H₂ production from food waste (FW) was investigated. A H₂ production plant was designed with capacity of 10 ton/day and lifetime of 10 years. Aspen Plus was utilized to simulate the mass and energy balance of the plant. It was noticed that the total capital investment, annual operation cost and annual revenue of the plant were USD707850, USD366700/year and USD574800/year, respectively. The payback period of the plant was 5 years with internal rate of return of 20.2%. The H₂ market price and operating labor cost were the most important parameters on the net present value of the plant. The unit H₂ production cost was

USD2.29/m³ which was cheaper than the H₂ market price (USD2.7/m³). The results demonstrated that the combined bioprocess was economically feasible for industrial H₂ production.

Keywords: Aspen Plus; economic analysis; food waste; H₂ production; sensitivity analysis

1. Introduction

The depletion of fossil fuel and the severe environmental pollution caused by the usage of fossil fuel have forced the researchers to look for the alternative energy sources^[1]. H₂ is regarded as a promising energy carrier since it is renewable and clean^[2,3]. Furthermore, it could be used in fuel cells for electricity production^[4]. At present, chemical or thermo-chemical ways are commonly used for H₂ production from fossil fuel, while a cost-effective method is still in great demand^[5]. Biological H₂ production, which could use raw materials as substrate to produce H₂, has attracted considerable attention^[6,7]. Generally, biological H₂ production could be separated into dark fermentation and photo fermentation. Compared to the photo fermentation, dark fermentation seems to be more attractive since it could produce H₂ with the absence of light. However, the high production cost is a major obstacle to realize dark fermentative H₂ production for industrial application^[8]. Using organic wastes as feedstock for dark

1 fermentative H₂ production is considered to be an attractive solution^[9,10].

2 Food waste (FW), which is produced 1.3 billion ton/year in the world^[11,12], is
3 regarded as an important part of municipal solid waste (MSW). The traditional methods
4 for MSW disposal, such as landfill and incineration, are not proper to treat FW due to
5 the limited land space and emission of toxic gas^[13,14]. FW could be used as substrate for
6 biofuels production (such as dark fermentative H₂ production) since it contains a great
7 amount of starch and protein^[15,16]. However, these nutrients need to be hydrolyzed into
8 glucose and free amino nitrogen (FAN) prior to be utilized by microorganisms which is
9 considered to be the limiting step for dark fermentative H₂ production^[17,18]. It is
10 reported that the physical and chemical pretreatments of FW are able to accelerate the
11 hydrolysis speed, while the inhibitory products for dark fermentative H₂ production are
12 also generated^[19]. Enzymatic hydrolysis of FW seems to be an attractive method since
13 the nutrients (glucose and FAN) could be released from FW with high hydrolysis speed
14 and low cost^[20,21].

15 In light of the above analysis, a novel bioprocess combining solid state fermentation
16 (SSF) and dark fermentation for H₂ production from FW has been successfully
17 developed^[22,23]. It has been proved that the hydrolysis rate and H₂ yield could be
18 effectively increased by this novel bioprocess. Therefore, the aim of the present work is
19 to perform the techno-economic analysis of the combined bioprocess. This study could

provide a protocol to build a bioenergy plant from organic wastes in practical application.

2. Materials and method

2.1 Description and advantages of the combined bioprocess for dark fermentative H₂ production from FW

The flow of the combined bioprocess for H₂ production from FW was shown in Fig. 1. The bioprocess included five phases: pretreatment and SSF, enzymatic hydrolysis of FW, seed culture, dark fermentative H₂ production and biogas purification.

In the pretreatment and SSF phase, FW was ground and used by fungi (*Aspergillus awamori* and *Aspergillus oryzae*) via SSF to produce the solid enzymes (glucoamylase and protease), respectively. The produced solid enzymes were then used to hydrolyze the pretreated FW to obtain the FW hydrolysate which was rich in glucose and FAN. In the seed culture phase, the H₂-producing bacteria of *Biohydrogenbacterium* R3 were cultured. The FW hydrolysate was pumped into the fermentor, where the R3 converted the FW hydrolysate to H₂ and CO₂. Finally, the produced biogas was purified by the purification system.

As a design basis, a feed of 10 ton/day of FW was selected. In addition, the heat exchanger was arranged to reduce the energy loss^[24]. Aspen Plus was used to simulate

the mass and energy balance of the H₂ production plant^[25,26].

The low hydrolysis rate and nutrient conversion efficiency are the main obstacles to realize dark fermentative H₂ production from FW for industrial application^[16,18]. In the previous study, a novel bioprocess combining SSF and dark fermentation for H₂ production from FW has been successfully developed with the maximum H₂ yield of 52.4 ml H₂/g FW^[23]. This result was comparable or higher than other literatures^[15,18] since the liquid FW hydrolysate rather than solid FW was utilized as feedstock and the ratio of starch conversion could achieve 96.2% within 24 h. Other reported pretreatments could convert a small part of the starch, while the bigger parts of starch retained in the solid FW^[17]. So, the combined bioprocess could be a promising method for industrial H₂ production due to the lower hydrolysis speed and higher nutrients conversion rate and H₂ yield.

2.2 Detailed bioprocess description

Table 1 showed the composition of the FW used in this study. FW was collected and transported to the H₂ production plant and stored in the tanks (E1). Then, FW was ground into smaller size in E2. Solid-state fermentation was performed in two reactors (E3) from pretreated FW by *A. awamori* and *A. oryzae*, respectively. The reactors (E3) were incubated to obtain the solid enzymes (glucoamylase and protease) at 30 °C for 4 days.

After the pretreatment and SSF, enzymatic hydrolysis of FW was performed in a bioreactor (E4) with the produced enzymes at temperature of 55 °C and agitation speed of 500 rpm. Water was introduced into the bioreactor (E4) with pretreated FW to provide a liquid medium for mixing. In order to reduce the energy loss, the heat exchanger (E5) was used to improve the efficiency of the H₂ production plant. The mixture was then centrifuged (E6) to produce the FW hydrolysate which was further utilized as the substrate for dark fermentative H₂ production.

Biohydrogenbacterium R3, the accession number of NCBI nucleotide sequence database was AY363375^[27], was used as the H₂-producing bacteria. It was cultivated in a shake flask (E10) at 37 °C, followed by seed fermentation (E9) with FW hydrolysate. The culture was purged with N₂ to ensure the anaerobic condition^[28].

Dark fermentative H₂ production from FW hydrolysate was performed in a fermentor (E7) at 37 °C. *Biohydrogenbacterium* R3 was inoculated into the fermentor (E7) with inoculum size of 2% by volume. Dark fermentative H₂ production was purged with N₂ and agitated at 300 rpm. The pH was automatically kept within 4.0-4.6 using sodium bicarbonate and sulphuric acid. The effluent of the H₂ production fermentor was centrifuged (E8) to get the soluble microbial product (SMP) which could be further utilized for biological methane production.

Finally, the produced biogas was introduced and purified in the purification system

(E11). It was reported that 8% of the produced H_2 could be lost and the purity of H_2 could reach 99%^[25].

2.3 Economic analysis of the H_2 production plant from FW

2.3.1 Estimation of total capital investment

The total capital investment (TCI) for a new plant consisted of the fixed capital cost (FCC), land cost and working capital cost (WCC). The FCC included the equipment purchase cost and the additional cost for the set-up of the plant. As a waste recycling and renewable energy production program, the local government would support to built the plant and provide the land for free. The WCC of the plant could be regarded as 6.5% of the FCC^[21]. So, the calculation of TCI could be expressed as the following Eq. (1).

$$TCI = FCC + WCC \quad (1)$$

2.3.2 Annual operation cost

In order to calculate the annual operation cost (AOC), the costs of raw material (C_{RM}), waste disposal (C_{WD}), utilities (C_U) and extra cost (C_E), which were essential to plant operation on an annual basis, should be taken into account (Eq. (2)).

$$AOC = C_{RM} + C_U + C_{WD} + C_E \quad (2)$$

The main C_{RM} was the chemical cost which was supplied from a local chemicals supplier. The energy consumption of the plant was used to calculate C_U which included water and electricity. The water and electricity requirements for each unit were

simulated from the energy balances using Aspen Plus. C_U was calculated according to the type and the price of energy for each unit^[29]. The C_{WD} was calculated from the annual quantity and the penalty of the waste produced. In this study, the solid waste produced was mainly the undigested FW which could be utilized as the animal feed^[21]. The wastewater (mainly volatile fatty acids and ethanol) could be used as substrate for biological CH_4 production. Therefore, the plant could produce only non-toxic wastes and the C_{WD} should not be considered.

2.3.3 Annual profitability and unit H_2 production cost

The revenue of the plant was the sale of the produced H_2 and service charge of FW treatment. The prices of H_2 and FW treatment were USD2.7/m³ and USD16.11/ton, respectively^[21,30]. The local tax was 15%. The annual profit of the plant was equal to the revenue minus AOC.

A mathematical model was developed and implemented to calculate the specific cost of H_2 production C_H (L/USD). It was understood as the sum of annual costs of capital C_C , utilities cost C_U , raw material cost C_{RM} and extra cost C_E (all the annual costs in USD/year), divided by the annual H_2 production (Eq. (3)).

$$C_H = (C_C + C_U + C_{RM} + C_E)/H_P \quad (3)$$

where H_P is the annual H_2 production of the plant.

2.3.4 Profitability criteria

In this study, the H₂ production plant was economically evaluated using general profitability criteria. The most significant was the net present value (NPV) which gave the profit of the H₂ production plant for a certain period by considering the time value of money. Other profitability criteria, such as internal rate of return (IRR) and payback period (PBP), were also calculated. The lifetime was assumed to be 10 years to evaluate the profitability of the plant.

3. Results and discussion

3.1 Total capital investment analysis

The TCI values and detailed calculations of the H₂ production plant were present in Table 2. Aspen Plus was used to simulate the mass and energy balance which was used to estimate the quantity of the required equipments. So, the total equipment cost of USD443100 could be achieved (Table 2). The additional costs for the set-up of the H₂ production plant was 50% of the equipment cost which was equivalent to USD221550^[29]. So, the FCC of the plant was USD664650. WCC, which was regarded to be 6.5% of the FCC, was USD43200. Therefore, according to the Eq. (1), the TCI of USD707850 could be calculated.

3.2 Annual operation cost analysis

Table 3 showed the annual operation cost for the H₂ production plant. The raw material

cost (C_{RM}) was USD118750/year with the largest part of N_2 cost (55.2%). The cost of the utilities (C_U) included the cost of the electricity and water. The utilities consumption were 500000 kWh which was estimated using the energy balances of the plant. As the local price of electricity was 0.084 USD/kWh, the C_U of USD42000/year could be calculated. Extra costs (C_E) included the costs of labor, maintenance and insurance. The operating labor cost was based on the estimation that a treating 10 ton FW would require 6 operators with an average salary of 30000 USD/year per operator. As a result, the operating labor cost was 180000 USD/year. The maintenance and insurance were 2% and 1% of the FCC, respectively^[26,29]. According to the above calculation, the annual operation cost of USD366700/year could be calculated.

3.3 Annual profitability analysis and unit H_2 production cost

The profitability of the plant included the sale of the produced H_2 and the charge of FW treatment (Table 4). As the H_2 production plant was designed with capacity of 10 ton FW per day, around 524 m³ of H_2 could be produced from FW per day^[23]. The annual H_2 production of 191260 m³ could be estimated (365 batches per year). According to the price of H_2 (USD2.7/m³), the revenue of H_2 (USD516400/year) could be calculated. On the other hand, according to the annual treated FW quantity (3650 ton) and FW treatment price (USD16.11/ton), the annual FW treatment revenue of USD58400/year could be estimated. Therefore, according to the above calculation, the annual revenue of

the H₂ production plant (USD574800/year) could be obtained. According to the local tax (15%) and annual operation cost (USD366700/year), the annual profitability (after the tax) of the H₂ production plant from FW was USD176885/year.

In this study, the unit H₂ production cost was USD2.29/m³ (Eq. (3)) which was lower than the market H₂ price (USD2.7/m³) probably because the advantages of the combined bioprocess for H₂ production (short hydrolysis time and high starch conversion rate)^[23]. Furthermore, the unit production cost of H₂ could be lower than USD2.29/m³ if the potential revenues were taken into account. For instance, the wastewater (mainly volatile fatty acids and ethanol) could be used for biological CH₄ production^[24]. And, the undigested FW could be utilized as the animal feeds. So, this novel combined bioprocess could be used for industrial H₂ production from FW due to the higher H₂ yield and lower H₂ production cost.

Table 5 showed the breakdown of the unit H₂ production costs. Obviously, the other costs (labor, maintenance and insurance) and raw material cost were the largest parts of H₂ production, 45.8% and 25.7%, respectively. Moreover, the FCC was also a big part for the unit H₂ production cost. However, the effects of utilities cost and WCC on the unit H₂ production were lower than other parameters.

3.4 Profitability criteria analysis

As shown in Fig. 2, the net present value (NPV) of the H₂ production plant increased

with the discount rate decreased from 30% to 0. The highest NPV of USD884115 and shortest payback period of 5 years were obtained (discount rate = 0). Obviously, the H₂ production plant became more attractive with the decrease of discount rate. The internal rate of return (IRR), which indicated the efficiency of the investment, was 20.2% in this study (Fig. 3). According to the above results and analysis, the H₂ production plant from FW was economically feasible.

Results from the sensitivity analysis were shown in Fig. 4 and Table 6, where variations in the prices of the most important parameters of the H₂ production plant were considered. As shown in Fig. 4, the effect of price sensitivity on the NPV was linear. It was observed that the H₂ market price and operating labor cost were the biggest parameters on the NPV. In addition, the raw material cost had a much greater influence than the FW treatment and utilities cost. The corresponding values of the sensitivities slopes were shown in Table 6. It was observed that only the H₂ market price and FW treatment were the revenue of the H₂ production plant. So, the slopes of the H₂ price and FW treatment were positive to NPV.

4. Conclusions

In this study, the techno-economic analysis of a novel bioprocess combining solid state fermentation and dark fermentation for H₂ production from food waste was investigated.

It was estimated that the total capital investment and annual operation cost were USD707850 and USD366700/year, respectively. The annual revenue of the plant was USD574800/year. The unit H₂ production cost was USD2.29/m³ with the largest parts of the other cost (45.8%). The payback period and the internal rate of return of the H₂ production plant were 5 years and 20.2%, respectively. The combined bioprocess for H₂ production from food waste was economically feasible and could be used for industrial application.

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1 **Figure legends**

2 **Table 1** Composition of FW used in this study (per 100 g FW).

3 **Table 2** Equipments cost of dark fermentative H₂ production plant.

4 **Table 3** Annual operation cost of dark fermentative H₂ production plant.

5 **Table 4** Annual profitability of dark fermentative H₂ production plant.

6 **Table 5** Unit H₂ production cost of dark fermentative H₂ production plant.

7 **Table 6** Sensitivity analysis results of dark fermentative H₂ production plant.

8 **Fig. 1.** The flow of the combined bioprocess for dark fermentative H₂ production from
9 FW.

10 **Fig. 2.** Net present value of dark fermentative H₂ production plant at different discount
11 rates.

12 **Fig. 3.** Internal rate of return of dark fermentative H₂ production plant from FW.

13 **Fig. 4.** Sensitivity analysis of dark fermentative H₂ production plant from FW.

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Table 1 Composition of FW used in this study (per 100 g FW).

Component	Value (g)	Component	Value (g)
Moisture	78.3 ± 1.5	Carbohydrate (dry basis)	42.7 ± 0.8
Total solid (TS)	19.6 ± 1.2	Volatile solid (VS)	17.8 ± 0.9
Starch (dry basis)	40.6 ± 0.6	Protein (dry basis)	10.5 ± 0.5
Lipid	6.2 ± 0.7	Total phosphorus (dry basis)	1.6 ± 0.06

1 **Table 2** Equipments cost of the dark fermentative H₂ production plant.

Code	Equipment	Specification	Quantity	Cost
E1	FW storage	Working capacity: 20 ton	1	15000
E2	FW grinding	Working capacity: 2 ton/h	1	72000
E3	Reactors for SSF	Oil jacket	2	24000
E4	Enzymatic hydrolysis vessel	Oil jacket with stirrer	1	66000
E5	Heat exchanger	Heat exchanger	1	45000
E6	Hydrolysate centrifugation and filtration	Working capacity: 670 L/h	1	28200
E7	Fermentor for H ₂ production	Oil jacket with stirrer Working volume: 1000 L	1	60000
E8	Centrifuge	Working capacity: 3000 L/h	1	51000
E9	Seed fermentor	Oil jacket with stirrer Working volume: 10 L	2	39000
E10	Shake flask rack	Growth of R3	2	90000
E11	Purification system	Separation of produced biogas	1	63000
Total		-	-	443100

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1 **Table 3** Annual operation cost of the dark fermentative H₂ production plant.

	Component	Price	Unit	Quantity	Cost
Raw material (Chemicals)	<i>A. awamori</i>	6.27	USD per kg	500	3135
	<i>A. oryzae</i>	37.63	USD per kg	500	18815
	N ₂	8.2	USD per m ³	8000	65600
	NaHCO ₃	9.9	USD per ton	2900	28710
	H ₂ SO ₄	3.9	USD per ton	638.5	2490
Utilities	Electricity	0.084	USD per kWh	500000	42000
	Process water	0.1	USD per m ³	60000	6000
Other costs	Labor	30000	USD per employee	6	180000
	Maintenance	2	% of FCC	-	13300
	Insurance	1	% of FCC	-	6650
Total	-	-	-	-	366700

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1 **Table 4** Annual profitability of the dark fermentative H₂ production plant.

	Price	Quantity	Value
H2 (1)	2.7/m ³ H ₂	191260 m ³	516400
FW treatment (2)	16	3650 ton	58400
Annual revenue	-	-	574800
(3) = (1) + (2)			
Annual operation cost	-	-	366700
(4)			
Annual profitability	-	-	176885
(5) = (3) – (4) – Tax			
(15%)			

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Table 5 Unit H₂ production cost of the dark fermentative H₂ production plant.

Items	Unit price (USD/m ³ H ₂)	Percentage (%)
FCC	0.35	15.3
WCC	0.02	0.9
Raw material	0.62	27.1
Utilities	0.25	10.9
Other costs	1.05	45.8
Total production cost	2.29	100

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Table 6 Sensitivity analysis results of dark fermentative H₂ production plant from FW.

Material	Sensitivity slopes
H ₂ market price	5E+06x + 884115
FW treatment	525600x + 884115
Utilities cost	-432000x + 884115
Raw material cost	-1E+06x + 884115
Operating labor cost	-2E+06x + 884115

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Fig. 1. The flow of the combined bioprocess for dark fermentative H₂ production from FW. (E1 FW storage; E2 FW grinding; E3 Reactors for SSF; E4 Enzymatic hydrolysis vessel; E5 Heat exchanger; E6 Hydrolysis centrifugation and filtration; E7 Fermentor for H₂ production; E8 Centrifuge; E9 Seed fermentor; E10 R3 shake flask; E11 Biogas purification system)

Fig. 2. Net present value of dark fermentative H₂ production plant at different discount rates.

Fig. 3. Internal rate of return of dark fermentative H₂ production plant from FW.

Fig. 4. Sensitivity analysis of dark fermentative H₂ production plant from FW.