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Economic Cost Analysis of Biodiesel Production: Case in Soybean Oil[†]

Yii-Der You,[‡] Je-Lueng Shie,^{*,§} Ching-Yuan Chang,[‡] Sheng-Hsuan Huang,[‡]
Cheng-Yu Pai,[§] Yue-Hwa Yu,[‡] and Chungfang Ho Chang^{||}

Graduate Institute of Environmental Engineering, National Taiwan University, Number 1, Section 4,
Roosevelt Road, Taipei 106, Taiwan, Department of Environmental Engineering, National I-Lan
University, Number 1, Section 1, Shen-Lung Road, I-Lan 260, Taiwan, and Department of International
Trade, Chung Yuan Christian University, Number 200, Chung-Pei Road, Chung-Li 320, Taiwan

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The economic costs of three biodiesel plants with capacities of 8000, 30 000, and 100 000 tons year⁻¹ were analyzed and assessed. The plants employ continuous processes using an alkali catalyst and the raw material of soybean oil. Six major economic cost factors were computed and examined. These include the fixed capital cost (FCC), total capital investment cost (TCC), total manufacturing cost (TMC), net annual profit after taxes (NNP), after-tax rate of return (ARR), and biodiesel break-even price (BBP). The NNP and ARR of plants with capacities of 8000, 30 000, and 100 000 tons year⁻¹ are -24×10^3 , 1975×10^3 , and 8879×10^3 U.S. dollars (USD), and -10.44 , 40.23 , and 67.38% , respectively. The values of BBP of the three plants are 862, 724, and 678 USD ton⁻¹ (price in July 2007). The plant with a capacity of 100 000 tons year⁻¹ is economically feasible, providing a higher NNP and more attractive ARR with a lower BBP. Among the system variables of the plants examined, plant capacity, price of feedstock oil and diesel, and yields of glycerine and biodiesel were found to be the most significant variables affecting the economic viability of biodiesel manufacture. In summary, this study aims at the need to obtain useful information for economic cost analysis and assessment of the production process of biodiesel using soybean oil. It provides an appropriate indication for the promotion of biodiesel in the future, targeting the reduction of the cost of feedstock oil with the increase of the yields of valuable products with a reasonable plant capacity.

Introduction

Biodiesel has recently become more attractive in Taiwan because of its environmental benefits and the fact that it is made from renewable biological sources, such as vegetable oils and animal fats. Its commercial use as a diesel substitute began in Europe in the late 1980s. Continued and increasing use of petroleum will intensify local air pollution and magnify the global warming problems caused by CO₂.¹ Combustion of petroleum diesel is a major source for emitting greenhouse gas (GHG). Apart from these emissions, it is also a major source for releasing other air contaminants, including NO_x, SO_x, CO, particulate matter, and volatile organic compounds (VOCs).² Exploring new energy resources, such as biodiesel fuel, has been of growing importance in recent years. Biodiesel containing mainly fatty acid methyl esters (FAMES) is one of such alternative energy resources. It may be obtained via four primary ways: (1) direct use and blending of oils, (2) microemulsions of oil, (3) thermal cracking (pyrolysis of vegetable oil), and (4) transesterification (alcoholysis of oil).³ The most commonly used method is transesterification of vegetable oils, such as soybean, rapeseed, sunflower, palm, coconut, tung, and waste cooking

oils. Oils from algae, bacteria, and fungi also have been investigated.¹ The transesterification refers to a chemical reaction involving vegetable oil (containing mainly triglycerides) and an alcohol to form esters and glycerol. A catalyst is usually used to improve the transesterification reaction rate and yield. Glycerol is produced as a byproduct. Alcohols that can be used in the transesterification process include methanol, ethanol, propanol, butanol, and amyl alcohol.³ Methanol is the most common alcohol employed because of its low cost. Thus, it is the alcohol of choice for the process examined in this study. Transesterification reactions can be alkali-, acid-, or enzyme-catalyzed. If the contents of free fatty acid (FFA) and water in oil are <1 and <0.5 wt %, respectively, then an alkaline catalyst is more suitable for the ester production. If the FFA content of oil is high (>1 wt %), then an acid catalyst is a good choice.⁴ Alkali-catalyzed transesterification is much faster than acid-catalyzed transesterification, most often used commercially, and employed for the process of this study. Many studies of alkali-catalyzed transesterification on the laboratory scale have been carried out. A reaction temperature near the boiling point of the alcohol and a range from 3:1 to 6:1 of the molar ratio of alcohol/soybean oil were recommended.^{5,6} One limitation to the alkali-catalyzed process is its sensitivity to the purity of reactants. The process is very sensitive to both water and FFAs. The presence of water may cause saponification of ester under

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* To whom correspondence should be addressed. Telephone: +886-3-935-3563. Fax: +886-3-935-3563. E-mail: jlshie@niu.edu.tw.

[‡] National Taiwan University.

[§] National I-Lan University.

^{||} Chung Yuan Christian University.

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alkaline conditions.^{7,8} Thus, usages of a dehydrated vegetable oil with less than 0.5 wt % FFA, an anhydrous alkali catalyst, and an anhydrous alcohol are necessary for commercially viable alkali-catalyzed systems.^{5,8} This requirement is likely to be a significant limitation to the use of waste cooking oil as a low-cost feedstock of biodiesel production. Usually, the level of FFA in waste cooking oil is greater than 2 wt %.^{9,10} The products formed during frying, such as FFA and some polymerized triglycerides, can affect the transesterification reaction and the biodiesel properties. Apart from these phenomena, the biodiesel obtained from waste cooking oil gives better engine performance and less emission when tested on commercial diesel engines.⁴ The two-step process (acid-catalyzed followed by alkali-catalyzed) is one of the better alternatives for the production of biodiesel from waste cooking oil.⁹ However, a two-step method is not feasible, because it requires more steps, which make the biodiesel process costly.⁴ In contrast to the alkali-catalyzed process, acid-catalyzed transesterification has received less attention because it has a relatively slow reaction rate. Nevertheless, it is insensitive to FFA in feedstock oil compared to the alkali-catalyzed system. The typical acid catalyst used in the reaction is sulfuric acid.⁸

A major obstacle in the commercialization of biodiesel, in comparison to petroleum-based diesel fuel, is its high cost of manufacturing, primarily the raw material cost. Biodiesel usually costs over 0.5 U.S. dollars (USD) L⁻¹. Its cost is approximately 1.5 times that of petroleum-based diesel depending upon feedstock oils.^{11,12} Bender¹³ reviewed 12 reports concerning the economic feasibility of biodiesel production, involving several feedstocks and operational scales. Calculated production costs, which included the costs of the feedstock and its conversion to biodiesel, were 0.3, 0.32–0.37, 0.4, 0.63, and 0.69 USD L⁻¹ for fuel produced from soybean oil,¹⁴ animal fats,¹⁵ canola oil, sunflower oil,¹⁴ and rapeseed oil,¹⁶ respectively. According to Nelson et al.,¹⁷ the significant factors that affect the cost of biodiesel are feedstock cost, plant size, and value of the glycerine byproduct. Waste cooking oil, which is much less expensive than pure vegetable oil, is a promising alternative to vegetable oil for biodiesel production. Restaurant waste oils and rendered animal fats are less expensive than food-grade canola and soybean oils.¹⁸ The production of biodiesel from waste cooking oil is one of the better ways to use it efficiently and economi-

cally. Canackci and Gerpen¹⁸ have developed a 190 L pilot plant using an acid-catalyzed pretreatment followed by an alkali-catalyzed transesterification. The estimated costs for biodiesel from soybean oil, yellow grease with 9% FFA, and brown grease with 40% FFA were 0.418, 0.317, and 0.241 USD L⁻¹, respectively. Also, from the same economic reason, Haas¹⁹ has investigated the production of biodiesel from soapstock (SS), a byproduct of edible oil refining that is substantially less expensive than edible-grade refined oils. An economic analysis model using ASPEN PLUS software suggested that the production costs of soapstock and soybean oil biodiesel would be approximately 0.41 and 0.53 USD L⁻¹, respectively, a 25% reduction relative to the estimated cost of biodiesel produced from soybean oil. For the production cost of 0.53 USD L⁻¹ of biodiesel from soybean oil, the single greatest contributor to this value was the cost of the oil feedstock, which accounted for 88% of the total estimated production cost.²⁰ Bender¹³ and Zhang et al.²¹ showed that the credit for the glycerol byproduct has a significant impact on the net value of the total manufacturing cost. The glycerol value led to a reduction in total production costs of 6 and 6.5% of biodiesel from Ethiopian mustard oil and used olive oil, respectively. Therefore, the use of waste cooking oil should greatly reduce the cost of biodiesel production because waste oil is available at a relatively low price. However, the data on the requirements of diesel fuel and availability of waste cooking oil for the countries using diesel fuel indicate that the biodiesel obtained from waste cooking oil may not replace diesel fuel completely,⁴ which is also reflected in Taiwan. Therefore, the Taiwan government plans to enable farmers to grow industrial oilseeds (e.g., sunflower seed, soybean seed, and rapeseed) to develop a share of 1–5% (B1–B5) of the biodiesel market for the fuels of public traffic vehicles, such as buses and garbage trucks.²² Bender¹³ and Van Dyne et al.²³ affirmed that biodiesel could compete with diesel fuel if produced in agricultural cooperatives. According to Bender,¹³ biodiesel from Ethiopian mustard oil can compete with diesel fuel only if tax exemption is applied, whereas biodiesel from used olive oil could compete.

The promotion of the production and usage of biodiesel in Taiwan is at its initial stage. The first Taiwanese factory producing biodiesel of 3000 tons year⁻¹ from waste cooking oil was established in the Chiayi county of Taiwan in October 2004; however, the laws, standards of oil, and methods of testing were not standardized. Under the plan of the Nuclear-Free Homeland of Taiwan in 2005, over 700 garbage trucks in 13 counties of Taiwan were on track. It was the first extensive test on the use of biodiesel for diesel vehicles in Taiwan.²⁴ In another study, various processes for producing biodiesel from virgin vegetable oil via alkali-catalyzed transesterification were developed.²⁵ A comparison of processes using different sources of virgin vegetable oils was presented from the point of view

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Table 1. Yields of Products from Different Production Steps of Biodiesel²⁵

		soybean oil (from Taiwan Sugar Corporation) (wt %)
materials	virgin soybean oil	100
	NaOH solution	11
	methanol	10
	acetic acid	1.4
	water	10
middle product	crude FAME	92.5
final products	glycerol	27.5
	refined FAME	62.5
	char	18.3
	others	11.8

Table 2. Elemental Analyses of Virgin Soybean Oil, Glycerine, and Crude FAME^a

	virgin soybean oil	glycerine	crude FAME
C (wt %)	77.56 (0.177)	52.77 (1.703)	74.25 (3.87)
H (wt %)	13.22 (0.057)	11.08 (0.051)	12.51 (0.559)
N (wt %)	0.025 (0.007)	<0.0001 (<0.0001)	0.0005 (0.0003)
S (wt %)	<0.0001 (<0.0001)		<0.0001 (<0.0001)
balance, O (wt %)	9.2	36.15	13.2395

^a Numbers in parentheses are standard deviations.

of their processing technology. Besides the evaluation of the technology and product yield, economic feasibility is also of great importance in assessing the process viability. Thus, the main objective of the present paper is to propose a simple economic assessment method assisting the comparison of alternative production routes revealing which route can achieve a very desirable reduction in production costs. In this way, a better evaluation of the biodiesel production processes, including feedstock, chemical process, and plant capacity and design, can be achieved from both the technological and economic points of view.

Methodology

Economic Studies. Economic consideration is a key driving force supporting the development of inexpensive feedstock and process technology for biodiesel production. Although total costs of biodiesel production depend heavily upon feedstock costs, there are some other considerations that must be taken into account. The main economic criteria noted in all of the cases cited above were the total capital investment cost (TCC), total manufacturing cost (TMC), and biodiesel break-even price (BBP). Different researchers used different economic criteria emphasizing different points of view to assess the biodiesel production processes. In the present paper, the economic criteria were based on TCC [including the fixed capital cost (FCC) and working capital cost (WCC)], TMC, after-tax rate of return (ARR), and BBP for biodiesel production. The total production cost (TPC) includes the direct operation cost (DOC), indirect operation cost (IOC), general expense (GE), and depreciation (DEPC). Therefore, TMC is equal to TPC minus the credits of byproducts of glycerine (CBP).

Reaction Process Studies. The way that biodiesel production was examined in this study was via transesterification, which refers to a catalyzed chemical reaction involving vegetable oil (triglycerides) and an anhydrous alcohol to form FAME (biodiesel) and glycerol. The alkali catalyst used in this study was NaOH, and the virgin vegetable oil was soybean oil. The technology processes for producing biodiesel from various virgin vegetable oils by alkali-catalyzed transesterification were developed and discussed in

Table 3. Basic Conditions for the Economic Assessment of the Process of This Study

item	specification	price per ton (USD ton ⁻¹)
1. chemicals ^a		
diesel		517 ^b (856) ^c
calcium oxide		46 ^d
glycerine	92 wt %	1380 ^d
glycerine	85 wt %	863 ^d
hexane	USD	471 ^d
methanol	99.85%	201 ^d
phosphoric acid	technical grade	391 ^d
sodium hydroxide		4600 ^d
sulfuric acid	98%	69 ^d
virgin soybean oil		487 ^d
2. utilities		
cooling water	400 kPa, 6 °C	6.25 × 10 ⁻⁴
electricity		2.5 × 10 ⁻³
low-pressure steam (superheated)	450 kPa, 210 °C	6.8
high-pressure steam (superheated)	2700 kPa, 500 °C	10
3. waste treatment		
liquid	hazardous	150
solid		40
4. plant capacity	biodiesel of <i>M</i> tons year ⁻¹	
5. thermodynamic model in process simulation	NRTL or UNIQUAC ^e	
6. methanol recovery	94%	
7. FAME purification ^f	99.65 wt %	
8. methanol recovery in the pretreatment unit	94%	

^a Unless specified, all prices are in USD ton⁻¹. Prices of chemicals are from the National Biodiesel Board (2000), <http://www.biodiesel.org>, Chemical Market Reporter (2000–2001), Vol. 258 (22) and Vol. 259 (9), and <http://www.chemconnect.com>, November 2000. Prices are based on the constant price in 2003. ^b Diesel price in Taiwan = 15.12 NTD L⁻¹ (2003) and 1 USD = 34.41 NTD (2003). ^c Diesel price in Taiwan = 23.48 NTD L⁻¹ (July 2007) and 1 USD = 32.78 NTD (July 2007). ^d Includes a 15% price increase with the shipping of materials from U.S.A. to Taiwan (2003). ^e NRTL, nonrandom two liquid; UNIQUAC, universal quasichemical theory. ^f FAME, fatty acid methyl ester.

another study.²⁵ However, for the need of economic analysis, the yields of products from different production steps of biodiesel are listed in Table 1. The yields of crude biodiesel, refined biodiesel, and glycerol via transesterification were 92.5, 62.5, and 27.5 wt %, respectively. The production process of biodiesel includes FAME distillation; therefore, the summation of products should not be 100 wt %. The results indicate the necessity of refining FAME and yielding glycerol of high price and FAME of high quality. The yield of biodiesel used in the cost analysis of this study was 62.5% of refined biodiesel. Table 2 shows the elemental analyses of virgin soybean oil, glycerol, and crude FAME, indicating that the major elemental contents of these materials are C, H, and O. The increase of the oxygen content in crude FAME can assist its combustion efficiency.

Results and Discussion

Zhang et al.^{8,21} designed and simulated four different continuous processes for biodiesel production from virgin oil or waste cooking oil using alkaline or acidic catalysts via a designed tool of HYSYS for the simulation of the flow rates and the chemicals involved. This study used the alkali-catalyzed process, economic assessment factors, and simulated model, which are similar to the previous studies,^{13,16,17,21} while employing the data of experiments using local vegetable oil conducted by Huang²⁵ for the cost evaluation. The basis, scope of calculations, and the factors of economic assessment are briefly described as follows.

1. Basis and Scope of Calculations. The cost evaluations of this study were based on the following assumptions: (1) The

Table 4. Equipment Sizes, Equipment Costs, and FCCs for the Processes of This Study^a

type	description	8000 tons year ⁻¹	30 000 ^b tons year ⁻¹	100 000 ^b tons year ⁻¹
reactor	transesterification			
	size ($D \times L, m \times m$)	1.8 × 5.4	2.7 × 8.1	2.7 × 8.1
	quantity (number)	1	1	3 (parallel)
	cost (in 10 ³ USD)	335	790	2371
reactor	neutralization			
	size ($D \times L, m \times m$)	0.3 × 1	0.45 × 1.5	0.7 × 2.3
	quantity (number)	1	1	1
	cost (in 10 ³ USD)	25	58	135
column	washing column			
	size ($D \times H, m \times m$)	0.8 × 10	0.8 × 10	0.8 × 10
	quantity (number)	1	4 (parallel)	12 (parallel)
	cost (in 10 ³ USD)	115	460	1380
column	FAME distillation			
	size ($D \times H, m \times m$)	1.2 × 12	1.2 × 12	1.2 × 12
	quantity (number)	1	4 (parallel)	12 (parallel)
	cost (in 10 ³ USD)	181	723	2170
column	glycerine purification			
	size ($D \times H, m \times m$)	N/A	N/A	N/A
	cost (in 10 ³ USD)			
	heat exchangers, cost (in 10 ³ USD)	4	11	23
	pumps, cost (in 10 ³ USD)	53	122	266
	others (separator and vacuum system), cost (in 10 ³ USD)	52	124	271
	total bare module capital cost (TBMCC ^c) (in 10 ³ USD)	765	2288	6616
	contingency fee (CFC) (in 10 ³ USD) = 0.18TBMCC	138	412	1191
	total basic module cost (TBMC) (in 10 ³ USD) = TBMCC + CFC	903	2700	7807
	auxiliary facility cost (AFC) (in 10 ³ USD) = 0.3TBMC	271	810	2342
	fixed capital cost (FCC) (in 10 ³ USD) = TBMC + AFC	1174	3510	10 149
	working capital (WCC) (in 10 ³ USD) = 0.15FCC	176	527	1522
	total capital investment cost (TCC) (in 10 ³ USD) = FCC + WCC	1350	4037	11 671

^a Includes a 15% price increase with the shipping of equipment from U.S.A. to Taiwan. Prices are based on the constant price in 2003. ^b Conversion equation of capacity: $\text{cost}_B = \text{cost}_A(\text{capacity}_B/\text{capacity}_A)^{nc} = \text{cost}_A(\text{size}_B/\text{size}_A)^{ns}$; nc and ns = 0.65. ^c TBMCC is the sum of the cost of each piece of equipment in the process.

plant capacity of biodiesel production was assumed as M tons year⁻¹. For the requirement of biodiesel in Taiwan, M can be simulated as 8000, 30 000, and 100 000 tons year⁻¹. The 8000 tons year⁻¹ plant capacity is consistent with the plant size discussed by Zhang et al.^{8,21} (2) Operating hours were assumed to be T h year⁻¹ (in general, $T = 8000$ h year⁻¹).²¹ (3) Virgin soybean oil, used as the feedstock for biodiesel production, was free of water and any solid impurities. (4) In the simulation, pump efficiency was assumed to be 70% and no spare pumps were taken into account. (5) The specifications and prices of superheated, low- and high-pressure steams and water are as listed in Table 3. (6) All chemical costs including raw materials, catalysts, solvent, and products are as given in Table 3. Further, all of the prices of raw materials, chemicals, catalysts, and solvent included the transportation fee from U.S.A. to Taiwan, insurance, and tax, being assumed as 15% of the costs purchased in U.S.A. (7) The chemical engineering plant index²⁶ was used as the price index.

2. Factors of Economic Assessment. Six major economic cost factors were computed and examined in this study. These include FCC, TCC, TMC, net annual profit after taxes (NNP), ARR, and BBP.

2.1. Fixed Capital Cost (FCC). FCC represents the cost of constructing a new plant (also called grassroots capital cost). Generally, FCC consists of three parts. The first part is the total bare module capital cost (TBMCC), which is the sum of the cost of each piece of equipment in the process. Part 2 consists of contingencies and fees (CFC), which are usually estimated as a certain percentage of the TBMCC (e.g., 18% as used in the present study).^{21,27,28} Part 3 is associated with the costs of auxiliary facilities (AFC), including items such as the purchase

of land, installation of electrical and water systems, and construction of all internal roads. AFC is usually represented as 30% of the total basic module cost (TBMC)^{27,28} where

$$\text{CFC} = 0.18\text{TBMCC} \quad (1)$$

$$\text{AFC} = 0.3\text{TBMC} \quad (2)$$

$$\text{TBMC} = \text{TBMCC} + \text{CFC} \quad (3)$$

Therefore,

$$\begin{aligned} \text{FCC} &= \text{TBMCC} + \text{CFC} + \text{AFC} = \text{TBMC} + \text{AFC} = \\ &1.3\text{TBMC} = 1.3(\text{TBMCC} + \text{CFC}) = 1.3(\text{TBMCC} + \\ &0.18\text{TBMCC}) \quad (4) \end{aligned}$$

The computed results are listed in Table 4.

2.2. Total Capital Investment Cost (TCC). TCC is calculated by adding WCC to the FCC. WCC is usually estimated as a certain percentage of the FCC (e.g., 15% as used in this study).^{21,27} Therefore,

$$\text{TCC} = \text{WCC} + \text{FCC} = 1.15\text{FCC} \quad (5)$$

FCC and TCC for the three plants with different capacities studied in this work are presented in Table 4.

2.3. Total Manufacturing Cost (TMC). TMC refers to TPC subtracting CBP (i.e., $\text{TMC} = \text{TPC} - \text{CBP}$). Therefore, TPC can be calculated as the total operating cost (TOC) adding DEPC (i.e., $\text{TPC} = \text{TOC} + \text{DEPC}$). TOC is the cost of the day-to-day operation of a plant and is usually divided into three categories: DOC, IOC [or fixed operating cost (FOC)], and GE.^{27,28} DOC consists of raw material costs (soybean

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Table 5. Total Manufacturing and Operating Costs and After-Tax Rate of Return for the Processes of This Study (in 10³ USD)

	8000	30 000	100 000
1. capacity (tons year ⁻¹)	8000	30 000	100 000
2. direct operating cost (DOC)			
2.1. oil feedstock (soybean) ^a	6234	23 376	77 920
2.2. methanol	196	732	2443
2.3. catalyst and solvent	368	1382	4606
2.4. operating labor	564	733 ^b	953 ^c
2.5. supervisory and clerical labor: 15% of operating labor	85	110	143
2.6. utilities			
low-pressure steam	30	113	375
high-pressure steam	60	225	750
electricity	20	75	250
cooling water	5	19	63
2.7. waste disposal			
liquid	9	34	113
solid	4	15	50
2.8. maintenance and repairs: 6% of FCC	70	211	609
2.9. operating supplies: 15% of maintenance and repairs	11	32	91
2.10. laboratory charges: 15% of operating labors	85	110	143
2.11. patents and royalties: 3% of total manufacturing cost (TMC)	207	621	1,940
subtotal, DOC	7948	27 788	90 449
3. indirect operating cost (IOC)			
3.1. overhead, packaging, and storage: 60% of the sum of operating labor, supervision, and maintenance	431	632	1023
3.2. local taxes: 1.5% of FCC	18	53	152
3.3. insurance: 0.5% of FCC	6	18	51
subtotal, IOC	455	703	1226
4. depreciation (DEPC): 10% of FCC	117	351	1015
5. general expenses (GE)			
5.1. administrative costs: 25% of overhead	108	158	256
5.2. distribution and selling cost: 10% of total manufacturing cost = 0.1TMC	658	2072	6468
5.3. research and development: 5% of total manufacturing cost = 0.05TMC	329	1036	3234
subtotal	1094	3265	9957
6. total production cost (TPC) = DOC + IOC + GE + DEPC	9614	32 108	102 648
7. glycerine credit ^d (CBP)	3038 ^d	11 392 ^d	37 972 ^d
8. total manufacturing cost (TMC) = TPC - CBP	(3185) ^e	(11 943) ^e	(39 807) ^e
9. revenue from refined biodiesel (RPB)	6576 ^d	20 716 ^d	64 676 ^d
10. net annual profit (NAP) = RPB - TMC	(6845) ^e	(21 717) ^e	(67 802) ^e
11. income taxes (IT): 50% of NAP	4136 ^d	15 508 ^d	51 695 ^d
12. net annual profit after taxes (NNP) = NAP - IT	(6845) ^e	(25 668) ^e	(85 561) ^e
13. after-tax rate of return (ARR) = (NNP - DEPC)/TCC (%)	-2440 ^d	-5208 ^d	-12 981 ^d
14. break-even price of biodiesel (BBP) (USD ton ⁻¹)	(-49) ^e	(3951) ^e	(17 759) ^e
15. BBP as USD L ⁻¹	-1220 ^d	-2604 ^d	-6491 ^d
16. BBP as NTD L ⁻¹	(-25) ^e	(1976) ^e	(8880) ^e
	-1220 ^d	-2604 ^d	-6491 ^d
	(-24) ^e	(1975) ^e	(8879) ^e
	-99.04 ^d	-73.2 ^d	-64.31 ^d
	(-10.44) ^e	(40.23) ^e	(67.38) ^e
	822 ^d	691 ^d	647 ^d
	(862) ^e	(724) ^e	(678) ^e
	0.699 ^d	0.587 ^d	0.550 ^d
	(0.733) ^e	(0.615) ^e	(0.576) ^e
	24.04 ^d	19.15 ^d	17.94 ^d
	(24.03) ^e	(20.16) ^e	(18.88) ^e

^a Yields of refined biodiesel and glycerine (85 wt % purity of glycerine) relative to input soybean oil are 62.5 and 27.5 wt % in this study, respectively. ^b Operating labor cost of 30 000 tons year⁻¹ is 1.3 times of that of 8000 tons year⁻¹.^{17,21} ^c Operating labor cost of 100 000 tons year⁻¹ is 1.3 times of that of 30 000 tons year⁻¹.^{17,21} ^d Price in 2003 [diesel price in Taiwan = 15.12 NTD L⁻¹ (2003), 1 USD = 34.41 NTD (2003), and 1 L = 0.85 kg (biodiesel)]. ^e Price in July 2007 [diesel price in Taiwan = 23.48 NTD L⁻¹ (July 2007) and 1 USD = 32.78 NTD (July 2007)]. Consumer price index (CPI) equation of cost: cost_(July 2007) = cost₂₀₀₃(CPI_(July 2007)/CPI₂₀₀₃), where CPI₂₀₀₃ = 99.52 and CPI_(July 2007) = 104.33 (in Taiwan).

oil price of U.S.A.), catalyst and solvent costs, operating labor fees, supervisory and clerical labor fees, utilities (including waste disposal), maintenance and repairs, operating supplies, laboratory charges, and expenses for patents and royalties. In brief, all charges related to materials and labors belong to this category²¹ and are listed in Tables 3 and 5. The operating labor fee was obtained from operation requirements for various pieces of process equipment.²⁸ Turton et al.²⁸ assumed that an operator worked on average 49 week year⁻¹ and that there were three shifts a day for a continuously running plant. The computation of Zhang et al.²¹ gave an operator's fee of 24 USD h⁻¹ and total operating labor fee of 141 120 USD year⁻¹ for three labors a day (one shift for one labor).

Table 6. Fraction of Total Production Cost, Cost of Oil Feedstock (Virgin Soybean Oil), and Glycerine Credit for the Processes of This Study (in Percentages)^a

	capacity (tons year ⁻¹)	8000	30 000	100 000
total production cost		100	100	100
glycerine credit		31.6	35.5	37.0
cost of oil feedstock (virgin soybean oil)		64.8	72.8	75.9

^a Yields of refined biodiesel and glycerine (85 wt % purity of glycerine) relative to input virgin soybean oil are 62.5 and 27.5 wt % in this study, respectively.

Considering the difference of labor fee between U.S.A. and Taiwan, we assumed an operator fee of 12 USD h⁻¹ and total operating labor fee of 564 480 USD year⁻¹ for 24 labors a

Table 7. Economic Evaluations for Biodiesel Production Plants or Processes from the References and This Study

	Nelson et al.	Noordam and Withers	Bender	Zhang et al.	this work	this work	this work		
plant capacity ^a (tons year ⁻¹)	100 000	7800	10 560	8000	8000	30 000	100 000		
process type	alkali-catalyzed continuous process	alkali-catalyzed batch process	alkali-catalyzed continuous process	process I: alkali-catalyzed process using virgin vegetable oil process II: alkali-catalyzed process using waste cooking oil process III: acid-catalyzed process using waste cooking oil process IV: acid-catalyzed process using hexane extraction virgin vegetable oil and waste cooking oil process I: 1.17 process II: 2.33 process III: 2.21 process IV: 2.77 process I: 1.34 process II: 2.68 process III: 2.55 process IV: 3.19 process I: 6.86 process II: 7.08 process III: 5.15 process IV: 5.62 process I: -1.03 process II: -1.14 process III: -0.18 process IV: -0.41 process I: -85.27 process II: -51.18 process III: 644 process IV: -21.48 process I: 884 process II: 702 process III: 0.77 process IV: 0.73 process I: 0.68 process II: 0.73	alkali-catalyzed continuous process	alkali-catalyzed continuous process	alkali-catalyzed continuous process	alkali-catalyzed continuous process	alkali-catalyzed continuous process
raw material	beef tallow	canola oil	animal fats	virgin vegetable oil	soybean oil	soybean oil	soybean oil		
FCC (in 10 ⁶ USD)	not reported	not reported	not reported	process I: 1.17 process II: 2.33 process III: 2.21 process IV: 2.77	1.17	3.51	10.15		
TCC (in 10 ⁶ USD)	12	not reported	3.12	process I: 1.34 process II: 2.68 process III: 2.55 process IV: 3.19	1.35	4.04	11.67		
TMC (in 10 ⁶ USD year ⁻¹)	34	5.95	not reported	process I: 6.86 process II: 7.08 process III: 5.15 process IV: 5.62	6.89	21.72	67.8		
NNP (in 10 ⁶ USD)	not reported	not reported	not reported	process I: -1.03 process II: -1.14 process III: -0.18 process IV: -0.41	-0.024	1.975	8.879		
ARR (in %)	not reported	not reported	not reported	process I: -85.27 process II: -51.18 process III: 644 process IV: -21.48	-10.44	40.23	67.38		
BBP (in USD ton ⁻¹)	340	763	420	process I: 857 process II: 884 process III: 702 process IV: 0.77	862	724	678		
glycerine credit (in 10 ⁶ USD)	6	0.9	1.2 for technical-grade glycerine	process I: 0.73 process II: 0.68 process III: 0.73 process IV: 0.73	3.19	11.94	39.81		

^a In terms of biodiesel production.

day for three shifts (one shift for eight labors) in this work. Other expenses, such as supervisory and clerical labor fees, maintenance and repair expenses, and operating supplies charges were calculated individually and multiplied by related factors,^{21,28} as shown in Table 5. IOC includes overhead, packaging, storage, local taxes, insurance, and depreciation. All of the items in this category are independent of the production rate in a plant.^{21,27,28} The last category, GE, includes administrative costs, distribution and selling costs, and research and development charges.^{21,27,28} The above items are also obtained via multiplication with various constant factors as shown in Table 5.

2.4. Net Annual Profit after Taxes (NNP) and After-Tax Rate of Return (ARR). ARR is a general economic performance criterion for the preliminary evaluation of a plant and is defined as the ratio of NNP relative to the TCC. NNP is equal to the net annual profit (NAP) subtracting income taxes (IT) (i.e., $NNP = NAP - IT$).^{21,27} ARR was also chosen as the response variable and objective function in the economic assessment of this study. The results are shown in Table 5.

2.5. Biodiesel Break-Even Price (BBP). >BBP is the price of biodiesel when the revenue from biodiesel product (RPB) is equal to TMC of a plant. The values of BBP are expressed as USD and New Taiwan dollars (NTD) in this study and are shown in Table 5 for biodiesel plants with different capacities.

Factors for Economic Assessment. The economic costs of three biodiesel plants with capacities of 8000, 30 000, and 100 000 tons year⁻¹ were computed as presented in Tables 4 and 5. The fractions of total production cost, cost of oil feedstock (virgin soybean oil), and glycerine credit are listed in Table 6. From Table 6, the fractions of the cost of oil feedstock and glycerine credit increase with the increase of the capacity of the biodiesel plant. The total production cost decreases with the increase of the glycerine credit and the decrease of the cost of the oil feedstock. A comparison of the results of factors for economic assessment obtained in the literature and this work is given in Table 7. In this study, the plants employ continuous processes using an alkali catalyst and the raw material of soybean oil. Six major economic cost factors were examined and compared. These include FCC, TCC, TMC, NNP, ARR, and BBP. The values of NNP and ARR (Table 5) of plants with capacities of 8000, 30 000, and 100 000 tons year⁻¹ are -24×10^3 , 1975×10^3 , and 8879×10^3 USD and -10.44 , 40.23 , and 67.38% , respectively. Therefore, both NNP and ARR turn from negative to positive when the plant capacity increases. The values of BBP of the three plants are 862, 724, and 678 USD ton⁻¹ or 0.733, 0.615, and 0.576 USD L⁻¹, respectively (price in July 2007). From Table 5, NNP and ARR of 2003 are all negative values because the biodiesel price in 2003 (Taiwan) is so low (15.12 NTD L⁻¹). However, with the increase of the price of diesel from 2003 (15.12 NTD L⁻¹) to July 2007 (23.48 NTD L⁻¹) in Taiwan, NNP and ARR increase and turn from negative to positive. The plant with a capacity of 100 000 tons year⁻¹ in this study is economically feasible, providing a higher NNP and more attractive ARR with a lower BBP. Zhang et al.²¹ proposed four different continuous processes for biodiesel production from virgin oil or waste vegetable oil using alkaline or acidic conditions. The values of BBP of these four processes are 857, 884, 644, and 702 USD ton⁻¹ as listed in Table 7. Therefore, the third process of the acid-catalyzed process using waste cooking oil was more economically feasible, giving lower TMC and BBP with

a more attractive ARR. As shown in Table 7, the value of BBP of the plant with a capacity of 100 000 tons year⁻¹ of this study (647 USD ton⁻¹) is close to that of the acid-catalyzed process using waste cooking oil proposed by Zhang et al.²¹ (678 USD ton⁻¹). It implies that the increase in the plant capacity with soybean oil has the same economic feasibility as using waste cooking oil as feedstock. Nelson et al.¹⁷ also evaluated the economic feasibility of a plant producing approximately 100 000 tons year⁻¹ of biodiesel. The feedstock of beef tallow was transesterified with methanol in the presence of an alkali catalyst, yielding a low BBP of 340 USD ton⁻¹ (Table 7). However, the beef tallow is not easily available in any country. Thus, from the point of view of easy feedstock, a plant with a reasonably large capacity with an alkali-catalyzed continuous process is economically feasible, as illustrated in this study using soybean oil as feedstock. The proposed process of this work having a large plant capacity has the same economic potential as that using the low-cost feedstock of waste cooking oil.

Conclusions

Among the system variables of the plant examined, plant capacity, price of feedstock oil, and yields of glycerine and biodiesel were found to be the most significant variables affecting the economic viability of biodiesel manufacture. A plant with capacity of 100 000 tons year⁻¹ assessed in this study is economically feasible, yielding higher NNP and ARR with a lower BBP. Increasing the plant capacity using a feedstock of soybean oil has the same economic feasibility as employing waste cooking oil as feedstock. In summary, this study aims at the need to obtain useful information for the cost analysis and assessment of the production process of biodiesel using soybean oil. The results provide an appropriate indication for the promotion of biodiesel production in the future, targeting the reduction of the cost of feedstock oil with the increase of the yields of valuable products with a reasonably large plant capacity.

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Nomenclature

DEPC = Depreciation
AFC = Costs associated with auxiliary facilities
ARR = After-tax rate of return
BBP = Biodiesel break-even price
CBP = Credits of byproducts of glycerine
CFC = Contingencies and fees
DOC = Direct operation cost
FAME = Fatty acid methyl ester
FCC = Fixed capital cost
FFA = Free fatty acid
FOC = Fixed operating cost
GE = General expense
GHG = Greenhouse gas
IOC = Indirect operation cost
IT = Income taxes
M = Plant capacity in term of biodiesel production
NAP = Net annual profit
NNP = Net annual profit after taxes
RPB = Revenue from refined biodiesel product

TBMC = Total basic module cost
TBMCC = Total bare module capital cost
TCC = Total capital investment cost
TMC = Total manufacturing cost
TOC = Total operating cost

TPC = Total production cost
VOC = Volatile organic compound
WCC = Working capital cost
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