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Research article

Process simulation and economic feasibility of biodiesel production from acid oil, a by-product of glycerol acidulation

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Abstract

Importance of the work: A new approach was investigated using acid oil from acidulation for its economic feasibility in biodiesel production.

Objectives: To investigate the esterification conditions of biodiesel production from acid oil, and conduct process simulation and cost investigation using the ASPEN software.

Materials & Methods: Reaction time (1–6 h) and the methanol-to-oil molar ratio (20:1–30:1) were varied with a fixed 4% H_2SO_4 catalyst at, 60 °C and 500 revolutions per minute. Based on the experimental data, the optimized conditions determined using the Minitab-17 software were used in the ASPEN process simulation. Then, the economic feasibility and sensitivity analysis were examined.

Results: The acid oil comprised 33.63% free fatty acid, 72.36% fatty acid methyl ester and 1.3% water. After esterification using an acid catalyst, Minitab determined the optimum conditions of biodiesel production from the acid oil at 3.4 h reaction time and a 25.9:1 methanol-to-oil ratio, which produced biodiesel containing fatty acid methyl ester of 96.8% and free fatty acid of 0.32%. Consequently, 26,579.5 kg/d biodiesel were produced from 27,300 kg/d acid oil and 30,903 kg/d methanol, with 95% conversion. Finally, the project was economically feasible based on the net present value (USD 34,092,719), the internal rate of return (56%), the payback period (5.1 yr) and the production cost (USD 0.77/L).

Main finding: Acid oil could be used as new raw material for biodiesel production. The results showed that the production process was economically suitable for investment. Minitab was a helpful tool for optimization, while ASPEN was excellent for process simulation and economic assessment.

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Introduction

Numerous kinds of research have revealed that biodiesel (BD) can be created as an alternative fuel because of its cost-saving, beneficial waste disposal effects on the environment and its value-added goals (Channapattana et al., 2015; Kolakoti and Rao, 2020). Biodiesel can be produced by transesterifying triglyceride or esterifying fatty acids with alcohol (Suppalakpanya et al., 2010).

Biodiesel production via transesterification generates crude glycerol as a by-product, that is higher than 10% (weight per weight, w/w), depending on the process of biodiesel production (He et al., 2017; Chol et al., 2018; Mena-Cervantes et al., 2020). Crude glycerol purification can be an environmental burden due to the waste produced, because its disposal is another economic barrier to the competitiveness of biodiesel as a renewable alternative energy source (Mena-Cervantes et al., 2020). Following crude glycerol purification, acidulation helps to split the soap into acid oil and sodium sulfate (Fig. 1).

Acidulation is a process for purifying glycerol by adding sulfuric acid to crude glycerol, where the crude glycerol is separated into three layers: upper (acid oil), middle (purer glycerol) and lower (salt) (Li et al., 2010). As a result, acid oil has been reported at 13% w/w of crude glycerol (Reakasame et al., 2010). Typically, acid oil contains high amounts of fatty acid methyl ester (FAME) and free fatty acid (FFA). However, local companies sell it at a low price. Therefore, no report has been found on the utilization of this acid oil.

Esterification is the chemical reaction of an organic acid (RCOOH) and alcohol (ROH) to produce an ester (RCOOR) and water, as shown in Fig. 2. Of the various alcohols affecting the synthesis of biodiesel, methanol (MeOH) is the most efficient because of its rapid reaction rate and strong ester formation (Sanli and Canakci, 2008). Even though biodiesel production using transesterification (as a base catalyst) is standard on a commercial production scale, esterification is used instead for its high FFA content raw material to avoid saponification (Chisti, 2007).

Process simulation is commonly used before economic assessment (Lee et al., 2011). Many commercial process simulators are available, such as ASPEN Plus, Super Pro (Gebremariam and Marchetti, 2021). However, ASPEN Plus version 12 was used in this study due to its comprehensive databases, vast component libraries and advanced calculation techniques (Abdulwahab et al., 2014). ASPEN Plus has been used to investigate waste cooking oil using an acid catalyst but not waste oil from the acidulation (Liu et al., 2021).

Economic feasibility is also known as techno-economic analysis and is critical to verify a technology before it can be used in commercial applications. Such a study supports the accuracy of outcomes from 20–30% of the actual expense (Turton et al., 2008; Swanson et al., 2010; Robert and Tristan, 2013). Generally, the investigation includes the economic performance of the total investment cost, the unit cost of production, the net present value, the internal rate of return and the project payback period (Lee et al., 2011; Gebremariam and Marchetti, 2021).

The current study integrated experimental investigation, simulation and economic feasibility work. First, the experiment used acid oil, a by-product and low-cost, as new raw material for biodiesel production. Acid oil was obtained from acidulation, a glycerol purification process which is an add-on process of biodiesel factories. The challenge was the possibility of producing this by-product in biodiesel factories in terms of technical and financial feasibility. Therefore, the study was divided into three parts: the experimental investigation of the esterification reaction conditions, the simulation for process optimization and design, and the economic feasibility.

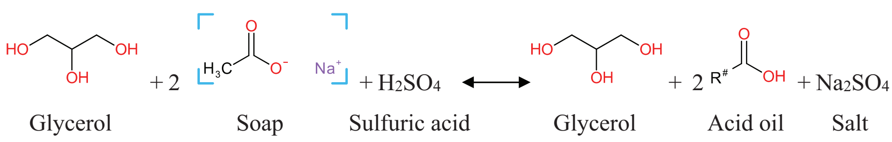

Fig. 1 Acidulation process (Mena-Cervantes et al., 2020)

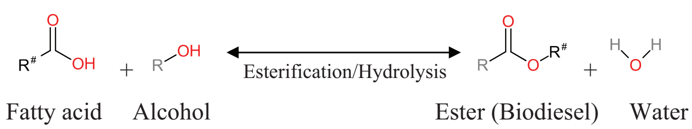

Fig. 2 Esterification reaction mechanism (Schuchardt et al., 1998)

Materials and Methods

Materials

A local biodiesel production company in Thailand supplied the acid oil obtained from its acidulation process. Therefore, it was used in this experiment. The required chemicals, such as methanol (99.8%), sulfuric acid (98%), potassium hydroxide (solid), toluene (99.9%), isopropyl alcohol (2-propanols, 100%), methyl heptadecanoate and heptane (99%) were bought from Zen Point, ACI Labscan, Fluka (Germany), and Merck (Germany) in analytical grades.

In this study, Minitab-17 was used to optimize the biodiesel production conditions based on the data obtained from the experiment. The ASPEN Plus version 12.0 software and the ASPEN process economic analyzer (APEA) module were used for the process design and financial analysis, respectively. This software can provide reliable information on process operations because of its comprehensive databases, vast component libraries and advanced calculation techniques. The valuable functions are various chemical components, flexible plant capacity and different chemical engineering unit operating and configuring input conditions (such as flow rate, temperature, pressure) (El-Galad et al., 2015; Juma, 2019).

Methodology

Esterification reaction

Water in the acid oil was removed before proceeding with the esterification reaction to minimize the backward reaction (Park et al., 2010; Chongkhong et al., 2012). Then, the acid oil was esterified using a 4% H_2SO_4 catalyst at a constant 60 °C and 500 revolutions per minute stirring speed. In addition, the reaction time (1–6 h) and MeOH-to-oil molar ratio (20:1–30:1) were varied to optimize the intended goal. After the reaction, the crude biodiesel was washed with 40 °C warmed distilled water. Finally, the biodiesel was purified using dehydration. Then %FFA and %FAME of biodiesel were measured according to the analytical methods. The range of conditions was based on Thepchan (2015). After the data had been obtained from the experiment, the Minitab program was used to optimize the conditions for esterification, targeting %FAME higher than 96.5 and minimized %FFA.

The necessary properties of crude acid oil were determined: %FFA, %FAME, water content, density and average molecular weight (MW_{Avg}). The FAME content and fatty acid components were analyzed using gas chromatography (Shimadzu GC-2010) with an EN 14103 with a capillary column of length 30 m, a film thickness of 0.25 µm and an inside diameter of 0.32 mm. The inlet was controlled at 250 °C using helium as a carrier gas. The operating conditions were oven temperature at 150 °C for 6 min, then adjusted for 15 min to 210 °C (at 7 °C/min). A flame ionization detector was used at 250 °C and the internal standard was methyl heptadecanoate. The percentage of FAME content was determined based on Equation 1:

$$\%FAME = \frac{(\sum A - A_{IS})}{A_{IS}} \times \frac{C_{IS} V_{IS}}{m} \times 100 \quad (1)$$

where; $\sum A$ is the total peak area of methyl ester (C_{12}– C_{24}), A_{IS} is the area of the internal standard and C_{IS} is the concentration of the internal standard (in milligrams per milliliter),

V_{IS} is the volume of the internal standard (in milliliters) and m is the weight of the biodiesel (in milligrams).

The %FFA was measured using an auto-titrant (848 Titrino Plus; Metrohm, Switzerland). Then, the water or moisture content was calculated using Equation 2:

$$\text{Moisture Content (\%)} = \frac{W_i - W_f}{W_i} \times 100\% \quad (2)$$

where Wi and Wf are the weight of the sample (100 milligrams) before and after boiling at 105 °C for 30 min.

Finally, the density was analyzed by weighing the sample (20 mL) at 30 °C, as shown in Equation 3:

$$\text{Density (kg/m}^3) = \frac{\text{sample weight (g)}}{\text{sample volume (mL)}} \times \frac{\text{kg}}{\text{1,000 g}} \times \frac{\text{1,000 mL}}{\text{m3}} \quad (3)$$

The average molecular weight (MW_{Avg}) of the acid oil was calculated by summing the molecular weight of each fatty acid composition (MW_i) of the acid oil using Equations 4 and 5 (Srinophakun, 2018):

$$MW_i = 14.027 * C - 2.016 * D + 31.9988 \quad (4)$$

$$MW_{Avg} = \sum \text{Fractional MW} \quad (5)$$

where C is the number of carbon atoms and D is the number of double bonds.

Process simulation and cost analysis

In the process design of biodiesel production from the acid oil, the amount of raw material was fixed at 27,300 kg/d (assuming 14 d of crude acid oil accumulation). All unit operations were selected from the ASPEN database. The factory was located in Bang Pa-in district, Ayutthaya province, Thailand (an extension of the current biodiesel factory). Costs and expenses provided in Thai baht were converted to US dollars based on the exchange rate quoted on 25 January 2022 of USD 1 = THB 33.2828 (Foreign Exchange Rates, 2022). The biodiesel manufacturing plant was designed to run for 8 hr/d and 300 d/y. Hence, the overall plant life was set at 20 y. Equipment costs were updated from 2020 to 2022 using the Chemical Engineering Plant Index, where I_{2020} = 596.2 and I_{2022} = 797.6, respectively (Vatavuk, 2002; Mignard, 2014).

The process comprised four steps: dehydration, esterification, methanol recovery and biodiesel purification (washing and dehydration). First, the acid oil compositions and optimum esterification conditions from the experiment and Minitab program were applied to the process. In addition, the fractions of raw materials, chemicals, water and operating temperatures were added, according to El-Galad et al. (2015) and Juma (2019). Next, proper unit operations were selected from the database of ASPEN and the software was run based on optimum operation conditions for each unit. Finally, all output volumes and mass fractions were obtained after completing the program. Then the economic analysis, utilities, equipment and installation costs were determined by running APEA.

Results and Discussion

Esterification of acid oil to biodiesel

Table 1 shows some parameters of the crude acid oil compared to crude palm oil and the biodiesel standard. For example, acid oil contained high levels of %FFA, %FAME and water content compared to crude palm oil. However, the %FFA was too high and the %FAME was too low compared to the biodiesel standard. Hence, esterification (Fig. 2) was required to convert FFA into FAME and reach > 96.5% conversion, according to the biodiesel standard. After the reaction, the results are shown in Fig. 3, with the FAME increasing as the FFA decreased up to 4 h, according to the forward reaction in Fig. 2. Then, the response was reversed due to the high concentration of FAME. As a result, the FFA increased and the FAME decreased.

Table 1 Some parameters of crude acid oil, crude palm oil and biodiesel standard

Item	Crude acid oil	Crude palm oil	Biodiesel standard
Density (kg/m^3)	838.99 (at 25 °C)	888.9–889.6 (at 50 °C)[1]	860–900 (at 15 °C)
Water content (%wt)	1.3	na[2]	0.05
FFA (%)	33.63	< 5.0	na[3]
FAME (%)	72.36	na	>96.5
Molecular weight (g/mol)	366.45	840–890[4]	na

FFA = free fatty acid; FAME = fatty acid methyl ester

[1] (MS 814, 2007); [2] indicated as moisture and impurities < 0.5 %wt (MS 814, 2007);

[3] displayed as an acid value of 0.5 mg KOH/g or estimated as 0.25% FFA; [4] calculated value

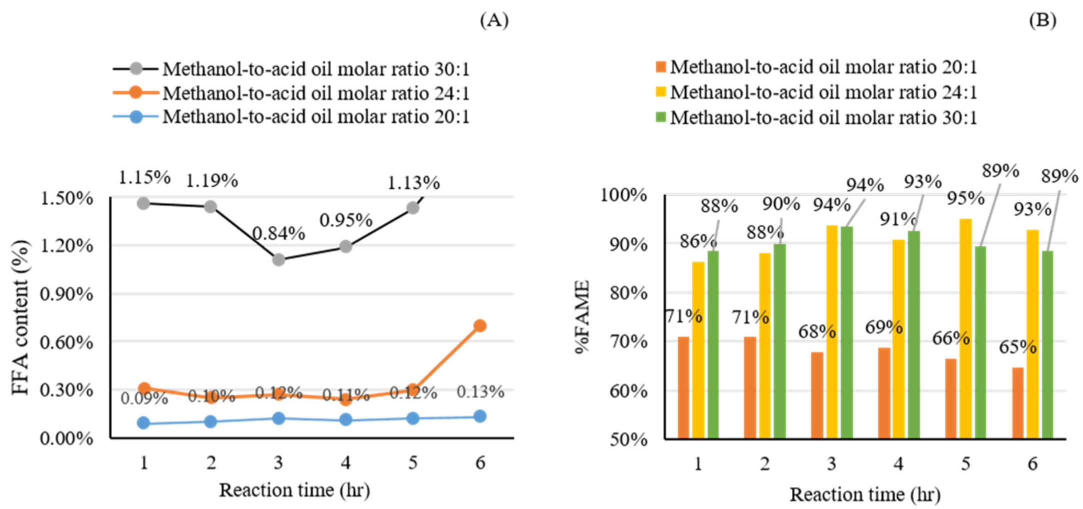

Fig. 3 Effect of reaction time at various methanol-to-acid oil molar ratios: (A) on free fatty acid (FFA) content; (B) on the percentage of fatty acid methyl ester (%FAME)

The experimental results were entered into the Minitab-17 program to determine the optimum conditions, as shown in Equations 6 and 7, with coefficient of determination (R^2) = 96.26% and 96.05%, respectively. According to the Minitab simulation, the optimum conditions were a 25.9:1 MeOH-to-oil ratio and 3.4 h reaction time at 4% wt H_2SO_4 catalyst, which produced 0.32% FFA or 99% FFA conversion and 96.8% FAME. Therefore, this study could get lower final %FFA (lower is more preferable) and higher %FAME (higher than 96.5% according to the commercial biodiesel standard) compared to Abbas and Abbas (2013) and Junsittiwate (2016). Abbas and Abbas (2013) used a higher %catalyst (5% wt) but got only 2% FFA conversion. Junsittiwate (2016), who esterified acid oil (initial 13.29% FFA and 85.7 %FAME) but got a higher final %FFA of 0.56 and lower %FAME of 94.7. Thus, a higher amount of catalyst and methanol was proven to drive good esterification forward (Hayyan et al., 2011).

$$Y_1 = 5.01 - 0.458\,X_1 - 0.174\,X_2 + 0.01111\,X_1{*}X_1 + 0.0287\,X_2{*}X_2 - 0.00017\,X_1{*}X_2 \quad (6)$$

$$Y_2 = -323.1 + 31.15\,X_1 + 0.60\,X_2 - 0.5853\,X_1{*}X_1 - 0.407\,X_2{*}X_2 + 0.0926\,X_1{*}X_2 \quad (7)$$

where Y_1 and Y_2 are the %FFA and %FAME, respectively, and X_1 and X_2 are the methanol-to-acid oil molar ratio (MeOH:oil) and reaction time, respectively.

Process design and simulation

The biodiesel production process from the acid oil was designed using ASPEN (Fig. 4) with the selected unit operations from its database (Table 2). Then, the fatty acid composition of the acid oil (Table 3) was esterified according to Equations 8 to 11. The reaction conditions for the MeOH-to-oil ratio were rounded up to 26:1 in the ASPEN simulation.

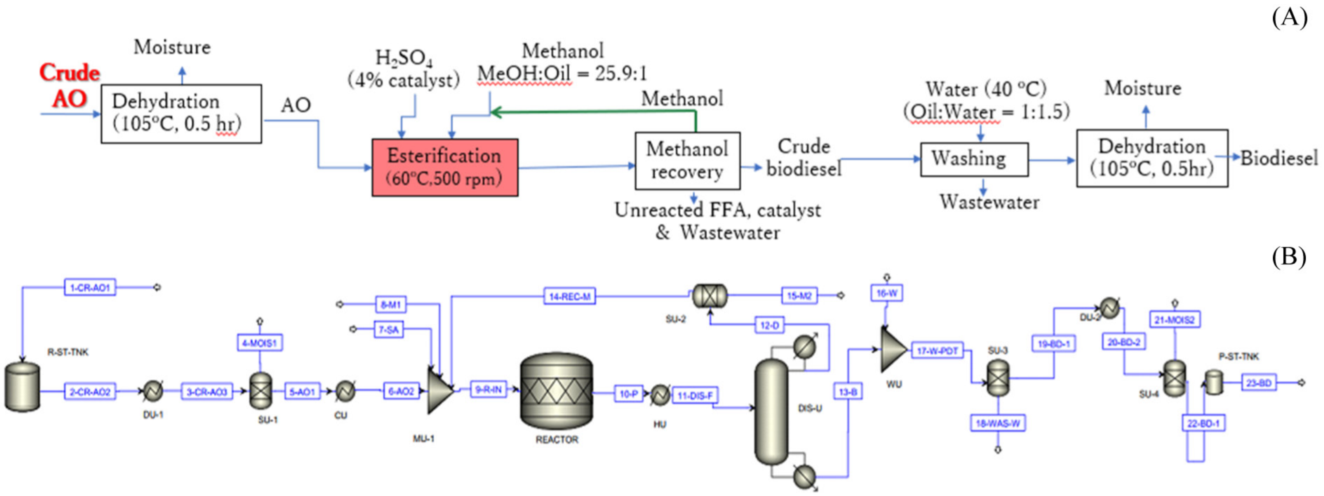

Fig. 4 Process design of biodiesel production from acid oil using esterification: (A) block diagram of process, where AO = acid oil), FFA = free fatty acid and rpm = revolutions per minute; (B) ASPEN simulation flow chart

Table 2 Selected equipment from APEA program for biodiesel production from crude acid oil

Sr.	Operation name	Equipment name	Operation unit name shortcut	Utilized volume of the equipment (L)
1	Raw material storage	Raw material storage tank	R-ST-TNK	34,000
2	Dehydration	Heater	DU-1	34,000
3	Separation	Separating tank	SU-1	34,000
4	Cooling	Heater	CU	34,500
5	Mixing	Mixer	MU-1	67,000
6	Esterification Reaction	Reactor	Reactor	67,000
7	Heating	Heater	HU	69,000
8	Distillation	Distillation column	DIS-U	270,000
9	Mixing	Mixer	MU-2	23,000
10	Washing	Washing tank	WU	98,000
11	Separation	Separating tank	SU-2	50,000
12	Dehydration	Heater	DU-2	39,000
13	Separation	Separating tank	SU-3	39,000
14	Product material storage	Product storage tank	P-ST-TNK	36,500

Table 3 Fatty acid composition of crude acid oil and water content

Acid oil	Weight (%)
Stearic acid (18:0) $C_{18}H_{36}O_2$	0.53
Linolenic acid (18:3) $C_{18}H_{30}O_2$	1.85
Arachidic acid (20:0) $C_{20}H_{40}O_2$	0.10
Lignoceric acid (24:0) $C_{24}H_{48}O_2$	96.22
Water content	1.30

In addition, other components, such as carboxylic acids, methyl esters, methanol, sulfuric acid and water, were retrieved from the ASPEN database library. Furthermore, ASPEN estimated other physical properties, such as volume, enthalpy and mole balances. Finally, the non-random two-liquid (NRTL) model was used to forecast the component activity coefficients in the liquid phase due to MeOH and the highly polar substances (El-Galad et al., 2015; Vanderveen et al., 2016; Juma, 2019). The input raw material of acid oil was fixed at 27,300 kg/d and 95% yield was used to calculate the product, according to the referenced factory. Then ASPEN calculated the mass balance of the plant-wide process, as detailed in the supplement.

The esterification reaction of stearic acid is shown in Equation 8:

$$\underset{\text{Stearic acid}}{C_{18}H_{36}O_2} + CH_3OH \rightarrow \underset{\text{Stearic acid methyl ester}}{C_{19}H_{38}O_2} + H_2O \quad (8)$$

The esterification reaction of linolenic acid is shown in Equation 9:

$$\underset{\text{Linolenic acid}}{C_{18}H_{30}O_2} + CH_3OH \rightarrow \underset{\text{Linolenic acid methyl ester}}{C_{19}H_{32}O_2} + H_2O \quad (9)$$

The esterification reaction of arachidic acid is shown in Equation 10:

$$\underset{\text{Arachidic acid}}{C_{20}H_{40}O_2} + CH_3OH \rightarrow \underset{\text{Arachidic acid methyl ester}}{C_{21}H_{42}O_2} + H_2O \quad (10)$$

The esterification reaction of lignoceric acid is shown in Equation 11:

$$\underset{\text{Lignoceric acid}}{C_{24}H_{48}O_2} + CH_3OH \rightarrow \underset{\text{Lignoceric acid methyl ester}}{C_{25}H_{50}O_2} + H_2O \quad (11)$$

Economic analysis and cost estimation

Economic performance is decisive in determining whether a business is financially acceptable. Therefore, project viability must be monitored to assess whether the company will make a profit or a loss. Costs were defined in terms of total capital cost, manufacturing cost, net present value and the payback period of biodiesel production (El-Galad et al., 2015). Based on the research evidence and real-time assessment, the prices and costs (including raw materials, products and wastewater treatment) are presented in Table 4. The calculation was based on the purchased prices from the local biodiesel company, while APEA provided the unit operation equipment cost, installation costs and utilities cost.

Total capital investment (TCI) comprises fixed capital investment (FCI) and working capital (WC), as shown in Table 5. FCI was the sum of direct and indirect costs, with the prices mostly obtained from Peters et al. (2003). The direct cost incorporated equipment cost, equipment installation cost, instrumentation and control cost, piping cost, electrical system cost, building cost, yard improvement, service facilities cost and land cost. For example, the average cost of land was the equivalent of USD 137,500/ha retrieved from the Treasury Department (2019). The appropriate land area was set as 1,600 m^2. On the other hand, the indirect cost included contractor's fees, legal expenses, engineering and supervision, construction expenses and contingency at 4%, 22%, 33%, 41% and 44%, respectively, of equipment costs. In addition, according to Peters et al. (2003), WC is proportional to TCI (15%).

TPC was used to assess the product production cost and unit cost. A detailed list of TPC components is expressed in Table 6, with the detail of labor cost in Table 7 (Engineer Average Salary in Thailand, 2022; Internal Auditor Average Salary in Thailand, 2022) and the utility cost from the APEA database. Mega Certification Company Limited quoted the International Organization for Standardization (ISO) certificate cost (Mega Certification Company Limited, 2022), and the wastewater treatment cost was from Table 4.

Table 4 Costs of raw materials, products and wastewater treatment cost used in this work.

Item	Price	Source
Raw materials		
acid oil	USD 0.30/L	Purchased price*
MeOH	USD 0.48/kg	Purchased price*
H_2SO_4	USD 0.27/kg	Purchased price*
Products		
biodiesel	USD 1.18/L	(Energy Policy and Planning Office, 2021)
Wastewater treatment cost		
Wastewater treatment	USD 0.01/L	Cost of wastewater treatment*

*supplied by the local biodiesel company

Table 5 Total capital investment

Cost parameter	Cost (USD)	Reference
Direct costs		
Purchased equipment cost	558,802	from the APEA simulation result
Equipment installation cost	2,808,991	from the APEA simulation result
Instrumentation and controls	201,169	36% of Equipment cost (Peters et al., 2003)
Piping	379,985	68% of Equipment cost (Peters et al., 2003)
Electrical systems	61,468	11% of Equipment cost (Peters et al., 2003)
Buildings	100,584	18% of Equipment cost (Peters et al., 2003)
Yard improvement	55,880	10% of Equipment cost (Peters et al., 2003)
Service facilities	391,161	70% of Equipment cost (Peters et al., 2003)
Land	21,935	(The Treasury Department, 2019)
Total direct plant cost	4,579,976	
Indirect costs		
Engineering and supervision	184,405	33% of Equipment cost (Peters et al., 2003)
Construction expense	229,109	41% of Equipment cost (Peters et al., 2003)
Legal expenses	22,352	4% of Equipment cost (Peters et al., 2003)
Contractor's fee	122,936	22% of Equipment cost (Peters et al., 2003)
Contingency	245,873	44% of Equipment cost (Peters et al., 2003)
Total indirect plant cost	804,674	
Fixed-capital investment (FCI)	5,384,650	(Direct + Indirect costs)
Working capital (WC)	950,232	15% of TCI (Peters et al., 2003)
Total capital investment (TCI)	6,334,882	(FCI + WC)

Table 6 Total production cost

Cost parameter	Annual cost (USD)
Manufacturing costs	
Direct costs	
Raw materials	5,659,207
Wastewater treatment cost	228,640
Utilities	259,011
Labor cost	108,849
Maintenance and repairs (2% of FCI)	107,693
Operating supplies (0.5% of FCI)	26,923
Fixed charges	
Local taxes (1% of FCI)	53,846
Insurance (0.4% of FCI)	21,539
ISO certification cost (detail in the supplement)	16,073
Plant-overhead costs (5% of TPC)	364,145
General expenses	
Administrative costs (5% of TPC)	364,145
Distribution and selling costs (1% of TPC)	72,829
Total production cost	7,282,900

FCI = fixed capital investment; TPC = total production cost

Table 7 Total labor costs

Labor cost	Position	USD/yr-person	USD/yr
Specialized engineering	1	18,029	18,029
Technician (including 1 QC)	3	10,817	32,452
Maintenance Engineer	1	7,742	7,742
Store manager	1	11,612	11,612
Internal quality audit	1	33,606	33,606
Security	1	5,409	5,409
Total annual labor cost			108,849

QC = quality control officer

In the next step, the net profit was estimated based on the money gained (positive result) or lost (negative result) from revenues after subtracting all associated costs (Equation 12) and was calculated by subtracting the TPC from the total income (Total product sales). In this study, biodiesel production cost USD 0.77/L, but the sale price was USD 1.18/L. Therefore, the total revenue was calculated based on the total biodiesel products of 31,680 L/d and working days of 300 d/y. As a result, the total annual production cost was USD 7,282,900 and the annual income was USD 11,191,812. As a result, the yearly profit was USD 3,908,911.

$$\text{Total profit} = \text{Total income} - \text{Total production cost} \tag{12}$$

Depreciation enables a taxpayer to recover some of the capital cost of a specific item through an income tax deduction, as shown in Equations 13 and 14. Hence, the percentage of salvage was assumed as 10%. The annual depreciation was calculated over the project life of 20 years. As a result, the yearly depreciation of this project was USD 241,322.

$$\text{Salvage value} = \frac{\text{FCI without land cost} \times \text{\% of salvage}}{100\%} \tag{13}$$

$$\text{Depreciation} = \frac{\text{FCI without land cost} - \text{Salvage value}}{\text{Project year}} \tag{14}$$

The economic indicators of net present value (NPV), internal rate of return (IRR), payback period (PB) and production cost per unit were valued after assessing the total capital (TCI) and annual production costs (TPC) of the plant. NPV specifies how much the development will contribute to monetary terms over the whole project period in present money value. Therefore, it is a practical parameter when a project occurs over an extended period, with high inflation rates and non-linear developments in prices and costs. The NPV is the difference between cash inflows' present value and cash outflows' current value, as shown in Equation 15. The weighted average cost of capital was set at 7%, and the discount rate or loan interest rate based in Thailand (r) was set at 5.415%, based on an announcement in April 2022 (Thailand Bank Lending Rate, 2022). From the calculation, the NPV of the desired project was USD 34,092,719. Therefore, investment in the process was worthwhile, since its NPV was positive.

$$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+r)^t} \quad (15)$$

where B_t is the total benefit, C_t is the total product cost, r is the discount rate and t is the number of years. If NPV < 0, investment decreases at an accepted discount rate. If NPV = 0, this links to the IRR, a financial risk measurement indicator used to value the profitability of the investment. If NPV > 0, the total investment increases at the assumed discount rate.

The IRR is valid for assessing the economic quality of a project and is used in capital budgeting to evaluate the profitability of potential investments, representing the interest rate. In contrast, the highest value of the IRR indicates the most profitable project, independent of project size and technology. In this study, IRR was calculated using the Excel function, as shown in Equation 16.

$$IRR\left(\sum_{t=0}^{n}(B_t - C_t)\right) \quad (16)$$

The IRR of the project was 56%. To determine whether a project is feasible, the IRR is compared to 20% of the minimum acceptable rate of return (MARR) which was set at 7% (El-Galad et al., 2015). Therefore, the project was feasible because the IRR was greater than the MARR. Farid et al. (2020) reported an IRR of 60% for biodiesel production from waste cooking oil with and NPV of USD 1,473,620 with a project life of 10 yr. The payback period is essential for the year of investment returns but not the maximum profit of the project. At first, the gross profit for year t (G^t) and the net profit after tax of year t (NP^t) were derived using Equations 17 and 18:

$$G^t = TCI - TPC^t \quad (17)$$

where t is the project year.

$$NP^t = N^t - PT^t \quad (18)$$

where $N^t = G^t$ – depreciation, $PT^t = T \times N^t$, PT^t is a provision for corporate income tax for year t and T is the corporate income tax, set at 20% based on Thailand Corporate Tax Rate (2022).

Then, the cash flow statement (see the supplement) was estimated from cash inflow (CI^t), cash outflow (CO^t), and cash in hand every year (Equations 19–21).

$$CI^t = \text{Previous balance} + \text{Total annual income} \quad (19)$$

$$CO^t = TCI + TPC^t + \text{Depreciation} + PT^t \quad (20)$$

$$\text{Cash in hand} = CI^t - CO^t \quad (21)$$

For year 1, there was no income, so CI was zero, while TPC^t and PT^t were also zero. In addition, TCI was only considered for year 1.

Comparing TCI (the initial investment) and cash in hand, the cash in hand covers TCI during years 5 and 6 (see the supplement). As a result, the payback period was calculated using Equation 22 (Cheremushkin, 2016):

$$\text{Payback period} = 5 + \frac{(\text{TCI - Cash in hand at year})}{(\text{Cash in hand at year 6})} = 5.1 \text{ yr} \quad (22)$$

where 5 is year 5.

Overall, the biodiesel production project from acid oil was interesting as it could provide a high FAME content and help to resolve a future shortage of diesel fuel. Furthermore, the economic assessment indicated excellent outcomes of 34,092,719 for the NPV, 56% for the IRR and a payback period of 5.1 years. Finally, risk assessment based on sensitivity analysis was performed based on the NPV and IRR. Therefore, biodiesel production parameters, such as plant capacity, process technology, raw materials and chemicals, were evaluated. In addition, the tolerance of 20% was investigated. The results are shown in Fig. 5.

The sensitivity analyses showed that the product sale price was the most sensitive factor affecting the NPV and IRR, followed by the total production cost. As expected, among the production costs, the raw material costs were the most sensitive factors for the desired project. Similar results were found in an analysis of biodiesel production from waste cooking oil (Shahbeig et al., 2020). An increase in the price of acid oil

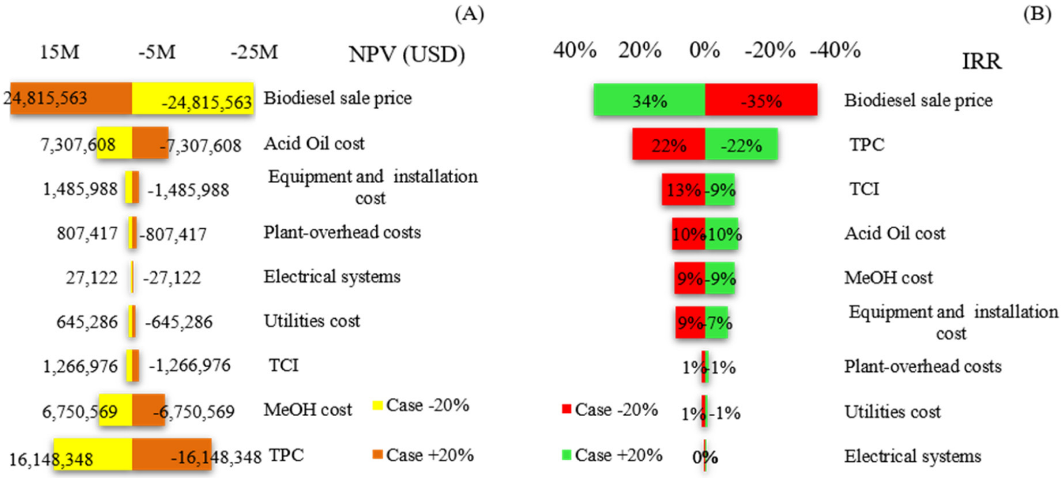

Fig. 5 Sensitivity analysis of percentages with ± 20% variation for: (A) net present value (NPV); (B) internal rate of return (IRR), where TCI = total capital investment, TPC = total capital cost

would affect the project's feasibility. If the %FFA or %FAME contents in the acid oil increased, the optimum conditions of esterification would change, tentatively, to use more methanol or acid catalyst. Increasing the methanol amount would reduce the NPV and IRR, as shown in Fig. 5. Therefore, using more catalysts rather than more methanol might be an excellent option to maintain a high NPV value for the current study.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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