Reaktor

3p-ISSN 0852 – 0798
e-ISSN 2407 – 5973

Website: http://ejournal.undip.ac.id/index.php/reaktor/

Reaktor, Vol. 26 No. 2, August Year 2026, pp. 1-12

Techno-Economic Analysis of Biodiesel Production from Microalgae

Rendra Panca Anugraha[1,*)], Adelia Melita Sari[1)], Habib Nurrohim[1)], Renanto[1)], Juwari[1)], Donny Satria Bhuana[1)]

[1)] Department of Chemical Engineering, Faculty of Industrial Technology and Systems Engineering, Institut Teknologi Sepuluh Nopember (ITS), Kampus ITS Sukolilo, Surabaya, East Java, 60111, Indonesia

[*)] Corresponding author: rendra@its.ac.id

(Received: 12 April 2026; Accepted: 8 August 2026; Published: 15 August 2026)

Abstract

The increasing global energy demand and the urgent necessity to mitigate greenhouse gas emissions have driven the exploration of renewable energy alternatives to fossil-based fuels, such as biofuels derived from sustainable biological sources. Among various potential feedstocks, microalgae have gained considerable attention due to their high lipid productivity, rapid growth rate, and ability to utilize CO_2 *efficiency through photosynthesis. This study presents the design and techno-economic evaluation of a biodiesel production plant utilizing Chlorella vulgaris microalgae as the primary feedstock. The cultivation process employs a Flat Plate Photobioreactor (FPPBR) system to enhance biomass productivity under controlled light and nutrient conditions. The production process adopts the Lurgi technology, beginning with the extraction of microalgae oil using n-hexane solvent, which is subsequently converted into biodiesel through esterification and transesterification reactions catalyzed by* H_2SO_4 *and NaOH, respectively. The designed plant capacity is 100,000 kL of biodiesel per year. Bontang, East Kalimantan, is selected as the plant site considering key factors such as raw material availability, access to utilities, land suitability, and transportation infrastructure. The plant consists of two main stages: microalgae oil production and biodiesel synthesis, with a total construction period of two years and an operational lifespan of 15 years. Economic feasibility analysis indicates an Internal Rate of Return (IRR) of 12.91%, a Net Present Value (NPV) of IDR 2,296,063,930,982, and a payback period of 13 years, confirming the financial viability of the project. These results demonstrate that biodiesel production from Chlorella vulgaris microalgae is both technically feasible and economically sustainable, providing a practical and scalable pathway to support Indonesia's transition toward renewable and low-carbon energy systems.*
Keywords: Biodiesel, *Chlorella vulgaris*, Greenhouse gas, Microalgae, Renewable energy, Techno-economic analysis.

How to Cite This Article: Anugraha, R.P., Sari, A.M., Nurrohim, H., Renanto, Juwari, and Bhuana, D.S., (2026) Techno-Economic Analysis of Biodiesel Production from Microalgae, Reaktor, 26 (2), 1–12, https://doi.org/10.14710/reaktor.83117

INTRODUCTION

Worldwide reliance on fossil energy sources, including petroleum, has become a critical issue worldwide, including in Indonesia. This dependence can threaten a country's energy security and cause economic losses when global oil prices rise. The Special Task Force for Upstream Oil and Gas Activities (SKK Migas) reported that Indonesia's petroleum reserves, based on February 2024 data, were recorded at 4.7 billion barrels. In addition, Indonesia's total oil production has shown a consistent downward trend, with an average annual decline rate of 3.8% from 2017 to 2023, which contrasts with the increasing trend in demand (IESR, 2024)

Issues surrounding the depletion of fossil fuels, particularly petroleum, and additionally, global climate change driven by the rising greenhouse gas (GHG) emissions from fossil fuel combustion has encouraged governments to enhance the contribution of new and renewable energy sources as part of strategies to sustain energy security and independence. The greenhouse effect refers to the mechanism by which specific gases trap heat within the Earth's atmosphere. This phenomenon is triggered by greenhouse gases including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Emissions of these greenhouse gases (GHGs) are highly dependent on the scale of energy use, particularly fossil fuels such as petroleum products, gas, and coal (Badan Lingkungan Hidup Kota Balikpapan, 2022).

Biofuels are energy sources originating from organic matter such as plants and animals, and are regarded as potential substitutes for petroleum-derived fuels. Examples of alternative energy sources synthesized from feedstocks such as vegetable oils and animal fats include biodiesel and bioethanol. The government has committed to increasing the contribution of new and renewable energy within the national energy composition. One of the ways is through the policy on the percentage of biodiesel and bioethanol blending, as specified in Ministry of Energy and Mineral Resources Regulation No. 12/2015 on the Third Amendment to Minister of Energy and Mineral Resources Regulation No. 32/2008 on the Provision, Utilization, and Trade of Biofuels as Alternative Fuels. Ministerial Regulation No. 12/2015 requires a biodiesel blending percentage of 15% (B15) in 2015 and 30% (B30) by 2025, as well as a bioethanol blending percentage of 2% (E2) in 2015 and 20% (E20) by 2025.

In line with the government's renewable energy regulation, biodiesel has become one of the most widely developed plant-based fuels as an alternative to fossil-based diesel. Biodiesel is an alternative fuel derived from plant or animal sources and processed into fatty acid methyl esters (FAME). As a renewable energy fuel, biodiesel possesses an essential role in minimizing fossil fuel dependency and carbon emissions. Its advantages include lower pollutant emissions, minimum sulfur content compared to diesel, and its biodegradable nature (able to decompose naturally). The following is the implementation of biodiesel in Indonesia.

Based on Table 1, it can be seen the overall development of biodiesel in Indonesia shows great potential in supporting energy security and reducing carbon emissions. However, existing biodiesel, whether from animal fats or vegetable oils, also has several weaknesses that need to be addressed.

Table 1. Realization of Biodiesel Implementation in Indonesia (APROBI, 2025)

Year	Production (kL)	Domestic (kL)	Export (kL)
2019	8,399,000	6,396,000	1,319,000
2020	8,594,000	8,400,000	36,000
2021	10,258,000	9,296,000	147,000
2022	11,816,000	10,430,000	371,000
2023	13,151,000	12,242,000	187,000
2024	13,930,000	13,158,000	27,000

The challenge with biodiesel from vegetable oil is the long production time. The production time for biodiesel depends on the harvest time of the plants used, which generally have a long harvest period. Meanwhile, biodiesel from animal fats is considered inefficient because it contains free fatty acids and high-water content, which can reduce quality. Additionally, the demand for raw materials may conflict with human food consumption and oleochemical production. Therefore, alternative natural materials with potential for biodiesel production need to be explored, such as biodiesel derived from microalgae oil (Mirzayanti *et al*., 2021). The production of biodiesel from microalgae presents an innovative renewable energy approach by utilizing single-celled microorganisms that convert light, carbon dioxide, and nutrients into lipids for fuel production. (Gaurav *et al*., 2024).

Microalgae biomass is an efficient renewable energy source for reducing CO_2 emissions because it can convert CO_2 into carbohydrates, fats, and proteins with higher productivity than land plants (Widodo *et al*., 2018). Microalgae grow quickly, contain high levels of lipids ((50–70) %wt), are environmentally friendly, and can produce 58,700–136,900 L/ha of oil, which is much more than palm oil, which only produces around 5,950 L/ha (Kiran *et al*., 2014), (Faried *et al*., 2017). According to Chen *et al*. (2014), the lipid content in *Chlorella vulgaris* biomass can reach 49.5%wt, and these lipid levels are sustainable under industrial cultivation conditions using flue gas. Under such conditions, the lipid content generally does not achieve the higher reported values but remains sustainable at 49.5%wt. In addition, microalgae can be cultivated in various types of water and infertile land without competing with food crops (Gaurav *et al*., 2024). The cultivation period is only 7 days, shorter than palm oil, which requires 30 days (Kang *et al*., 2018), (de Vos *et al*., 2023). The FFA content of microalgae is lower (4%) than that of CPO (6%), so the refining process is lighter and produces higher biodiesel yields (Rincón *et al*., 2014). On the other hand, increased CPO use for biodiesel could lead to land conversion, food-energy conflicts, and emissions from palm oil expansion.

The Lurgi process was chosen for biodiesel production from microalgae oil. The selection of Licensor Lurgi is supported by its ability to operate efficiently at atmospheric pressure (1 atm) while achieving a 100% yield comparable to the high-pressure of Axens process (Oh *et al*., 2012). The conversion of microalgae oil into biodiesel is carried out through the esterification–transesterification process. This method offers several advantages, such as producing high-quality biodiesel with glycerol as a valuable by-product and achieving significant greenhouse gas (GHG) reduction of up to 78%, second only to thermal cracking at 80% (Wan Osman *et al*., 2024a). As summarized in Table 2, the esterification – transesterification route also demonstrates relatively low energy consumption (5.8 MJ/L) and moderate water usage compared to other biodiesel synthesis methods, making it attractive for large-scale implementation (Wan Osman *et al*., 2024a), (Zheng & Cho, 2025).

Table 2. Environmental Performance Indicators of Biodiesel Synthesis Methods (Wan Osman *et al*., 2024a)

Synthesis method	Greenhouse gas reduction (%)	Energy Consumption (MJ/L)	Water usage (L)
Transesterification (Lurgi Process)	78	5.8	3
Direct Use Blending	50 – 60	Not reported	Not reported
Micro-Emulsion	70	Not reported	Not reported
Thermal Cracking	80	Not reported	Not reported

However, the esterification–transesterification process also has several drawbacks. It is highly sensitive to water and free fatty acid (FFA) content in the feedstock (Wan Osman *et al*., 2024a), which can lead to saponification during the reaction. Therefore, a pretreatment step, typically esterification, is required to reduce the FFA level (Zheng & Cho, 2025). Moreover, the use of catalysts in this process raises environmental concerns due to possible chemical waste generation (Wan Osman *et al*., 2024a). In addition, to measure the feasibilty of microalgae-based biodiesel production, it required techno-economic study which can provide the information of the operational cost and profitabilty (Anugraha *et al*., 2024) (Anugraha *et al*., 2024).

Considering the points mentioned above, it can be seen that biodiesel production from microalgae is an attractive and promising prospect, as it not only reduces carbon dioxide emissions into the atmosphere but also produces a product with economic value. This approach is not only more sustainable than conventional production methods but can also help reduce the pressure on natural resources and the environment that has been exerted so far. By integrating the production process with other industrial plants, biodiesel production can become part of efforts to reduce emissions and promote more efficient energy use, while contributing to climate change mitigation and global environmental sustainability efforts. Therefore, the study aims to assess the techno-economic feasibility of a large-scale microalgae-based biodiesel plant utilizing the Lurgi process. This study discusses a new concept for optimizing the integration of industrial flue gas as a carbon source for microalgae cultivation, offering a sustainable solution for biodiesel production that simultaneously reduces carbon emissions.

MATERIAL AND METHOD

DATA COLLECTION

Feedstock Composition

Three primary feedstocks utilized in the microalgae cultivation process are flue gas as the CO_2 source, NPK fertilizer as the nutrient supply, and inoculum as the initial algal seed. Their specifications are detailed in Table 3 to Table 5.

Table 3. Flue Gas Specifications from a Gas-Fired Power Plant (Song *et al*., 2004)

Component	% Mole	% Weight
CO_2	10	15.87
H_2O	20	12.99
O_2	3	3.46
N_2	67	67.68
Total	100	100

Table 4. Characteristics of *Chlorella vulgaris* (Blades Biological Limited, 2025)

Parameter	Data
Volume	150 mL
Weight	400 grams
Density	2.67 g/mL
Temperature	20 °C

Table 5. NPK Fertilizer (Pupuk Kalimantan Timur, 2021)

Component	% Weight
Nitrogen	15
Phosphorus as P_2O_5	15
Potassium as K_2O	6
Magnesium as MgO	4

Product Composition

Table 6 shows the composition data of products used in this study based on the Ministry of Energy and Mineral Resources of Republic of Indonesia.

Product Capacity

Recently, Indonesia has experienced a growing demand for biodiesel. Table 7 summarizes the national biodiesel market data over the last six years, based on reports from APROBI. A market projection analysis for biodiesel in Indonesia was conducted using a discounted approach (Kusnarjo, 2010).

Table 6. Biodiesel Product Specifications (LEMIGAS, 2020)

Parameter	Unit	Data
Density at 40 °C	kg/m^3	850 - 890
Kinematic viscosity at 40 °C	mm^2/s (cSt)	2.3 – 6
Cetane number	min	51
Flash point	°C, min	100
Sulfurized ash	% weight, max	0.02
Sulfur	mg/kg, max	10
Phosphorus	mg/kg, max	4
Acid number	mg KOH/g, max	0.4
Free glycerol	% weight, max	0.02
Total glycerol	% weight, max	0.24
Methyl ester content	% weight, min	96.5
Monoglyceride	% weight, max	0.8
Moisture content	ppm, max	350
CFPP (Cold Filter Plugging Point)	°C, max	15
Metal I (Na+K)	ppm, max	5
Metal II (Ca+Mg)	ppm, max	5
Total Contaminants	mg/liter, max	20

Table 7. Indonesian Biodiesel Market Data

Year	Production (kL)	i (%)	Production (kL)	i (%)	Production (kL)	i (%)
2019	8,399,000	-	1,319,000	-	6,396,000	-
2020	8,594,000	2	36,000	-97	8,400,000	31
2021	10,258,000	19	147,000	308	9,296,000	11
2022	11,816,000	15	371,000	152	10,430,000	12
2023	13,151,000	11	187,000	-50	12,242,000	17
2024	13,930,000	6	27,000	-86	13,158,000	7
Avg	11,025,000	11	348,000	46	9,987,000	16

National biodiesel demand in 2028 is forecasted to reach 2,781,731.80 kL/year (equivalent to 2,372,817.23 tons/year). The designed facility is intended to supply approximately 3.5% of this demand, corresponding to 100,000 kL/year or 85,300 tons/year. This capacity also represents approximately 0.72% of Indonesia's total biodiesel production in 2024 (13,930,000 kL).
The selected production capacity is justified by two primary considerations. First, when compared to 25 operating biodiesel plants, the proposed capacity is approximately 43.5% smaller than the smallest existing facility, PT Pelita Agung Agrindustri (229,885 kL/year), while also considering the emergence of seven new biodiesel companies. Second, the capacity aligns with the land requirements for microalgae cultivation, estimated at 931 hectares. Thus, a production capacity of 100,000 kL/year is feasible under current industry conditions and resource availability.

Site and Utility Availability

To ensure an efficient and economically viable process, selecting an appropriate plant location is a critical factor. The site influences competitiveness within the industry, product distribution efficiency, and raw material availability. Two main categories are typically considered in plant site selection: primary and secondary factors. Primary factors include raw material availability, market proximity, utility access (water, electricity, and fuel), geographical conditions, and the surrounding community. Secondary factors include transportation access, labor availability, waste management systems, site characteristics, and applicable regulations (Kusnarjo, 2010).

Considering these factors, the proposed microalgae-based biodiesel plant is planned to be located in Bontang, East Kalimantan. This location offers proximity to key raw materials for microalgae cultivation, CO_2 and NPK fertilizer. Additionally, methanol required for the transesterification process is supplied by PT Kaltim Methanol Industri (KMI), which operates in the same area. The site also provides strategic access to imported materials via a nearby port or jetty. According to data from BPS (Statistics Indonesia), the total electricity production in Bontang reached 327,840,676 kWh in 2023. The coastal location ensures easy access to seawater, with the nearest intake just 2.3 km away.

PROCESS DESCRIPTION

In biodiesel production plant from microalgae, there are several stages, namely the microalgae cultivation, microalgae biomass harvesting, drying of microalgae biomass culture, pre-treatment (cell disruption process), microalgae oil extraction, esterification, transesterification, and biodiesel purification. The entire process can be described into five major parts as follows.

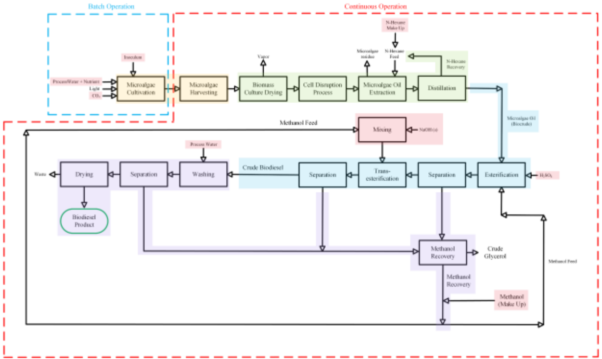

Figure 1. Block Flow Diagram of Biodiesel Production from Microalgae

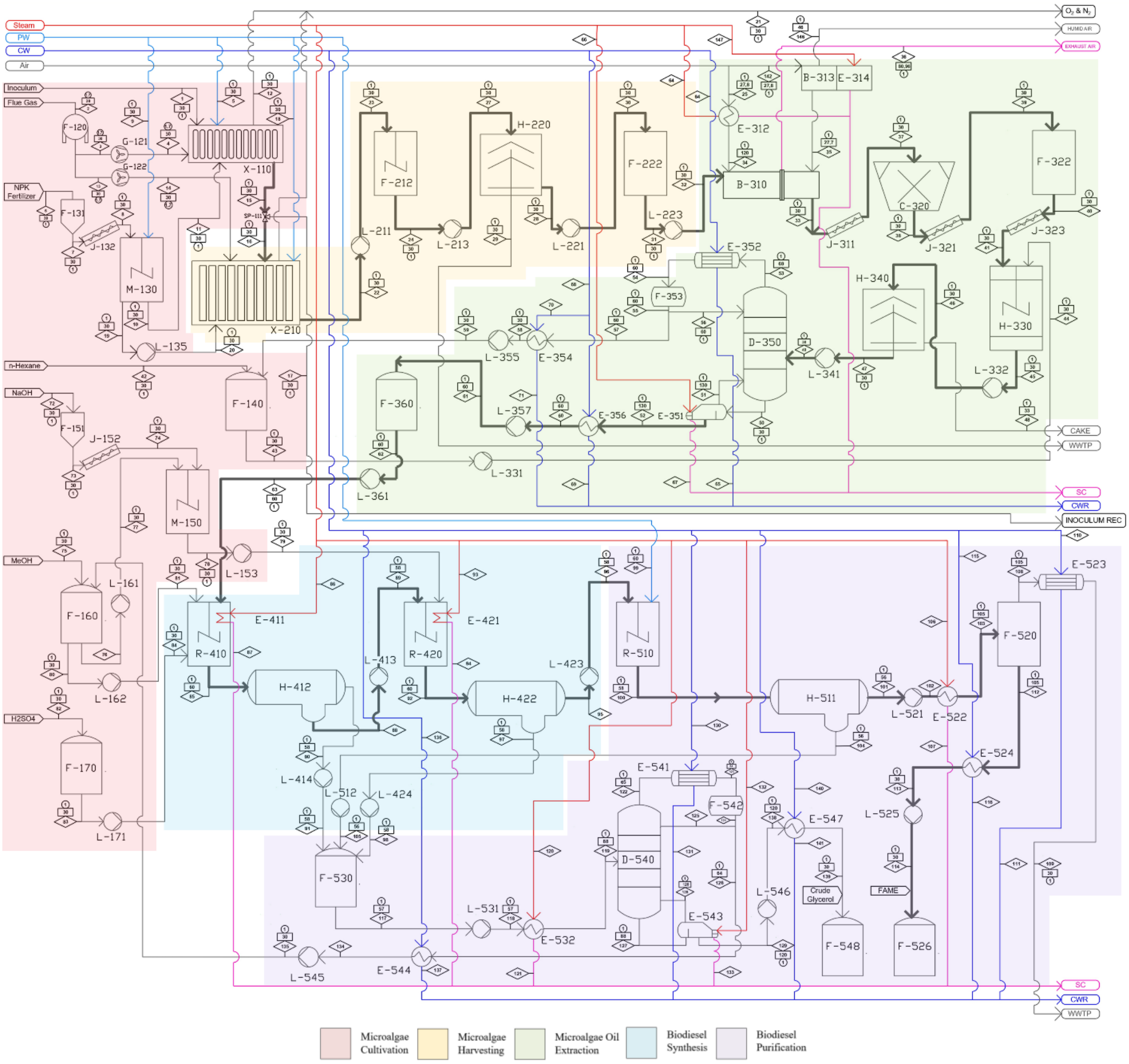

Figure 2. Process Flow Diagram of Biodiesel Production from Microalgae

Microalgae Oil Production Process

Microalgae Cultivation. The cultivation process of *Chlorella vulgaris* microalgae begins with the purchase of inoculum from Blades Biological Ltd (UK), which is then cultivated in an inoculum pond (X-110) at a temperature of 30°C and a pressure of 1 atm, using water, CO_2 gas, and diluted NPK fertilizer in a mixing tank (M-130) before being transferred to the pond. . This process is called preculture. The CO_2 gas is directly captured from flue gas within the FPPBR during the microalgae cultivation process. According to Singh *et al*. (2025), microalgae can capture CO_2 within a 6–12% mole range contained in flue gas for cultivation. In this study, flue gas with a CO_2 concentration of 10% mole was used, which in the operable range and suitable for capture by the system. The resulting culture will be cultivated for 7 days in a flat plate photobioreactor (X-210) under the same operating conditions and with similar nutrient supply. The resulting microalgae culture has a density of 0.3–1 g/L and is stored in a storage tank (F-212). Since *Chlorella vulgaris* requires optimal lighting of 200 µmole m^{-2} s^{-1} (equivalent to 8.55 MJ m^{-2}/day), even though the light intensity in Bontang, East Kalimantan (11.9 MJ m^{-2}/day) is sufficient, Philips GreenPower LED lights (219 µmole m^{-2} s^{-1}, 70 W) were used to ensure light stability, especially during nights or cloudy conditions. These lights have a light spectrum optimized for photosynthesis, high energy efficiency, and low heat and power consumption. To maintain optimal lighting, a light illumination sensor is used to automatically adjust the light intensity based on the available natural light. The microalgae cultivation process flow diagram is shown in Fig. 2.

Microalgae Biomass Harvesting. *Chlorella vulgaris* microalgae culture with a density of 0.3–1 g/L stored in a storage tank (F-212) will be harvested using disc stack centrifuges (H-220) at a temperature of 30°C and a pressure of 1 atm with a continuous operating system to increase the concentration of microalgae biomass. The biomass must be concentrated for efficient downstream operations and process scaling (Kang *et al*., 2018). This concentrated biomass is called concentrated algal biomass and will be stored in a harvesting tank (F-222), while the water that has been separated from the biomass culture will no longer be used in the following process (Hoffman *et al*., 2017). The microalgae biomass harvesting until microalgae oil extraction process is shown in Fig. 2.

Drying of Microalgae Biomass Culture. Concentrated algal biomass from the harvesting tank (F-222) is continuously dried using a rotary dryer-cooler (B-310) with hot air at a temperature of 120°C and a pressure of 1 atm, then cooled with dry air at a temperature of 27.8°C and a pressure of 1 atm. Hot air is obtained from atmospheric air heated by a heater (E-312) of the Shell and Tubes 1-2 type, while dry air is derived from atmospheric air dried using a dehumidifier (B-313). This process aims to remove intracellular water from the microalgae to enhance lipid extraction efficiency (Harahap et al., 2019). The product of drying is called dried biomass (Hoffman *et al*., 2017).

Pre-Treatment (Cell Disruption Process). Dried biomass that has been dried and cooled to a temperature of 30°C using a rotary dryer-cooler (B-310) is transferred using a screw conveyor (J-311) to a bead mill (C-320) for a pre-treatment process involving cell disruption. This process aims to release the contents of the cells into the extracellular environment so the biomolecules can interact more easily with the solvent during lipid extraction (Dickinson *et al*., 2017). Bead mill (C-320) operates continuously at a temperature of 30°C and a pressure of 1 atm. The biomass obtained from cell disruption is then transferred using a screw conveyor (J-321) for microalgae oil extraction.

Microalgae Oil Extraction. The microalgae biomass obtained from cell disruption is transferred using a screw conveyor (J-321) to an agitated vessel extractor (H-330) for oil extraction using n-hexane. The extraction process is carried out continuously at a temperature of 30°C and a pressure of 1 atm, producing a slurry containing biomass, solvent, and microalgae oil, which is then separated using disc stack centrifuges (H-340). The mixture of n-hexane and microalgal oil is then separated in a distillation column (D-350) equipped with a condenser (E-351) and a reboiler (E-352), operating continuously at a pressure of 1 atm, with a reboiler temperature of 130°C and a condenser temperature of 69.23°C. The boiling point of n-hexane is 68.73°C, so it can be vaporized in the reboiler and condensed in the condenser. The condensed n-hexane is cooled to 30°C by the cooler (E-354) and stored back in the storage tank (F-140). The n-hexane recovery in this separation step reaches 97.61%, indicating an efficient solvent recovery and enabling its reuse in subsequent extraction cycles. Meanwhile, the microalgae oil (biocrude) will be cooled to 60°C using a cooler (E-356) and stored in a storage tank (F-360). The microalgae residue is no longer used, and the microalgae oil will be further processed into biodiesel.

Biodiesel Production Process

Esterification Process. The esterification reaction in reactor R-410 serves as a pretreatment stage to convert the high free fatty acid (FFA) content in microalgal oil and prevent saponification reactions (Wan *Osman et al*., 2024). The reaction mechanism is as follows:

$$\mathrm{FFA} + \mathrm{CH_3OH} \xrightarrow{\mathrm{H_2SO_4}} \mathrm{FAME} + \mathrm{H_2O} \quad (1)$$

The reaction is carried out at 60 °C and 1 atm for 1 hour, with a mass ratio of FFA : methanol : H_2SO_4 of 1 : 2.25 : 0.05, resulting in a methyl ester (biodiesel) conversion of 95.6% (Amin & Prabandono, 2017). Sulfuric acid (H_2SO_4) was selected as the catalyst because it effectively promotes the esterification of free fatty acids even in oils with high FFA content. In addition, H_2SO_4 possesses hygroscopic properties that allow it to absorb water formed during the reaction, driving the equilibrium toward ester formation and thereby increasing the product yield (Darojat & Rachmaditasari, 2024). The product is then separated using Decanter I (H-412), where the upper phase (water and methanol) is directed to the neutralization tank (F-530), and the lower phase (methyl ester, TAG, and H_2SO_4) is transferred to the transesterification reactor (R-420). The esterification process flow diagram is in Fig. 2.

Transesterification Process. Methanol from the storage tank (F-160) is mixed with sodium hydroxide (NaOH) in a mixer (M-150) to produce sodium methoxide (CH_3ONa), a base catalyst used in the transesterification reaction (Gerpen *et al*., 2004). The transesterification process converts triglycerides (TAG) into methyl esters (biodiesel) and glycerol through reaction with methanol in the presence of a base catalyst (Wan Osman *et al*., 2024). The reaction mechanism is as follows:

$$\mathrm{TAG} + 3\ \mathrm{CH_3OH} \xrightarrow{\mathrm{NaOH}} 3\ \mathrm{FAME} + \mathrm{C_3H_8O_3} \quad (2)$$

The transesterification reaction is conducted in reactor R-420 at 60 °C and atmospheric pressure, with an alcohol-to-oil molar ratio (ATOR) of 6:1 and 2 wt% NaOH catalyst relative to the oil. The reaction is maintained for 60 minutes, resulting in a triglyceride-to-methyl ester conversion of up to 98% (Khan *et al*., 2020). Sodium hydroxide (NaOH) was selected as the catalyst because it is inexpensive, widely available, and easy to handle compared to the other base catalyst such as Potassium hydroxide (KOH). In addition, NaOH provides high catalytic activity and yields a high biodiesel conversion under mild operating conditions, making it one of the most used catalysts in transesterification processes (Darojat & Rachmaditasari, 2024). The reaction mixture is then transferred to Decanter II (H-422) to separate glycerol and prevent emulsion formation during the subsequent washing stage. The upper phase (biodiesel and impurities) is directed to the washing tank (R-510), while the bottom phase (crude glycerol) is sent to the neutralization storage tank (F-530). The transesterification process flow diagram is shown in Fig. 2.

Biodiesel Purification Process. The biodiesel washing process is conducted in the washing tank (R-510) by adding warm water at 60°C, equivalent to 50% v/v of the biodiesel volume. This step removes glycerol, catalyst residues, methanol, soap, and other impurities based on solubility differences (Abbaszadeh *et al*., 2014). Water also serves to neutralize residual catalysts and eliminate salts formed during the reaction. The resulting mixture is then separated into Decanter III (H-511), utilizing density differences and residence time to produce an upper fraction containing biodiesel and a lower polar fraction, which is directed to the neutralization storage tank (F-530). The biodiesel is transferred to a flash tank (F-520) to evaporate residual methanol and water, yielding a bottom product of purified biodiesel. This product is then cooled to 30 °C using a cooler (E-524) and stored in the biodiesel storage tank (F-526). Meanwhile, the polar mixture from tank F-530 is sent to a distillation column (D-540) for methanol recovery. The overhead product (methanol) is returned to the methanol storage tank (F-160), while the bottom product is discharged to the crude glycerol waste storage tank (F-548) for further handling (Gerpen *et al*., 2004). The biodiesel purification process flow diagram is shown in Fig. 2.

Mass and Energy Balance Calculation

Every chemical process requires both mass and energy balance calculations to ensure that input and output quantities are properly accounted for. These calculations are generally carried out under the steady-state assumption. The mass balance can be expressed using Eq. (3).

$$m_a = m_i - m_o + m_g - m_c \qquad (3)$$

Here, m_a denotes the mass accumulated within the system, m_i refers to the mass entering the process unit, m_o represents the mass leaving the unit, m_g corresponds to the mass generated, and m_c indicates the mass consumed during the process. Under steady-state conditions, the accumulated mass (m_a) is assumed to be zero. In addition to mass balance, a chemical process also requires energy balance which is closely related to the thermodynamic state of a process. Assuming a steady state, the energy balance can be formulated as in Eq. (4).

$$\Delta H_{in} + Ek_{in} + Ep_{in} + Q = \Delta H_{out} + Ek_{out} + Ep_{out} + Ek_{in} + W_s \qquad (4)$$

In equation 4, ΔH denotes the change in enthalpy, E_k represents kinetic energy, E_p refers to potential energy, Q is the heat transferred from the surroundings to the process, and W_s signifies the shaft work or mechanical work performed on the process fluid. Commonly, the changes in kinetic and potential energies are considered negligible, simplifying the energy balance to involve only enthalpy variation, heat transfer, and shaft work.

2.3 Economical basis assumption

Economic analysis is one indicator for assessing whether establishing a plant is a feasibility decision or not. As a basis for determining the economic feasibility of a plant, calculations related to raw material requirements and product volume are required, which are sourced from a previously calculated mass balance. Additionally, other aspects that need to be considered include the cost of production equipment, which is determined based on the specifications of the required equipment as calculated in the mass and energy balance. In addition to these factors, cost analysis is also essential for operating a plant, involving utilities, the number and salary of employees, and land acquisition. Therefore, to assess the economic feasibility of a plant, it is necessary to calculate various parameters in the economic analysis.

The economic evaluation is performed by accounting for the time value of money based on net cash flow, with its value projected to the present. The underlying assumptions are as follows:

1. Equity capital of 40% and bank loan capital of 60%.
2. Bank interest rate of 8.50% per annum (Bank Mandiri Corporate Credit).
3. Inflation rate of 1.6% per annum (Bank Indonesia).
4. Plant construction period of 2 years using equity and loans divided equally over the construction period.
5. Loan repayment is made over a period of 15 years, divided equally.
6. Plant production capacity:
   - Year 1 : 60%
   - Year 2 : 80%
   - Year 3 : 100%
7. Income tax of 22% (Law No. 7 of 2021 concerning Harmonization of Tax Regulations)

Several supporting parameters are also assumed as the basis for economic analysis calculations, as follows:

1. Plant production capacity : 100,000 kL/year
2. Operating period : 330 days/year
3. Exchange rate of rupiah (1 USD) : Rp16,258.05
4. Plant economic lifespan : 15 years

The basic material costs used are as follows in Table 8.

Table 8. The basic material costs

Material	Value (Rp/kg)
Microalgae inoculum	1,596,813.75
N-hexane	19,419.28
Methanol	4,861.16
Process water	13.50
NPK fertilizer	8,530.00
H_2SO_4	1,509.87
NaOH	1,969.00

One of the key parameters for assessing plant feasibility is the Net Present Value (NPV). NPV represents the difference between the present value of projected annual cash inflows and outflows. It serves as an essential indicator in capital investment analysis for evaluating a project's potential profitability. A positive NPV implies that the anticipated future revenues will yield profit, while a negative NPV indicates a potential financial loss. The NPV calculation can be determined using the equation provided by Bagajewicz (Bagajewicz, 2008), as shown in Eq. (5).

$$NPV = \sum_{i=1}^{N} \frac{CF_i}{(1+r)^i} - I \qquad (5)$$

Where CFi denotes the after-tax cash flow for a given period, I represents the capital investment, and r refers to the minimum required rate of return, commonly known as the "opportunity cost of capital." In addition to net present value, the engineering discipline assesses project feasibility through several other indicators, such as the internal rate of return (IRR), as expressed in Eq. (6).

$$I = \sum_{i=1}^{N} \frac{CF_i}{(1+IRR)^i} \qquad (6)$$

The Internal Rate of Return (IRR) is defined as the discount rate that equates the Net Present Value (NPV) to zero. This metric is often favored because it expresses the profitability of an investment as a percentage return on the capital invested (Bagajewicz, 2008). In addition to NPV and IRR, the Weighted Average Cost of Capital (WACC) is commonly used as a benchmark to evaluate project feasibility. WACC is a weighted average cost of a company's debt and equity financing. This parameter is crucial for evaluating investment projects because it represents the minimum acceptable rate of return for investors. Typically, a project is deemed economically viable if its IRR is greater than its WACC. The WACC can be calculated using Eq. (7)

$$WACC = \left(\frac{E}{D+E}\right) R_e + \left(\frac{D}{D+E}\right) R_d \qquad (7)$$

where E represents equity, D denotes debt, R_e is the cost of equity, and R_d is the cost of debt. Meanwhile, the Break-Even Point (BEP) denotes the condition at which total revenue equals to the sum of variable and fixed costs, resulting in neither profit nor loss. Graphically, the BEP is represented by the intersection point between total revenue (sales) and total costs (Kampf *et al*., 2016).

The break-even point is defined as the proportion of total plant capacity determined through the calculations presented in Eq. (8).

$$BEP = \frac{(FC + 0{,}3 \times SVC)}{(S - 0{,}7 \times SVC - VC)} \times 100\% \qquad (8)$$

where BEP represents the production volume at the break-even point, FC denotes the fixed cost, SVC indicates the semi-variable cost, S refers to the selling price, and VC corresponds to the variable cost.

RESULTS AND DISCUSSION

MASS AND ENERGY BALANCE

Based on the results of the mass balance calculation, a biodiesel plant with a production capacity of 100,000 kL/year produces 1,866.77 tons/week biodiesel (equivalent to 88,004.86 tons/year) which requires the following main raw materials: 15.49 tons of *Chlorella vulgaris* inoculum, 2,121,428.57 tons/year of flue gas, and 132,000 tons/year of NPK fertilizer. In addition, the required auxiliary raw materials include 23,912.56 tons/year of n-hexane, 11,090.75 tons/year of methanol, 1,821.59 tons/year of NaOH catalyst, and 400.35 tons/year of H_2SO_4 catalyst. The detailed mass balance on a weekly basis is shown in Table 9 and Table 10.

Table 9. Raw Materials Required for Microalgae-Biodiesel Plant with capacity 100,000 kL/year

Material	Ton/Week
Inoculum	15.49
Flue gas	45,000.00
NPK fertillizer	2,800.00
Process water	436,047.22
Atmospheric air	39,041.67
N-hexane (make-up)	714.54
Methanol (make-up)	235.26
NaOH	38.64
H_2SO_4	8.49
Total	523,901.31

During operation, the plant requires various utilities to support the production process, as shown in Table 11. Process water is utilized to operate the mixing tank, inoculum pond, FPPBR, and biodiesel washing reactor. Meanwhile, air is utilized to operate the rotary dryer–cooler and dehumidifier. Steam is utilized to operate the air heater, reboiler, esterification reactor, transesterification reactor, and heater. Cooling water is utilized to operate the condenser and cooler. Electricity powers the mixing tank, FPPBR, disc stack centrifuge, rotary dryer cooler, bead mill, vessel extractor, reactor, blower, conveyor, and pump.

Table 10. The Products of Microalgae-Biodiesel Plant with capacity 100,000 kL/year

Material	Value (Rp/kg)
Biodiesel	1,866.77
Gas O_2, N_2	37,304.20
Inoculum to laboratory	1,298.16
Exhaust	34,869.05
Humid air	4,912.70
WWTP 1	436,511.78
Cake	5,529.62
Crude glycerol waste	1,604.07
WWTP 2	4.97
Total	523,901.31

Table 11. Utility Requirement for Microalgae-Biodiesel Plant with capacity 100,000 kL/year

Utility	Unit	Requirement
Process water	Ton/hour	328.89
Atmospheric air	Ton/hour	232.39
Steam	Ton/hour	79.85
Cooling water	Ton/hour	962.38
Electricity	kWh	45,891.96

ECONOMIC ANALYSIS

CAPEX (Capital Expenditure) is an expenditure used to purchase, repair, or renew fixed assets that have a long useful life, such as land, buildings, equipment, and technology. CAPEX is also defined as a long-term investment that is expected to provide economic benefits in the future and is recorded as an asset recorded on the company's balance sheet. CAPEX, also known as TCI (Total Capital Investment) of this plant, has a value of Rp13,299,242,079,758. OPEX (Operating Expenditure) is an expenditure used to run the company's daily operations, such as salaries, utilities, raw materials, and routine maintenance.

OPEX is considered an operational cost necessary to support business activities on an ongoing basis and is recorded as an expense in the company's income statement. OPEX is considered an operational cost necessary to support sustainable business activities and is recorded as an expense recognized in the company's income statement. OPEX, also known as TPC (Total Production Cost), for this company amounts to Rp4,734,908,886,152 per year.

To further illustrate the distribution of economic contributions across the main processing stages, a breakdown of capital and operational expenditures for each major process is presented in Table 12. In this analysis, the CAPEX estimation is based solely on the equipment purchase cost of each processing unit, without considering installation, civil work, instrumentation, or other indirect capital costs. Similarly, the OPEX estimation accounts only for utility consumption, excluding other operational cost components such as labor, raw materials, maintenance, and waste treatment. Therefore, the economic values presented represent a partial CAPEX and OPEX assessment. This simplified approach is adopted to identify the main processes with the largest cost contribution and to provide a comparative insight into cost dominance among processing stages

Table 12. Equipment-Based CAPEX and Utility-Based OPEX Distribution for Each Main Process

Process	CAPEX (Rp)	CAPEX Contribution (%)	OPEX (Rp)	OPEX Contribution (%)
Microalgae Cultivation	53,676,692,531.92	4%	13,032,781.69	12%
Microalgae Harvesting and Oil Extraction	1,288,305,349,520.84	92%	91,894,658.47	86%
Biodiesel Synthesis	23,464,445,151.81	2%	1,154,119.94	1%
Purification	30,253,738,777.54	2%	1,163,549.03	1%

The plant feasibility factor is calculated by evaluation results summarized in Table 13 and Fig. 7.

Table 13. Factors Affecting the Feasibility of Plant Establishment

Net Present Value (NPV)	Rp2,296,063,930,982
Internal Rate of Return (IRR)	12.91%
Pay Out Time (POT)	13 years
Break Even Point (BEP)	38.51%

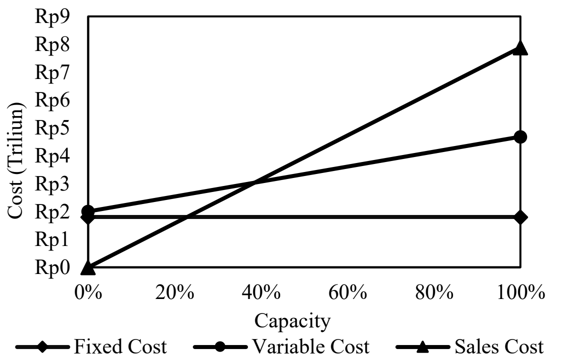

Figure 3. Break Even Point Analysis

A positive NPV signifies that the investment is projected to yield profits, whereas a negative NPV suggests potential losses. In this analysis, the company used a discount rate of 9.98% (equal to WACC) and obtained an NPV of Rp2,296,063,930,982, which indicates that this investment is feasible and expected to provide economic benefits in the future.

After the calculation, the project or investment has an IRR of 12.91%, which is higher than the WACC of 9.98%. This suggests that the investment is anticipated to generate returns exceeding the minimum required rate, thereby indicating its feasibility and profitability.

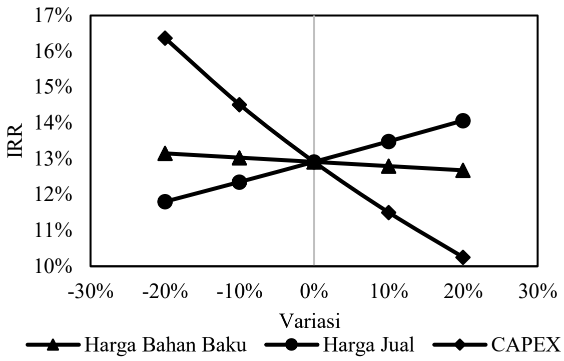

Figure 4. IRR Sensitivity Analysis

The sensitivity analysis reveals that IRR is most responsive to changes in CAPEX, with a 20% reduction increasing IRR to 16.37% and a 20% increase lowering it to 10.25%. In contrast, raw material price variations have minimal impact, shifting IRR only between 12.68% and 13.15%. A rise in product selling price positively influences IRR, elevating it to 14.07% with a 20% increase, while a decrease reduces IRR to 11.80%. Furthermore, the sensitivity of the payback time (POT) aligns with the sensitivity of IRR, it means a higher IRR corresponds to a shorter POT.

When accumulating profits, the project has a POT of 13 years, indicating that it will take that many years to recover the entire initial investment from the cash flow generated. This indicates that the project requires this period of time before it begins to generate economic benefits for the company. Although a POT of 13 years is close to the end of the plant's designed operational life of 15 years, this value is still acceptable because it is within the return period before the technical period ends, even though ideally a good POT is generally in the range of one-third of the plant's economic lifespan to reflect more optimal economic feasibility. To improve the project's financial viability and shorten the POT, two potential options could be considered. First, the biomass residue from the oil extraction process could be sold as fertilizer at a price of IDR 500 per kg (Permentan, 2020). Another option is to implement a nutrient recycling system for the NPK fertilizer, which could reduce raw material costs.

SOCIAL AND ENVIRONMENT ASPECTS

The establishment of a microalgae biodiesel plant is expected to generate both positive and negative social and environmental impacts on the surrounding area. On the positive side, the project will create new employment opportunities and contribute to regional economic growth. The recruitment process will prioritize local communities, both for plant operations and construction services, while cooperation with local businesses as suppliers of goods and services will further enhance regional income and economic activity.

Conversely, potential negative impacts may arise from waste generation and air pollution associated with the production process. The n-hexane solvent loss is represented by the make-up flowrate, which is estimated at 714.54 ton/week and has been accounted for in the operational expenditure (OPEX). From an environmental perspective, although the solvent loss appears relatively high, the overall environmental impact of the plant remains favourable due to its significant contribution to greenhouse gas reduction. The microalgae cultivation process absorbs approximately 7,141.5 ton/week of CO_2 from flue gas, which substantially offsets the environmental burden caused by solvent losses. To further mitigate these effects, the plant will implement comprehensive waste and air pollution management measures, including the installation of hazardous and toxic waste treatment units, the development of green areas around the facility, and the reuse of utility water to minimize consumption. These efforts aim to ensure that the plant's operation supports sustainable development while maintaining environmental quality and promoting socio-economic benefits for the local community.

CONCLUSION

Based on the results presented in the previous sections, the following conclusions can be drawn: The plant is designed to operate for 330 days per year, with a batch process consisting of 3 days for preculture and 7 days for microalgae cultivation, while the continuous processes run 24 hours per day. The targeted production capacity is 100,000 kL per year, with an economic lifespan of 15 years and a construction period of 2 years. The economic analysis indicates an Internal Rate of Return (IRR) of 12.91%, Payback on Time (POT) of 13 years, Break-Even Point (BEP) of 38.51%, and a Net Present Value (NPV) of Rp2,296,063,930,982. Based on these indicators, the plant is considered economically feasible for construction and operation starting in 2028.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGEMENTS

This research was funded by Ministry of Higher Education, Science and Technology, Republic of Indonesia under “Penelitian Fundamental Reguler” scheme with Contract No.017/C3/DT.05.00/PL/2025 and No.1299/PKS/ITS/2025.

REFERENCES

Abbaszadeh, A., Ghobadian, B., Najafi, G., and Yusaf, T., (2014). An experimental investigation of the effective parameters on wet washing of biodiesel purification. *International Journal of Automotive and Mechanical Engineering*, *9*(1), pp. 1525–1537. https://doi.org/10.15282/ijame.9.2013.4.0126

Amin, S. and Prabandono, K., (2017). Biodiesel production from microalgae. *Algal Biofuels*, 16, pp. 66–102. https://doi.org/10.1201/9781315152547

Anugraha, R. P., Pratiwi, V. D., Renanto, R., Juwari, J., Islami, A. N., and Bakhtiar, M. Y., (2024). Techno-economic analysis of CO2 cryogenic distillation from high CO2 content gas field: A case study in Indonesia. *Chemical Engineering Research and Design*, 202(July 2023), pp. 226–234. https://doi.org/10.1016/j.cherd.2023.12.035

Anugraha, R. P., Renanto, R., Maulana, R. A., and Kusumo, R. D., (2024). Techno-Economical Study on the Production of High Octane Gasoline in Light Naphtha Plant. *Journal of Chemical Technology and Metallurgy*, 59(1), pp. 81–86. https://doi.org/10.59957/jctm.v59.i1.2024.9

APROBI, (2025), *REALISASI IMPLEMENTASI BIODISEL*, https://www.aprobi.or.id/id/data/realisasi-implementasi-biodisel/

Badan Lingkungan Hidup Kota Balikpapan, (2022), *Penurunan Emisi Gas Rumah Kaca*.

Bagajewicz, M., (2008). On the Use of Net Present Value in Investment Capacity Planning Models. *Industrial & Engineering Chemistry Research*, 47(23), pp. 9413–9416. https://doi.org/10.1021/ie071008l

Blades Biological Limited, (2025), *Chlorella vulgaris*, https://blades-bio.co.uk/shop/living-organisms/algae-protozoa-nematode/algae/chlorella-large/

Darojat, M. I., and Rachmaditasari, R., (2024). *Pra Desian Pabrik Biodiesel dari Palm Fatty Acid Distillate (PAFD)*. *Jurnal Teknik ITS,* 13(1), pp. 1–6

de Vos, R. E., Nurfalah, L., Tenorio, F. A., Lim, Y. L., Monzon, J. P., Donough, C. R., Sugianto, H., Dwiyahreni, A. A., Winarni, N. L., Mulani, N., Ramadhan, G., Imran, M. A., Tito, A. P., Sulistiawan, P., Khoirul, M., Farrasati, R., Pradiko, I., Grassini, P., and Slingerland, M., (2023). Shortening harvest interval, reaping benefits? A study on harvest practices in oil palm smallholder farming systems in Indonesia. *Agricultural Systems*, 211(February), 103753. https://doi.org/10.1016/j.agsy.2023.103753

Dickinson, S., Mientus, M., Frey, D., Amini-Hajibashi, A., Ozturk, S., Shaikh, F., Sengupta, D., and El-Halwagi, M. M., (2017). A review of biodiesel production from microalgae. *Clean Technologies and Environmental Policy*, 19(3), pp. 637–668. https://doi.org/10.1007/s10098-016-1309-6

Faried, M., Samer, M., Abdelsalam, E., Yousef, R. S., Attia, Y. A., and Ali, A. S., (2017). Biodiesel production from microalgae: Processes, technologies and recent advancements. *Renewable and Sustainable Energy Reviews*, 79(July 2016), pp. 893–913. https://doi.org/10.1016/j.rser.2017.05.199

Gaurav, K., Neeti, K., and Singh, R., (2024). Microalgae-based biodiesel production and its challenges and future opportunities: A review. *Green Technologies and Sustainability*, 2(1), 100060. https://doi.org/10.1016/j.grets.2023.100060

Gerpen, J. Van, B.Shanks, Pruszko, R., Clements, D., and Knothe, G., (2004). Biodiesel Production Technology. *Catalysis from A to Z, July*. https://doi.org/10.1002/9783527809080.cataz01943H arahap, A. F. P., Ramadhan, M. Y. A., Lestari, T., Gozan, M., & Srinophakun, P. (2019). Preliminary Plant Design of Biofuel from Algae in Balikpapan, East Kalimantan. *IOP Conference Series: Earth and Environmental Science*, 353(1), 012059. https://doi.org/10.1088/1755-1315/353/1/012059

Hoffman, J., Pate, R. C., Drennen, T., and Quinn, J. C., (2017). Techno-economic assessment of open microalgae production systems. *Algal Research*, 23, pp. 51–57. https://doi.org/10.1016/j.algal.2017.01.005

IESR, (2024), *Indonesia Energy Transition Outlook 2025: Navigating Indonesia's Energy Transition at the Crossroads*, Institute for Essential Services Reform, Jakarta

Kampf, R., Majerčák, P., and Švagr, P., (2016). Application of Break-Even Point Analysis. *Naše More*, 63(3), pp. 126–128. https://doi.org/10.17818/NM/2016/SI9

Kang, S., Heo, S., and Lee, J. H., (2018). Techno-economic Analysis of Microalgae-Based Lipid Production: Considering Influences of Microalgal Species. *Industrial and Engineering Chemistry Research*, 58(2), pp. 944–955. https://doi.org/10.1021/acs.iecr.8b03999

Khan, A., Sivapirakasam, S. P., and Anand, R., (2020). Biodiesel production from Chlorella Vulgaris; optimization of process parameters and characterization. *International Journal of Scientific and Technology Research*, 9(1), pp. 3378–3386.

Kiran, B., Kumar, R., and Deshmukh, D., (2014). Perspectives of microalgal biofuels as a renewable source of energy. *Energy Conversion and Management*, 88, pp. 1228–1244. https://doi.org/10.1016/j.enconman.2014.06.022

Kusnarjo, (2010), *Desain Pabrik Kimia*, ITS Press, Surabaya, pp 9-10

LEMIGAS, (2020), *Peningkatan dan Pemanfaatan Biofuel*, Kementerian Energi dan Sumber Daya Mineral, Jakarta

Mirzayanti, Y. W., Syafutra, R. E., Vinataningsih, Y., and Irawan, C. (2021). Konversi Mikroalga Nannochloropsis s.p menjadi Biodiesel melalui Proses Transesterifikasi secara In-Situ. *Buletin Profesi Insinyur*, 4(2), pp. 80–84. https://doi.org/10.20527/bpi.v4i2.113

Oh, P. P., Lau, H. L. N., Chen, J., Chong, M. F., and Choo, Y. M., (2012). A review on conventional technologies and emerging process intensification (PI) methods for biodiesel production. In *Renewable and Sustainable Energy Reviews,* 16(7), pp. 5131–5145 https://doi.org/10.1016/j.rser.2012.05.014

Permentan, (2020), *Peraturan Menteri Pertanian tentang Kumpulan Peraturan Pupuk 2020*, Kementerian Pertanian RI, Jakarta

Pupuk Kalimantan Timur, (2021), *Product Knowledge PKT*, Bontang

Rincón, L. E., Jaramillo, J. J., and Cardona, C. A., (2014). Comparison of feedstocks and technologies for biodiesel production: An environmental and techno-economic evaluation. *Renewable Energy*, *69*, pp. 479–487. https://doi.org/10.1016/j.renene.2014.03.058

Song, C., Pan, W., Srimat, S. T., Zheng, J., Li, Y., Wang, Y. H., Xu, B. Q., and Zhu, Q. M., (2004). Tri-reforming of methane over Ni catalysts for CO2 conversion to Syngas with desired H2CO ratios using flue gas of power plants without CO2 separation. *Studies in Surface Science and Catalysis*, 153(August 2021), pp. 315–322. https://doi.org/10.1016/s0167-2991(04)80270-2

Singh, U., Naaz, F., Hawkins, T. R., Weinberg, E., Banerjee, S., Mroz, R., Ohri, N., Zhang, J., Lee, Y.-Y., Chen, F., Hill, R., and Li, Y., (2025). Direct flue gas capture for algae cultivation and subsequent valorization: evaluating life cycle emissions and costs. *Sustainable Energy & Fuels*, 9, pp. 4392–4403. https://doi.org/10.1039/d5ee00329f.

Wan Osman, W. N. A., Rosli, M. H., Mazli, W. N. A., and Samsuri, S., (2024). Comparative review of biodiesel production and purification. *Carbon Capture Science and Technology*, 13(July), 100264. https://doi.org/10.1016/j.ccst.2024.100264

Widodo, L., Ihsan, I. M., and Santoso, A. D., (2018). Profitabilitas Biodiesel dari Biomasa Mikroalga. *Jurnal Teknologi Lingkungan*, 19(1), pp. 117. https://doi.org/10.29122/jtl.v19i1.2551

Zheng, F., and Cho, H. M., (2025). Study on Biodiesel Production: Feedstock Evolution, Catalyst Selection, and Influencing Factors Analysis. *Energies*, 18(10), pp. 1-26. https://doi.org/10.3390/en18102533