Techno-economic analysis of biodiesel and bioethanol production from *Chlorella sp.* algae biomass

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Abstract. Indonesia's energy consumption mostly comes from non-renewable energy sources, with 32% dedicated to the transportation sector. The Indonesian government is currently increasing the application of a 30% biodiesel blend in diesel fuel and aiming for a 20% blend of bioethanol in gasoline by 2025. Microalgae is one of the most promising sources for biodiesel production, yielding ethanol and glycerol as by-products. The main processes in this biodiesel plant are cultivation, transesterification, and washing, with glycerol as a side product. For bioethanol, the processes include hydrolysis, fermentation, and separation. The cultivation process utilizes a photobioreactor to promote microalgae growth by controlling environmental parameters. The plant's biodiesel production capacity is 87,107.82 gallons per year, with bioethanol production at 65,330.88 gallons per year and glycerol at 217,769 gallons per year. With the government's tax incentive for the sustainable energy industry applied in this economic analysis, the Internal Rate of Return (IRR) value for this plant is 3%, while the Rate of Interest is 13%.

1 Introduction

The use of renewable energy sources has become increasingly important in recent years due to the growing concern over climate change and the depletion of fossil fuel resources. One promising source of renewable energy is biofuels, which can be produced from various types of biomass.

Indonesia is a country with rapidly growing energy demand. In 2020, the total energy production in Indonesia reached 18,697.41 terajoules [1]. Fossil fuels supplied 93 percent of Indonesia's 7.6 exajoules primary energy demand, with coal, oil, and natural gas being the three major sources, contributing to more than 32% of the demand in the transportation sector.

The Indonesian government has recognized the significant role of biofuels in road transport, aiming to reduce fuel imports and greenhouse gas emissions. The Ministry of Energy and Mineral Resources has mandated that gasoline fuel be blended with bioethanol,

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setting targets of 20 percent by 2025, while 30% biodiesel is to be blended with diesel fuel [2].

Biodiesel and bioethanol are types of biofuels that can be produced from renewable biomass sources such as plants, algae, and microbes [3], [4]. Biofuels are an attractive alternative to fossil fuels because they can be produced sustainably and have a lower impact on the environment [5].

Chlorella algae is a type of microalgae that has shown great potential as a source of biomass for biofuel production. This is because Chlorella algae can grow rapidly and accumulate large amounts of lipids, glucose, and carbohydrates, which can be converted into biodiesel and bioethanol, respectively [6].

The cultivation of Chlorella algae for biofuel production can be done in closed, open, or hybrid systems. Closed photobioreactors are considered the most efficient system for cultivating algae [7]. The yield of algal biomass and the resulting biofuel production can be influenced by various factors such as light, temperature, nutrients, carbon dioxide, and pH [8].

In this study, we conducted a techno-economic analysis of biodiesel and bioethanol production from *Chlorella sp*. algae biomass in Indonesia. We evaluated the feasibility of using this microalgae species as a feedstock for biofuel production by analyzing the costs and benefits associated with the cultivation, harvesting, and processing of the biomass. Our results provide valuable insights into the potential of *Chlorella sp*. as a sustainable source of biofuels in Indonesia and can inform future research and development efforts in this field.

2 Methods and Process Overview

2.1 Procedure

In this study, we conducted a preliminary study to evaluate the feasibility of using *Chlorella sp.* algae biomass as a feedstock for biodiesel and bioethanol production. The study included technology selection for cultivation, harvesting, trans-esterification for biodiesel proudction, hydrolysis, and fermentation for bioethanol production [7], [9]–[11].

The results from the preliminary study were utilized as the design basis in Aspen HYSYS. The process designed is a semi-continuous process for both biodiesel and bioethanol. Besides, the biodiesel and bioethanol produced are optimized to produce fuel-grade (99,5%-wt) [12], [13], while the bioethanol must also be completely dry and anhydrous [14]. Glycerol, for market specifications, must be 95% -wt [15]. The specification of the fuel-grade biodiesel and market-grade glycerol are shown in Table 1 and 2 respectively.

Table 1. Key specification for fuel-grade biodiesel

Specification	**Value**
Flash point	Minimum 93 °C
Methanol content	Maximum 0.2% mass
Water & Sediment	Maximum 0.05% vol
Kinematic Viscosity at 40°C	1.9-6.0 mm^2/sec
Sulfated Ash	Maximum 0.02% mass
Total Glycerin	Maximum 0.240% mass
Sodium/Potassium, combined	Maximum 5 ppm
Oxidation Stability	Minimum 3 hours

Table 2. Key specification for market-grade glycerol

Specification	**Value**
Molecular weight	92.094 g/mol
Melting point	18 °C (64.4 °F)
Boiling point	290 °C (554° F) at 760 mm Hg
Density	1.2613 g/cu cm at 20 °C (68 °F)
Purity	99%
Color	Colorless
Appearance	Clear
Smell	Fragrant
Taste	Sweet
pH level	9

Economic analysis was conducted to assess the viability of the process. This study calculated both the capital and operating costs of the plant, which were then used to analyze net present value (NPV), minimum acceptable rate of return (MARR), internal rate of return (IRR), rate of interest (ROI), and the payback period of the plant.

2.2 Process and plant overview

The overall processes of this plant include pre-treatment, biodiesel production, bioethanol production, and utility. The pre-treatment process consists of algae cultivation, drying, and mechanical pressing. Biodiesel production involves the trans-esterification reaction and washing. Bioethanol production comprises the hydrolysis reaction, fermentation, and distillation. The utility process produces water and steam for various purposes. The overall processes are illustrated in Figure 1.

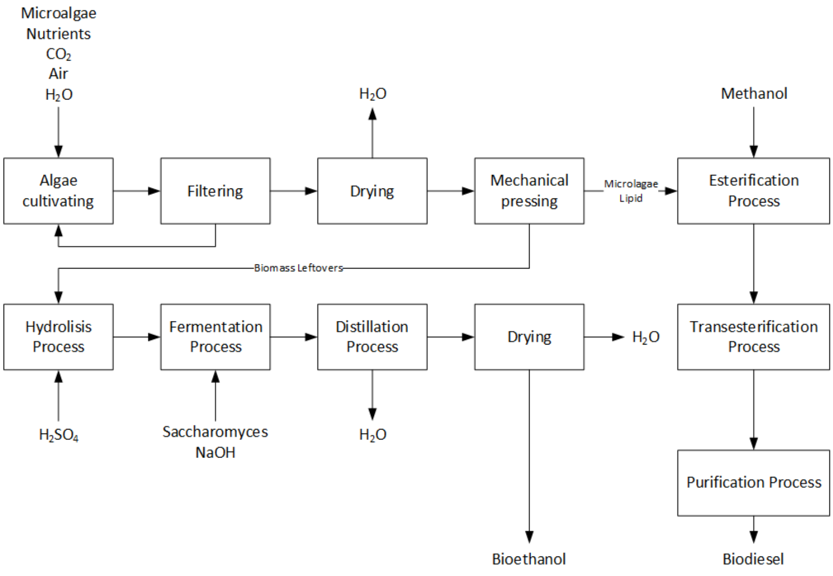

Fig. 1. Overall Process Diagram of Biodiesel and Bioethanol Plant from Algae

The first step in the process is the cultivation of *Chlorella sp.* algae. This is performed in photobioreactors where factors such as light, temperature, and nutrients are controlled and optimized to promote rapid growth and high lipid production [16], [17]. Following cultivation, the algae are harvested and subjected to a filtering and drying process to separate them from water and reduce their moisture content through oven drying. The dried algae are then processed through a mechanical press to extract the oil, leaving behind a solid residue that is processed into bioethanol.

The extracted algal oil undergoes transesterification reaction to produce biodiesel. In this process, the oil is reacted with methanol, in the presence of a zinc catalyst. The result of this reaction is the formation of crude biodiesel and glycerol [18]. Then, they are separated using decanter and membrane. Then, crude biodiesel is washed in an agitated tank.

The production of bioethanol from *Chlorella sp.* involves hydrolysis and fermentation. During hydrolysis, the carbohydrates from solid residue present in the algal biomass are broken down into simple sugars [19]. This is achieved using combination of sulfuric acids and cellulase enzymes. The resulting simple sugars are then converted into ethanol through a fermentation process in a ferementer facilitated by yeast [20]. The ethanol produced is purified through distillation.

Utility process for this plant consists of water purification and steam production. Water purification process takes water from water sources, then mixed with alum solution then processed to remove minerals. Steam produced by heating the water through a boiler.

The plant under consideration is situated within the Kaltim Industrial Estate, specifically at PT. Pupuk Kaltim, Guntung, in the city of Bontang, East Kalimantan, Indonesia. This strategic location is in close proximity to the Makassar Strait, providing an abundant source of seawater. The plant spans an area of 17,222 m², with a length of 158 m and a width of 109 m.

2.3 Process design and simulation

Processes were reviewed, evaluated, and selected from the preliminary study are synthesized to build an industrial-scale semi-continuous process. The process flow diagram of the synthesized main process and the utility is shown in Figure 2 and Figure 3 respectively.

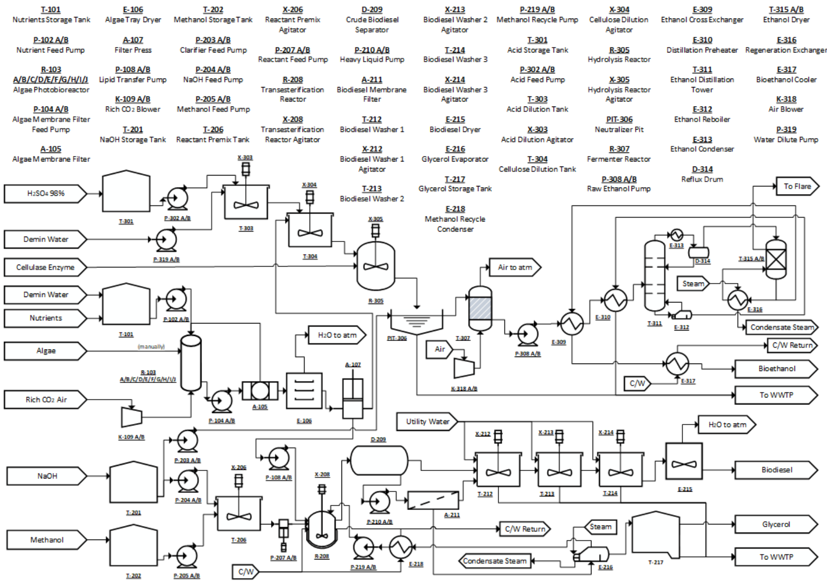

Fig. 2. Process Flow Diagram of Biodiesel and Bioethanol Plant from Algae

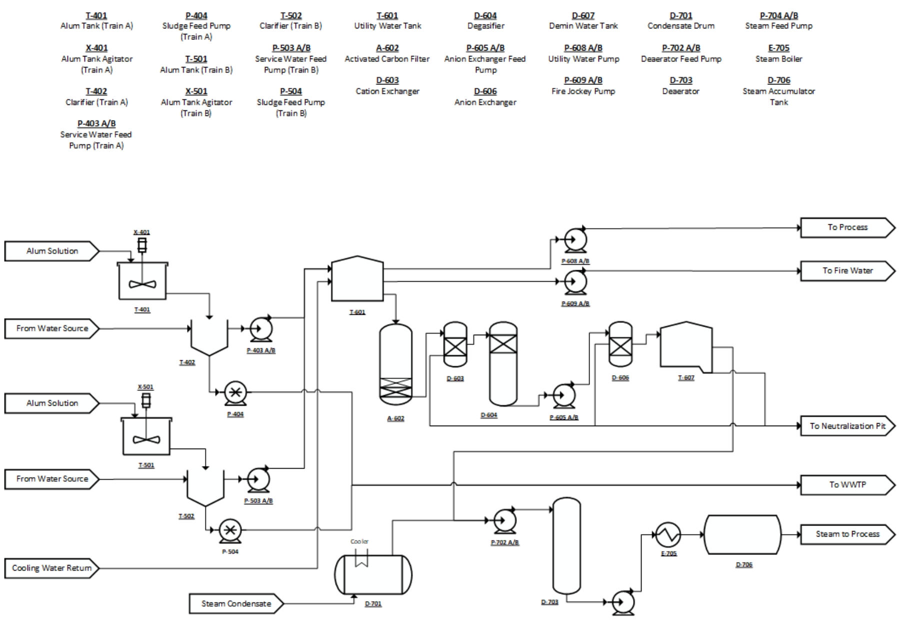

Fig. 3. Utility Flow Diagram of Biodiesel and Bioethanol Plant from Algae

The computational model of the plant was developed and simulated using Aspen HYSYS V10, a process modeling tool widely used in the industry for the design, analysis, and optimization of process plants. The model was built based on the process described in the previous section, which includes algae pre-treatment, biodiesel production and bioethanol production.

2.3.1 Algae Pre-treatment

Algae, akin to plants, utilize sunlight for photosynthesis, a vital biochemical process where light energy is converted to chemical energy. *Chlorella vulgaris*, a type of algae, captures light energy through photosynthesis and transforms inorganic substances into simple sugars using the captured energy [21].

A photobioreactor (PBR) provides a controlled environment, enabling high productivity of algae [22]. As it is a closed system, all growth requirements of algae are introduced into the system and controlled according to the requirements. PBRs facilitate better control of the culture environment such as carbon dioxide supply, water supply, optimal temperature (20-27℃) at atmospheric pressure, efficient exposure to light, culture density, pH levels, gas supply rate, and mixing regime [23].

The photobioreactor itself is designed to promote biological growth by controlling environmental parameters including light. The tubes of the PBR are made of acrylic and are designed to have light and dark intervals to enhance the growth rate [24]. The PBR has a built-in cleaning system that internally cleans the tubes without halting production.

After the algae have completed their flow through the photobioreactor, they return to the feeding vessel. As they progress through the hoses, oxygen sensors determine the amount of oxygen that has built up in the plant and this oxygen is released in the feeding vessel itself. It is also at this stage that the optical Cell Density sensor determines the harvesting rate. When the algae are ready for harvesting, they pass through the connected filtering system. This filter collects the algae ready for processing, while the remaining algae return to the feeding vessel.

The algal biomass is then directed to a drying apparatus to decrease its moisture content, thereby enhancing the efficiency of oil extraction via a pressing machine. The biomass is subjected to high pressure (approximately 170 – 250 MPa) using a hydrostatic machine, which ruptures the individual cell walls of the algae, facilitating oil extraction without damaging complex carbohydrate molecules.

2.3.2 Biodiesel production

In biodiesel production, the oil derived from algae is combined with a catalyst mixture of sodium hydroxide and methanol, initiating a process known as transesterification. This process is carried out in a Continuous Stirred-Tank Reactor (CSTR) under operating conditions of 65℃ and 40.76 psia, with vigorous stirring for 20 minutes. The biomass-catalyst mixture is then stirred intensively for an additional 3 hours to expedite the transesterification process [25], [26].

Following this, the solution is allowed to settle for 16 hours to distinctly separate the biodiesel and sediment layers. The mixture then proceeds to an oil separator machine to segregate the oil from the sediments and mixtures.

To meet the industrial standard, biodiesel undergoes a washing process where it is mixed with water. As water is denser than biodiesel, it absorbs excess alcohol, catalyst, and soap suspended in the fuel. After washing and settling, the water and impurities can be drained from the bottom of the container. Multiple wash cycles are typically required, with roughly one gallon of water needed per gallon of biodiesel for each wash cycle.

Bubble washing is performed by placing a bubbler in a layer of water beneath the biodiesel. The rising bubbles are coated with water that collects impurities as it ascends and descends through the biodiesel. Post-washing, the biodiesel should be dried until it attains crystal clarity. This drying process involves heating the biodiesel at a mild temperature of 48°C for several hours.

2.3.3 Bioethanol production

Hydrolysis is a pivotal stage in bioethanol production, facilitating the conversion of complex carbohydrates into simpler monomers. Enzymatic hydrolysis, as compared to acid hydrolysis, necessitates less energy and milder environmental conditions (e.g., pH 4.5–5.0 and temperature 40–50 °C), and does not pose a corrosion issue [27]. Consequently, this process is anticipated to yield low utility consumption and minimal toxicity in the hydrolyzates.

Cellulose hydrolysis is catalyzed by a group of enzymes known as cellulases, produced by both bacteria and fungi. Trichoderma, among various cellulolytic microbial strains, is a well-studied fungal strain that produces cellulase and hemicellulase. During enzymatic hydrolysis, cellulose is degraded by cellulase into fermentable sugars, which are then converted into ethanol by yeasts or bacteria. The cellulolytic enzyme action involves three steps: adsorption, biodegradation, and desorption. Enzymatic hydrolysis has been proven to be 300 – 500% more effective than chemical hydrolysis depending on the algal source, thus providing an economic advantage to the overall process despite the higher cost of enzymes compared to chemicals used for chemical hydrolysis.

Fermentation employs microorganisms that utilize all five major biomass sugars—glucose, xylose, mannose, galactose, and arabinose—derived from the enzymatic hydrolysis of algae biomass. *Saccharomyces cerevisiae* yeast is renowned for ethanol production from hexoses [28]. In this process, enzymatic hydrolysis and fermentation are conducted separately. The fermentor operates at 35°C and 14.7 psia, where pretreated algae biomass is hydrolyzed to glucose and subsequently fermented to ethanol in separate units. The primary advantages of this process include low chemical costs, short residence time, and simple equipment system, promoting its application on a large scale.

Lastly, distillation facilitates the economic recovery of dilute volatile products from streams containing various impurities.

2.4 Economic analysis

The economic feasibility of the plant designed for biodiesel and bioethanol production from *Chlorella sp*. algae biomass is a crucial component of this study. In this context, we undertake an economic analysis to assess the potential return on investment for this plant.

We compute pivotal financial metrics including the Net Present Value, Minimum Acceptable Rate of Return, Internal Rate of Return, Return on Investment, and the Payback Period. The NPV reflects the worth of the project and is employed in capital budgeting and investment planning to scrutinize the profitability of a projected investment or project [29]. MARR represents the minimum rate of interest that is deemed acceptable for initiating a project, considering its risk and opportunity cost [30]. IRR is used to reveal the attractiveness of the project and predict the possibility of generating profit. While ROI is utilized to gauge the efficiency or profitability of an investment. Payback Period signifies the duration required for an investment to generate an amount equivalent to the original investment [31]. These metrics are calculated in eq. (1), (2), and (3).

$$\mathbf{NPV} = \sum_{n=1}^{n=T} \frac{\mathbf{CF}_n}{1+i^n} - \mathbf{TCI} \tag{1}$$

$$\mathbf{PB} = \mathbf{FC} + \frac{\boldsymbol{I}}{\mathbf{P+D}} \quad (2)$$

$$\mathbf{ROI} = \frac{\mathbf{C}}{\mathbf{TCI}} * \mathbf{100\%} \quad (3)$$

Where NPV is net present value, CF_n is net cashflow during period T, TCI is total capital investment, i is discount rate, T is number of time periods, FC is depreciable fixed capital investment, *I* is interest on TCI during estimated service life, P is average profit per year, D is average depreciation per year, ROI is rate of investment, and C is annual net profit after tax.

The outcomes of this economic analysis will furnish a comprehensive understanding of the potential economic benefits and risks associated with the operation of this plant. To achieve this, some parameters are considered as follows:

- Plant will be built by early 2024 for one year and start to operate in the beginning of 2025.
- Manufacturing of biodiesel and bioethanol begins at early 2024 with service life of 30 years.
- Some equipment will have salvage value in the end of its lifetime value.
- The discount rate is 9.95% based on the Indonesia government's-owned bank [32].
- Tax rate is 22% [33].
- Depreciation expense is 10% for main equipment and 3% for supporting and building with the straight line depreciation method [34].

Total capital investment, comprising fixed and working capital investments, includes all process equipment and auxiliary components. Fixed capital is divided into direct costs, which are directly involved in production, and indirect costs, which cannot be easily attributed to a specific product activity. Working capital includes starting up production cost, raw materials and other materials' inventory cost. The estimation of these costs is estimated from the indexed time of plant establishment to the bare module factor [35].

3 Results and Discussion

3.1 System Performance

Technical design of all equipment is carried out based on the chosen process and technology. The technical design includes reactors, fermenter, and separators. The specifications are developed based on heuristics of process design and equipment design, and evaluated in Aspen HYSYS V11 software [36], [37]. The results are presented in Table 3.

Table 3. Technical specification of main equipment

Equipment	Capacity	Temperature (K)	Power consumption (kW)	Diameter (mm)	Height (mm)
Photobioreactor	1600 kg/batch	308.15	Lamp: 1.5	300	800
Transesterification Reactor	5400 kg/batch	408.15	Agitator: 2.2	1789	2150
Hydrolysis Reactor	4700 kg/batch	308.15	Agitator: 2.2	1590	2380
Fermentor	5100 kg/batch	308.15	Agitator: 2.2	1630	2440
Bioethanol Distillation Column	4200 kg/batch	Reboiler: 493.15 Condenser: 313.15	24	1100	11000
Algae Filter	13300 kg/hr	308.15	Pump: 0.002	2400	4200
Biodiesel Membrane	3370 kg/hr	308.15	Pump: 0.014	800	1100
Biodiesel Washer Tank 1	204.46 kg/hr	308.15	Agitator: 2.2	4014	3211
Biodiesel Washer Tank 2	317.92 kg/hr	308.15	Agitator: 2.2	4611	3689
Biodiesel Washer Tank 3	331.85 kg/hr	308.15	Agitator: 2.2	4631	3705
Freeze Dryer	666.1 kg/batch	213.15	23	1500	2700
Biodiesel Dryer	5534.58 kg/batch	413.15	15	2400	4000
Bioethanol Dryer	666.1 kg/ hr	393.15	4.75	1000	4700

The plant has biodiesel production capacity of 87,107.82 gal/year, a bioethanol production capacity of 65,330.88 gal/year, and a glycerol production capacity of 217,769 gal/year. The planned factory area for this plant is 17,222 m^2.

The electricity requirement of the plant was determined by summing up the electricity needs of each piece of equipment based on the simulation conducted in Aspen HYSYS V11. This total was then multiplied by 1.25 to account for line losses and contingencies. The electric power required for this plant is 3,115.46 kWh/day for direct power and 210.572 kWh/day for office and supporting facility electricity. The total estimated electricity consumption cost per year is USD 84,127.92.

Water utilization in the plant is generally categorized into process water and domestic water. The process water usage was calculated from the amount of water needed in each process, amounting to 14,980 kg/day, including steam form. Meanwhile, domestic water usage was calculated based on the usage of water for drinking, toilets, laboratory, mosque, canteen, and gardening, using data from the USGS [38] as a basis for this calculation. The total usage of domestic water was found to be 480 kg/day.

3.2 Economic analysis

The economic analysis of this plant is conducted by calculating the capital expenditure (CAPEX) and operational expenditure (OPEX), which are subsequently evaluated using profitability analysis. CAPEX encompasses the total equipment cost, site development cost, building cost, offsite facilities cost, contingency cost, contractor fees, working capital, supporting facilities, bulk material cost, and additional cost. The total equipment cost was calculated using Aspen HYSYS V11 with necessary adjustments in the total bare module. The computation of total CAPEX is presented in Table 4.

Table 4. Total capital expenditure calculation

Component	Cost (US$)
Equipment	11,353,744.60
Site Development	307,220.61
Land and Building	5,487,027.13
Other	29,630.80
Start-Up	2,428,155.72
Working Capital	3,993,865.48
Contractor and Contigency	3,086,638.62
Total Capital	**27,405,178.74**

The operational expenditure (OPEX) of this plant comprises equity, raw material cost, utility cost, labour cost, maintenance cost, insurance cost, distribution cost, marketing cost, and depreciation. The computation of OPEX and depreciation is detailed in Tables 5 and 6.

Table 5. Total operational expenditure calculation without equity and depreciation

Component	Cost/year (US$)
General	523,860.58
Maintenance	1,726,142.66
Insurance	503,733.65
Raw Material	59,739.00
Utility	84,374.69
Labor	989,814.00
Total Operational Per Year	**3,887,664.59**

The calculation of income and cash flow is integral to the profitability analysis. Income is ascertained by the revenue generated from product sales after deducting tax and expenses. In this study, the government's policy for the sustainable energy industry is applied for tax relief. Cash flow is calculated by subtracting outgoings from the income, and the cumulative cash flow is illustrated in Figure 4.

Table 6. Total capital expenditure calculation

Year	Total Depreciation (US$)	Total Salvage Value (US$)
0	-	12,308,348
1	864,025	11,444,323
2	788,626	10,655,697
3	720,438	9,935,259
4	658,748	9,276,510
5	602,917	8,673,594
6	552,367	8,121,227
7	506,580	7,614,647
8	465,088	7,149,558
9	427,471	6,722,087
10	393,348	6,328,739
11	362,379	5,966,360
12	334,256	5,632,104
13	308,702	5,323,402
14	285,467	5,037,935
15	264,327	4,773,608
16	245,078	4,528,530
17	227,539	4,300,992
18	211,544	4,089,448
19	196,946	3,892,501
20	183,612	3,708,890
21	171,420	3,537,470
22	160,262	3,377,208
23	150,040	3,227,168
24	140,667	3,086,501
25	132,061	2,954,440
26	124,153	2,830,287
27	116,876	2,713,411
28	110,173	2,603,237
29	103,991	2,499,246
30	98,282	2,400,964

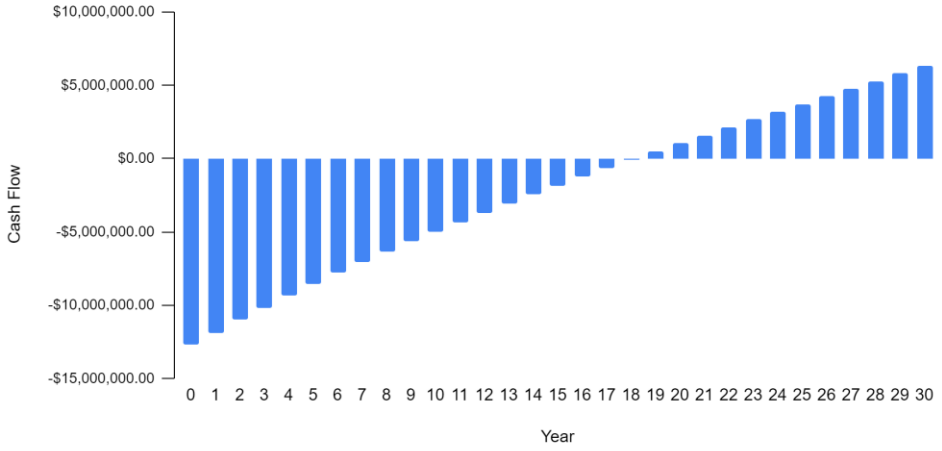

Fig. 4. Cumulative Cash Flow of Biodiesel and Bioethanol Plant from Algae

The plant's profitability is evaluated based on the calculated cash flow, through the computation of the MARR, IRR, NPV, Payback Period, and ROI. The results of this profitability analysis are presented in Table 7.

Table 7. Total operational expenditure calculation without equity and depreciation

Component	Value
MARR	14.51%
IRR	3%
NPV in US$	10,428,575.43
Payback Period	18.80 years
ROI	13%

For the project to be classified as profitable, the IRR must exceed the MARR. Based on the calculations, the ROI and IRR obtained are 13% and 3%, respectively, which indicates that it is not profitable and not attractive to investors. The Payback Period for this plant is 18.80 years, which is considered too long for a fuel producing factory [39]. The obtained NPV is $10,428,575.43, which is less than the initial capital investment.

When compared to other studies, the results indicate that this plant is less profitable than most of the biofuel's factory. For instance, Rafa et al. found that a biofuel plant with a discounted rate of 7.34%, a negative net present value of $26 million and an IRR of 0.38% were attributed to the high capital investment ($55.6 million) [40]. Despite the low profit, an annual benefit of $4.82 million was recognized from revenues generated via biodiesel, animal feed, and electricity. Conversely, a study on bioethanol production from Turkish hazelnut husk process found that assuming a sales price of USD 1.50 per kg of bioethanol, achieved via governmental subsidy and tax incentives, the return on investment of the project comes to 12.61% with an 8-year payback period [41]. Another study used multi lignocellulosic feedstocks for bioethanol production generated IRR of 8.94% with a payback period of 10.07 years and NPV of $17.5 million [42]. In comparison, this factory could produce a net profit per year of $3.4 million. Therefore, we conclude that constructing this factory is feasible but not attractive.

4 Conclusion

The production of biodiesel and bioethanol from *Chlorella sp*. presents a promising avenue towards achieving Indonesia's sustainable fuel targets. Our analysis indicates that while the plant exhibits a relatively long payback period and an unfavourable break-even point, the overall costs are feasible. Specifically, the payback period is estimated to be 18.80 years. The Return on Investment (ROI) and Internal Rate of Return (IRR) are calculated to be 13% and 3%, respectively, suggesting potential for profitability in the long term. Furthermore, the Net Present Value (NPV) of this plant is projected to be $10,428,575.43, indicating that the project's present value of future cash flows is positive. These findings underscore the economic viability of this plant and its potential contribution to Indonesia's sustainable fuel initiatives.

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