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Jurnal Surya Teknika

| ISSN (Print) 2354-6751 | ISSN (Online) 2723-7222 |

Research Article

Techno-Economic Analysis of Betaine Surfactant Production from Hydrogenated Palm Kernel Oil: A Preliminary Plant Design

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ARTICLE INFORMATION

Submitted : March 26, 2026
Accepted : May 22, 2026
Published : June 12, 2026

KEYWORDS

Betaine surfactant production, Hydrogenated palm kernel oil, Plant Design, Techno-Economic Analysis.

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ABSTRACT

Indonesia's high dependency on betaine surfactant imports, which grow at 8.15% per year, necessitates the development of domestic production based on local raw materials. This study aims to design an Amidopropyl Betaine plant from Hydrogenated Palm Kernel Oil (HPKO) with a capacity of 20,000 tons per year. The production process consists of three main stages: amidation reaction (85% conversion), separation and purification via distillation, and carboxymethylation reaction (99% conversion). An economic feasibility analysis yielded a Net Present Value (NPV) of Rp 325 billion, Return on Investment (ROI) of 36.93%, Payback Period (PBP) of 1.53 years, Internal Rate of Return (IRR) of 29,38%, and Break-Even Point (BEP) of 35.84%, indicating that the plant is highly feasible and profitable. This study concludes that the establishment of an HPKO-based betaine surfactant plant is not only techno-economically feasible but also strategic for reducing import dependency and adding value to the national palm oil industry.

1. INTRODUCTION

Amidopropyl betaine represents a class of amphoteric surfactants with significant commercial importance, particularly in the personal care and cosmetic industries. Its molecular structure, featuring both positive and negative charges in the hydrophilic group, enables excellent compatibility with other surfactants while providing foam boosting, viscosity enhancing, and skin irritation mitigating properties [1]. These characteristics make it particularly valuable in formulations for sensitive skin applications, including shampoos, shower gels, and various cosmetic products [2]. The Indonesian surfactant market faces a substantial supply-demand gap, with domestic production capacity insufficient to meet nationalrequirements. According to Statistics Indonesia [3], surfactant imports reached 20,000 tons annually, growing at 8.15% per year. Specifically for betaine surfactants, imports account for approximately 15,000 tons per year [4]. This import dependency represents both an economic burden and a strategic vulnerability in the national chemical industry supply chain.

Indonesia's position as the world's largest palm oil producer offers a strategic advantage for developing bio-based surfactant industries. Hydrogenated Palm Kernel Oil (HPKO), a palm derivative rich in lauric acid, serves as an ideal feedstock for betaine surfactant production through amidation and carboxymethylation reactions [5]. Utilizing HPKO aligns with national down streaming policies for the palm oil industry while supporting sustainable development goals through renewable resource utilization.

The production technology for amidopropyl betaine typically involves two main reaction stages. The primary stage involves amidation reaction between fatty acids from HPKO and dimethylaminopropylamine (DMAPA) to form amidoamine intermediate [6].

The subsequent carboxymethylation reaction

DOI: 10.37859/jst.v13i1.11248

between amidoamine and sodium monochloroacetate (SMCA) yields the final betaine product. Optimization of reactor design, particularly the Continuous Stirred Tank Reactor (CSTR) for the carboxymethylation stage, represents a critical technical aspect in plant design.

Previous research has investigated various aspects of betaine surfactant production. Recent studies [7] focused on catalyst development for reaction efficiency improvement, while [8] evaluated surfactant performance in final product formulations. However, comprehensive techno- economic analyses of betaine surfactant production from HPKO under Indonesian conditions remain limited. Furthermore, detailed engineering design and environmental impact assessments at industrial scale require further investigation.

This study presents a techno-economic analysis for an amidopropyl betaine production plant from HPKO with a capacity of 20,000 tons per year. The research outlines the complete process flow diagram along with comprehensive mass and energy balances for the preliminary plant design. Economic feasibility is assessed through detailed capital and production cost calculations, profitability analysis, and sensitivity analysis considering raw material and product price fluctuations.

2. METHOD

The methodology for this study on betaine surfactant production from Hydrogenated Palm Kernel Oil (HPKO) was developed through a systematic approach encompassing process selection, technical design, economic analysis, and feasibility assessment. The process selection was based on comprehensive literature review of existing production methods, including direct synthesis from fatty acids [1], methyl ester routes [6], and glycerin ester processes. The HPKO- based route through amidation and carboxymethylation reactions was selected as the primary process due to its technical maturity and compatibility with Indonesian raw material availability [4][5].

The technical design phase involved developing detailed process flow diagrams using Aspen HYSYS V12 software, with particular emphasis on the two main reactor systems: the amidation reactor (R-101) operating at 85°C and the carboxymethylation reactor (R- 301) operating at 95°C. Mass and energy balance calculations were performed for all unit operations to determine precise raw material requirements and utility consumption rates for the planned production capacity of 20,000 tons per year. The reactor designs incorporated Continuous Stirred Tank Reactor (CSTR) technology based on established chemical engineering principles [9]. Additionally, the plant location was determined by evaluating critical factors such as production capacity, feedstock availability, transportation infrastructure, and market accessibility, ensuring optimal operational and economic feasibility. Economic evaluation was conducted using the bare module cost method for capital cost estimation, incorporating both direct equipment costs and associated infrastructure expenses [9]. The analysis included comprehensive assessment of indirect costs such as supervision fees, contractor expenses, contingency allocations, and working capital requirements. Production cost estimation accounted for manufacturing expenses including raw materials, labor, utilities, and local taxes, combined with general costs covering distribution, administration, and research activities.

Profitability analysis employed multiple financial indicators including cumulative cash flow, return on investment (ROI), payback period (PBP), internal rate of return (IRR), and net present value (NPV). Sensitivity analysis was performed to evaluate project resilience under varying economic conditions, with particular focus on HPKO price fluctuations and betaine surfactant market price variations. ROI was calculated as the ratio of net annual profit to total capital investment, while PBP determined the capital recovery duration. IRR accounted for the time value of money through evaluation of unrecovered investment balances, and NPV was calculated by discounting cumulative cash flows at a 19% discount rate which was assumed based on typical investment criteria for chemical industry [9]. The economic indicators were calculated using the following equations :

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{CF_t}{(1+i)^t} \qquad (1)$$

$$\mathrm{ROI} = \left(\frac{\text{Annual Net Profit}}{\text{TCI}}\right) \text{x } 100\% \qquad (2)$$

$$\mathrm{PBP} = \frac{\text{TCI}}{\text{Annual Net Cash Flow}} \qquad (3)$$

$$\mathrm{BEP} = \frac{\text{Fixed Cost}}{(\text{Sales}-\text{Variable Cost})} \text{ x } 100\% \qquad (4)$$

The following assumptions were justified to improve scientific validity:

a. HPKO price was based on 2024 Indonesian market prices (Rp 4,956.12/kg)
b. Conversion efficiencies were derived from industrial operating data with amidation conversion of 85% and carboxymethylation conversion of 99% [5]
c. Equipment costs were updated using the Chemical Engineering Plant Cost Index (CEPCI) [6]
d. Plant operational life was assumed to be 15 years with 330 operating days per year
e. Construction period was set for 2 years (2026-2027) with plant operation commencing in 2028

3. RESULT AND DISCUSSION

3.1. Process Description

The block flow diagram of the selected process is illustrated in Figure 1. Figure 1 illustrates the synthesis process of betaine surfactant, beginning with the amidation reaction between HPKO (Hydrogenated Palm Kernel Oil) and DMAPA (Dimethylaminopropylamine). This reaction takes place at a temperature of 85°C and a pressure of 1 atm, producing amidoamine as the main product

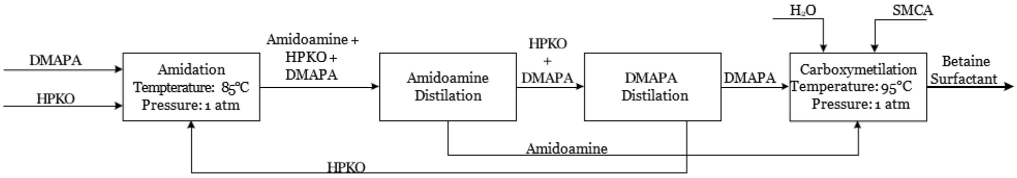


Figure 1. Block Flow Diagram of Betaine Surfactant Production from Hydrogenated Palm Kernel Oil

The resulting amidoamine then undergoes a distillation process to remove any unreacted HPKO and DMAPA, ensuring the purity of the amidoamine intermediate. Following this, the purified amidamine proceeds to the carboxymethylation stage, where it reacts with SMCA (Sodium Monochloroacetate) at a temperature of 95°C and a pressure of 1 atm.

This carboxymethylation step converts the amidoamine into betaine, a surfactant known for its mild and stable foaming properties. The final product, betaine surfactant, is then obtained after appropriate separation and purification, ready for use in various applications such as personal care and detergent formulations. Throughout the process, water is managed as a by-product, and unreacted materials such as DMAPA are recycled via distillation to improve process efficiency and sustainability.

3.2. Material and Energy Balance

Mass and energy balance calculations were conducted using data based betaine surfactant production plants in the world. The Evonix Group operate with a production capacity of 80,000 tons per year, while KAO chemicals has capacity of 20,000 tons per year. The production capacity of 20,000 tons per year (equivalent to 2.525 tons per hour) was selected for this study, based on the availability of HPKO and betaine surfactant need in Indonesia. The mass and energy balance were calculated using the parameters listed in Table 1. Materials balance results for each process stage are illustrated in Figure 2 - Figure 5

Table 1.
Process Design Parameters for Mass and Energy Balance

Feedstock	Hydrogenated palm kernel oil composition (%-mass): 57.6% lauric acid; 18.24 % myristic acid; 9.6% palmitic acid; 4.8% capric acid; 4.8% caprilyc acid; 0.48% oleic acid; 0.48% linoleic acid; 4% water
Amidation	P 1 atm and T 95˚C
Carboxymetilation	P 1 atm and T 95˚C

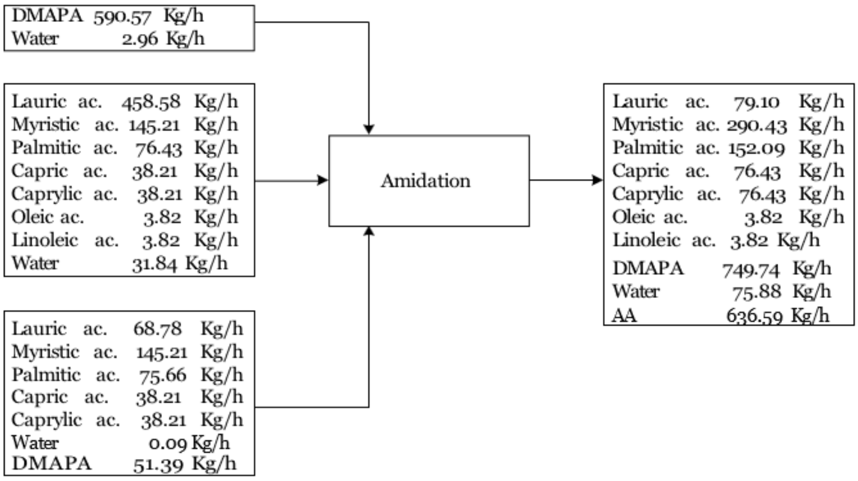


Figure 2. Material Balance on Amidation Reactor

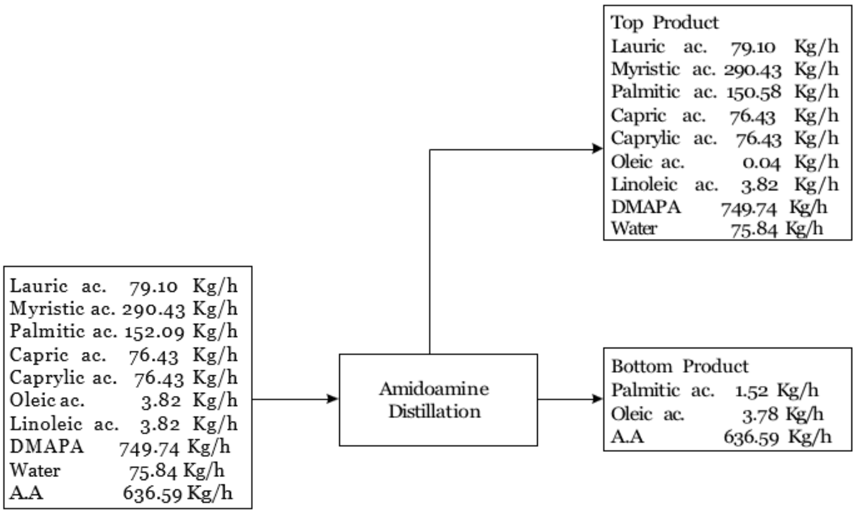


Figure 3. Material Balance on Amidoamine Distillation Column

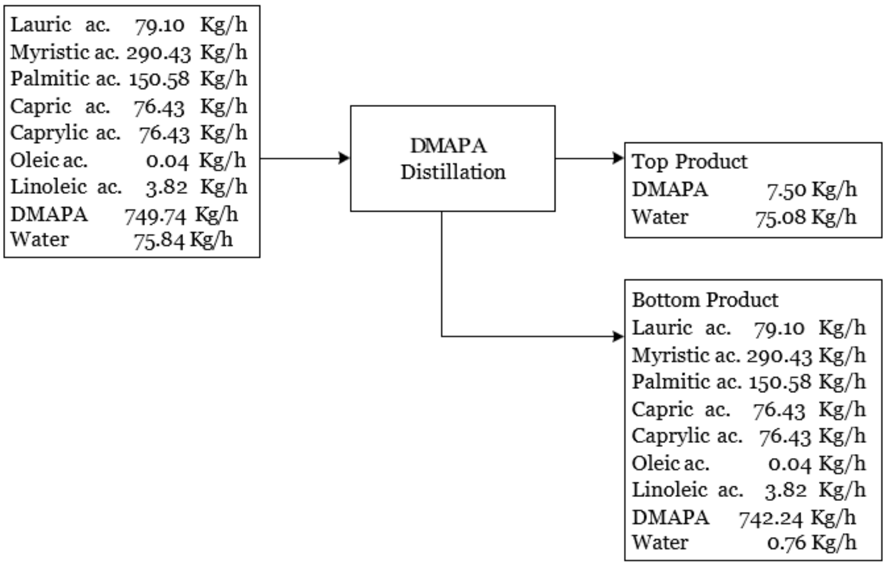


Figure 4. Material Balance on DMAPA Distillation Column

DOI: 10.37859/jst.v13i1.11248

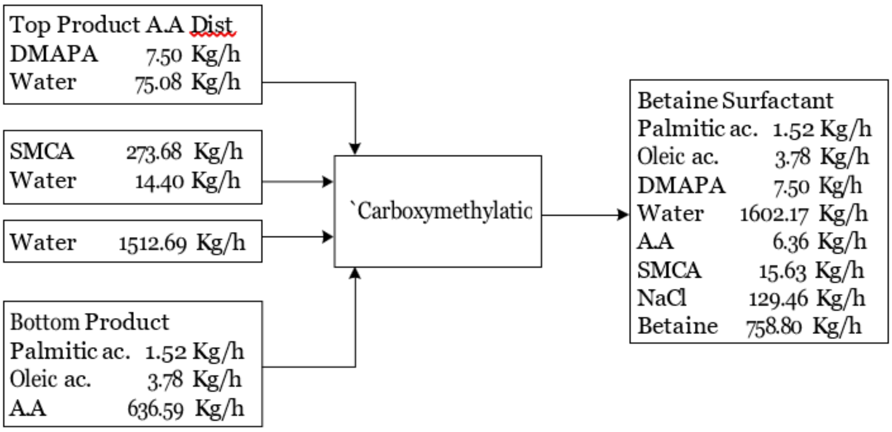


Figure 5. Material Balance on Carboxymetilation Reactor

The mass balance calculation indicated that producing 2.525 tons per hour (20,000 tons per year) of Betaine Surfactant with 30.5% w/w purity requires 0.7956 ton per hour (approximately 6,300 tons per year) of hydrogenated palm kernel oil as feedstock. Energy balance calculations were carried out to determine utility requirements for equipment involving heat transfer. The energy balance for each unit operation was based on stream enthalpies, using a reference temperature of 25°C (298 K) and appropriate specific heat capacities. A summary of the plant’s utility requirements is provided in Table 2.

Table 2.
Summary of The Utility Requirements of Betaine Surfactant Plant

Cooling water	31,045.436	Kg/h
Steam	8,780.656	Kg/h
Domestic water	3,459.95	Kg/h
Hydrant water	363.29	Kg/h
Total	43,649.446	Kg/h
Over Design	48,014.391	Kg/h

3.3. Economy Analysis

The capital cost estimation was performed using the bare module cost method. Base costs and correction factors for each process unit were obtained based on estimates using data from 2013 and adjusted for 2024 [9]. The equipment cost index values was projected using the Chemical Engineering Plant Cost Index (CEPCI) [9], with CEPCI value of 800 for 2024. The cash flow analysis was carried out based on the assumptions listed in Table 3.

Table 3.
Assumption Used in Economic Analysis

Plant Construction	2026
Duration of Construction	2 years
Operating Year	2028
Plant Life Time	15 years
Operating Time	330 days/year with 35 days of maintenance
Debt Payback Period	8 years
Capital Structure	20% equity, 80% debt
Bank Interest	8.05%
Tax	22% from income
Rate of Return Criteria	≥16%
Betaine Selling Price	2 USD/Kg
HPKO Price	1000 USD /1000 Kg

The total capital cost was determined by summing the total bare module cost of the main process and utility equipment with additional expenses, including site preparation, service facilities, contingencies, land, royalties, start-up, and working capital. A summary of the Total Capital Investment (TCI) calculation is presented in Table 4.

Total Capital Investment (TCI) refers to the overall cost required to build and operate a plant until it begins production. As showed in Table 4, the calculation begins with determining the Total Bare

Module Cost (CTBM), representing the cost of the main equipment and utilities. Additional costs for land preparation (Csite) and supporting facilities (CServ) are included to obtain the Direct Permanent Investment (CDPI). Contingency funds and contractor fees (CCont) are then added to calculate the Total Depreciable Capital (CTDC). The Total Permanen Investment (CTPI) is determined by adding land acquisition (Cland), royalties (Croyal), and start-up costs (CStartup) to CTDC. This results in a total capital investment (TCI) of Rp 524,952,524,624. Production costs are categorized into fixed and variable components.

Table 4.
Total Capital Investment Estimation

Cost	Definition/Formula	Value (Rp)
Total Bare Module Cost (C_{TBM})	Total bare module cost of main process equipments	271,982,597,406.17
Total Bare Module Cost Utilities (C_{alloc})	Total bare module cost of utility equipments	26,560,227,222.77
Cost of Site Preparation (C_{site})	10% CTBM	27,198,259,740.62
Cost of Services Facilities (C_{serv})	5% CTBM	13,599,129,870.31
Direct Permanent Investment (C_{DPI})	$C_{TBM} + C_{alloc} + C_{site} + C_{serv}$	339,340,214,240
Cost of Contingencies and Contractor Fee (C_{cont})	18% C_{DPI}	61,081,238,563
Total Depreciable Capital (C_{TDC})	$C_{DPI} + C_{cont}$	400,421,452,803
Cost of land (C_{land})	3% C_{TDC}	12,012,643,584
Cost of royalties (C_{royal})	1% C_{TDC}	4,004,214,528
Cost of plant startup ($C_{startup}$)	10% C_{TDC}	40,042,145,280
Total Permanent Investment (C_{TPI})	$C_{TDC} + C_{land} + C_{roya}l + C_{startup}$	456,480,456,195
Working Capital (C_{WC})	15% C_{TPI}	68,472,068,429
Total Capital Investment (TCI)	$C_{TPI} + C_{WC}$	524,952,524,624

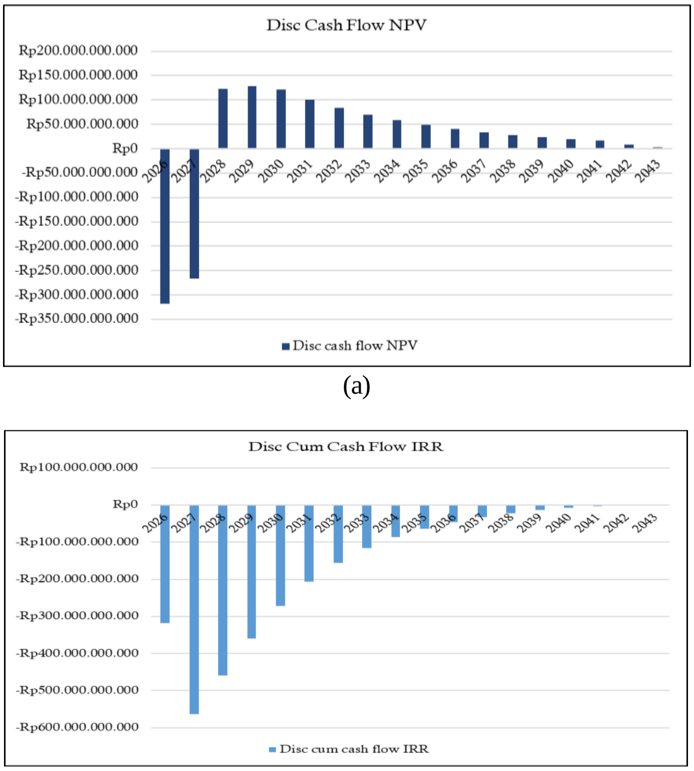
Fixed costs are generally independent of production volume, while variable costs fluctuate based on production levels. As summarized in Table 5, the total production cost for producing 20,000 tons of betaine per year from HPKO is estimated at 394 Billion Rupiah.

Table 5.
Total Production Cost

Cost	Value
Variable Cost	
Feedstock	Rp218,283,855,940
Utility	Rp 5,618,659,101
Total Variable Cost	Rp223,902,515,042
Fixed Costs	
Operations	Rp 17,089,400,000
Maintenance	Rp 33,049,926,951
Operating Overhead	Rp 5,584,598,676
Property Taxes & Insurance	Rp 8,008,429,056
General Expenses	Rp 75,878,880,000
Depreciation	Rp 31,406,894,862
Total Fixed Cost	Rp171,018,129,545
Total Production Cost	Rp394,920,644,586

Variable costs were dominated by feedstock and utility expenses, while the total fixed cost was estimated at Rp171,018,129,545, consisting of operational expenses, maintenance, operating overhead, property taxes and insurance, general administrative costs, and asset depreciation. These costs are allocated regularly to ensure uninterrupted plant operations.

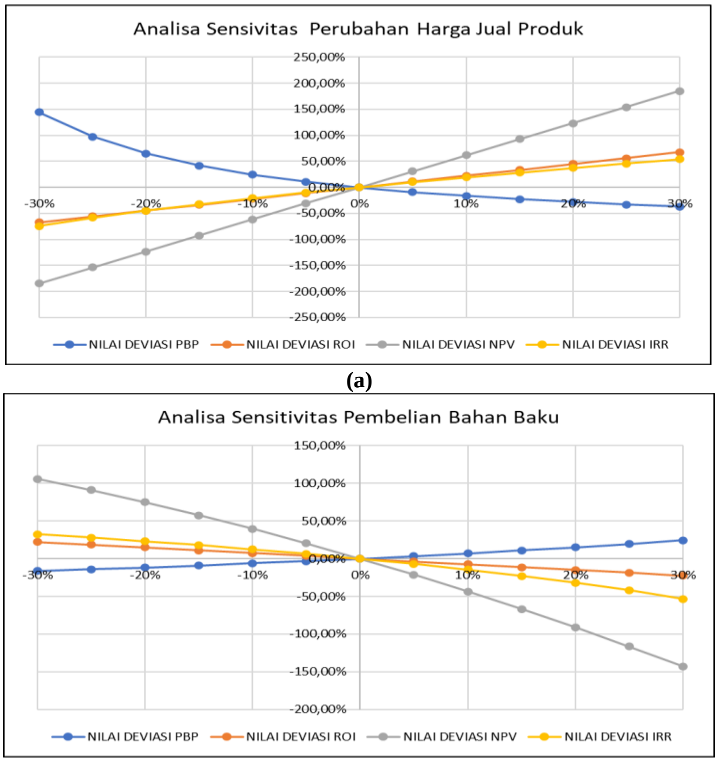
The total capital investment and production costs were used to estimate project cash flow, based on the assumptions outlined in Table 3. The cumulative cash flow is presented in Figure 6.a, while the discounted cumulative cash flow is presented in Figure 6.b



(a)

(b)

Figure 6. Cummulative Cash Flow Chart **(a)** cummulative cash flow, and **(b)** discounted cummulative cash flow



(a)

(b)

Figure 7. Sensivity Analysis for **(a)** product cost change and **(b)** feedstock cost change

The spider plot in Figure 7 illustrates that profitability parameters are more responsive to fluctuations in product prices than to changes in raw material costs. For example, a 80% increase in raw material costs reduces the Return on Investment (ROI) below the 16% threshold, while a more 26% decrease in product prices results in a similar decline in ROI. This indicates that the betaine surfactant plant's financial performance is highly dependent on product price variations. Consequently, effective pricing strategies are crucial, as even small reductions in product prices can significantly impact overall profitability.

3.3 *Safety Consideration and Plant Location*

Health and safety are critical aspects in any industrial plant. To ensure safe and secure plant operations, various safety devices are integrated into the process equipment. These include check valves on pump discharge lines to prevent backflow, as well as pressure relief valves installed on storage tanks, pressure vessels, and heat exchangers to protect against overpressure resulting from process disturbances or thermal expansion. All equipment containing hazardous liquids is clearly labeled, and essential control devices such as level, temperature, and pressure sensors are installed to maintain process variables within defined safe operating limits. In terms of environmental protection, pollution prevention measures include the installation of gas ventilation systems designed to controlled manner, ensuring that ground-level concentrations remain within permissible and environmentally safe limits. All wastewater generated by the plant is treated in a dedicated water treatment facility using activated sludge, in compliance with the maximum allowable discharge parameters set forth in the Indonesian Ministry of Environment Regulation Number 03 of 2010 concerning Wastewater Quality Standards.

The plant is strategically located in Sungai Sembilan, Dumai, Riau Province, Indonesia, providing advantageous access to both the provincial capital and the national capital. The selected location provides good access to palm oil industries and transportation infrastructure, supporting stable HPKO supply and product distribution

4. CONCLUSIONS

The preliminary plant design successfully achieved a production capacity of 20,000 tons/year of betaine surfactant, requiring approximately 6,300 tons/year of HPKO as the main feedstock. Mass and energy balance calculations confirmed the technical feasibility of the amidation, purification, and carboxymethylation processes. Economic evaluation showed that the project is financially feasible, with an IRR of 29.38%, PBP of 1.53 years, and NPV of Rp 325 billion over a 15-year operating period. The total capital investment and annual production cost were estimated at Rp 524 billion and Rp 394 billion, respectively. Sensitivity analysis indicated that profitability is more affected by product price fluctuations than raw material costs. Future study should focus on reactor optimization, heat integration through pinch analysis, and environmental assessment to improve process efficiency and sustainability.

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