Techno-economic evaluation of integrated levulinic acid, formic acid, and furfural plant from oil palm empty fruit bunch with pre-treatment variations

Evaluasi teknoekonomi pabrik asam levulinat, asam format, dan furfural terpadu dari tandan kosong kelapa sawit dengan variasi perlakuan awal

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Abstrak

Asam levulinat, sebuah platform biokimia, dapat digunakan sebagai aditif biodiesel dalam produksi biodiesel. Permintaan global asam levulinat mencapai 3.820 ton pada 2020, sedangkan roadmap target biodiesel di Indonesia mencapai 20% dari konsumsi solar pada 2016-2025. Angka-angka ini menjadi pertimbangan untuk mendirikan pabrik asam levulinat di Indonesia. Fokus penelitian menganalisis kelayakan ekonomi rancangan pabrik produksi asam levulinat terpadu berbasis Tandan Kosong Kelapa Sawit (TKKS) di Indonesia. TKKS dipilih sebagai bahan baku karena limbah padat yang dihasilkan perkebunan kelapa sawit sangat besar. Dalam perancangan pabrik, software SuperPro Designer 9.0 digunakan sebagai alat simulator proses. Analisis ekonomi menunjukkan Net Present Value (NPV) sebesar US$ 548.850.764, Internal Rate of Return (IRR) 24,75%, dan payback period (PBP) diperkirakan dalam enam tahun dengan Minimum Attractive Rate Return (MARR) 6,1%. Kapasitas produksi optimal asam levulinat, furfural dan asam format masing-masing adalah 12.425; 15.105 dan 6.074 ton/tahun.

[Kata kunci: selulosa, delignifikasi, asam levulinat, TKKS, simulasi]

Abstract

Levulinic acid, a platform biochemical, might be utilized as a biodiesel additive in biodiesel production. Global demand for levulinic acids was 3,820 tons in 2020, while the roadmap target of biodiesel in Indonesia will reach 20% of diesel consumption in 2016-2025. These figures become the considerations for establishing the levulinic acid plant in Indonesia. The study's focus analyzed the economic viability of integrated levulinic acid production plant design based on Oil Palm Empty Fruit Bunches (OPEFB) in Indonesia. OPEFB was selected as raw material due to the enormous solid waste generated by oil palm plantations. In the plant design, software SuperPro Designer 9.0's used as a process tool simulator. The economic analysis showed the Net Present Value (NPV) as the US $ 548,850,764, an Internal Rate of Return (IRR) of 24.75%, and a payback period (PBP) estimated within six years with a Minimum Attractive Rate Return (MARR) of 6.1%. The optimal production capacities of levulinic acid, furfural, and formic acid are 12,425; 15,105 and 6,074 tonnes/year.

[Keywords: cellulose, delignification, levulinic acid, OPEFB, simulation]

Introduction

The awareness of sustainable energy use in Indonesia is visibly increasing as more biodiesel is in demand. However, there are still some disadvantages to using biodiesel. The price is higher than conventional diesel. Biodiesel is 20 times more susceptible to water contamination than that can cause corrosion, filter damage, and pitting in the pistons. Other shortcomings are the low oxidation stability of biodiesel, which is more corrosive than conventional diesel and its vulnerability to damage at low temperatures (Climent *et al.,* 2014).

Levulinic acid is a compound that can be used as a platform chemical in biodiesel production (Gozan *et al.*, 2020). In biodiesel production, acidic compounds derived from levulinic acid are used as additives to make the engine work more efficient, although with biodiesel. The acidic compounds (4-oxopentanoic acid) also act as builder substances to manufacture other compounds such as 5-bromolevulinat acid, valeric acid, MTHF, and methyl pyrrolidone, and others (Gozan *et al.*, 2018). In Asia-Pacific, China has become the primary

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manufacturer of levulinic acid (Mordor, 2020). In 2020, global demand for levulinic acid was predicted to reach 3,820 tons, with an increased rate of 5.7% per year (Research, 2020)

Oil palm empty fruit bunches (OPEFB) are potential biomass feedstock in levulinic acid production. One ton of oil palm fresh fruit bunches produces 22-23% Oil Palm Empty Fruit Bunches (OPEFB) (Gozan *et al.*, 2020). The cellulose content of OPEFB can reach 44.2%, while the rests are hemicellulose (33.5%) and lignin (20.4%) (Chin *et al.*, 2013).

Delignification is required to separate lignin from these lignocellulosic materials. Pretreatment studies have been done using different approaches such as sodium hydroxide soaking (Sadrina *et al.*, 2019), microwave-assisted ammonia pretreatment (Harahap *et al.*, 2019a) and white-rot fungi (Samsuri *et al.*, 2008). Hydrolysis of cellulose from pretreated OPEFB can produce levulinic acid (Gozan *et al.*, 2018), while hemicellulose hydrolysis from OPEFB can produce furfural (Panjaitan *et al.*, 2017). Formic acid is produced from the hydrolysis of both cellulose and hemicellulose (Harahap *et al.*, 2019b; Panjaitan & Gozan, 2017).

This study examines the economic feasibility of constructing an integrated levulinic acid plant based on OPEFB with different pretreatment scenarios. Economic feasibility is examined by comparing the internal rate of return (IRR), payback period (PBP), net present value (NPV), and sensitivity analysis.

Material and Methods

Materials

Oil palm empty fruit bunches (OPEFB) used in the study was collected from PT Perkebunan Nusantara (PTPN) VIII Malimping, Banten. Characterization of OPEFB was conducted at Balai Besar Pulp dan Kertas (BBPK), Bandung, by using the Indonesian national industry-standard (SNI), ie. SNI 7460 for Ash, SNI 0492-2008 for lignin, SNI 0444:2009 for cellulose and SNI 14-1304-1989 for hemicellulose contents.

Economic evaluation

The evaluation of economic parameters is applied through a profitability analysis to determine the values of Internal Rate of Return (IRR), Net Present Value (NPV), and Payback Period (PBP). Defined values for the parameter references in profitability analysis were based on chemical industry values. Additional analysis performed was sensitivity analysis of the economic parameters from the initial cost of investment (capital investment) and the selling price of products. The study's economic calculation for determining the estimated capital investment cost referred to Guthrie's Method (Individual Factors of Guthrie Methods). All

calculations were accomplished by Microsoft Excel spreadsheet within the following assumptions applied:

a) The estimated cost of each type of equipment in the study will use the Chemical Engineering Plant Cost Index.
b) The plant had a working day for 355 days in one year, with full working hours of 24 hours a day.
c) The age of the plant was 20 years.
d) Plant equipments were purchased in 2022
e) Acid Hydrolysis Residues (AHRS) and lignin produced in the production process were used as fuel for Steam Generator.
f) The calculation of depreciation used the declining balance method.
g) The income tax rate used in calculating cash flow was 25%.
h) The Minimum Attractive Rate of Return (MARR) was 6.1%, and the Risk-free rate was 7.1%.
i) The selling price of levulinic acid, furfural, and formic acid were US $ 8,000/ton, US $ 1,500/ton and US $ 750/ton, respectively.

Raw material supply and analysis

Oil palm empty fruit bunches (OPEFB) was selected as raw materials in the integrated levulinic acid production based on Indonesia's abundant availability as the solid waste in palm oil production. The palm oil production in Indonesia was 46.2 million tons in 2021 (Statista, 2022). About 46 to 49 million tonnes of OPEFB were produced in 2020 (Gozan *et al.*, 2020). Indonesia's oil palm plantation significantly rises to 16 million hectares in 2020 (Purnomo *et al.*, 2020). It also indicates that the availability of raw materials in the co-production of levulinic acid, furfural, and formic acid is guaranteed.

Process configuration of integrated levulinic acid production

The production of integrated levulinic acid consists of phase processes started from OPEFB pretreatment. The stage included shredding, washing, ash, and dirt removal, neutralizing OPEFB as the primary raw material. The second phase of the production process was hydrolysis. In the study, we used two hydrolysis process stages for the maximum conversion process of OPEFB to levulinic acid, furfural, and formic acid. PFR-CSTR reactor configuration was used for the hydrolysis process based on patent US 5.608.105 (BiofineTM Technology) (Kapanji *et al.*, 2021). The final phase was the main product's separation process, levulinic acid with side products, and the distillation column was utilized to get a high purity (>95%). The flow of the production process for base case is illustrated in Figure 1.

Techno-evaluation of scenarios

The calculations performed above (base case) are then compared with the configuration process scenarios on the OPEFB pretreatment process. The variation scenario is done by pretreatment because attacking the structure of lignin EFB could reduce cellulose's crystallinity. It would increase the porosity and make the cellulose more accessible for hydrolysis (Ya'aini *et al*., 2012). The explanation of all alternatives is depicted in Table 1.

The alternative I scenario uses no pretreatment process. Alternative II uses Aqueous Ammonia Soaking (AAS). Alternative III uses Ammonia Fiber Explosion (AFEX). Aqueous Ammonia Soaking (AAS) method used ammonium hydroxide (NH_4OH) with maximum ammonia composition of 30%, and OPEFB was soaked for 12 h at 35°C (Gozan *et al*., 2020). On the other hand, the AFEX method used anhydrous liquid ammonia mixed with the biomass and water at a ratio of 0.3:0.25:1 (Hassan *et al*., 2020). The operation condition for the process was set within temperature at 90°C and pressure at 21 atm. Residence time for the process was about 45 minutes.

Results and Discussion

Characterization of OPEFB was conducted, and the results are depicted in Table 2. The cellulose content of this OPEFB is 40.3%, which is common for OPEFB. However, this is relatively high for lignocellulosic biomass (Gozan *et al*., 2020).

Production capacity determination

In the study, the determination of plant capacity focused on levulinic acid production as a primary product. Based on the demand analysis and market requirements, levulinic acid was 3,934 tonnes/year in 2018. The existing plant in China and Europe has controlled about 46% market share globally for levulinic acid. The remaining potential market can be taken at around 54%, which amounts to 2,124 tonnes/year. Assuming the study's economic evaluation was conducted by taking 75% of the potential remaining market share, the plant's levulinic acid production capacity is 1,593.3 tonnes/year. The economic analysis and profitability trial conducted with the capacity obtained showed the value of one of the economic
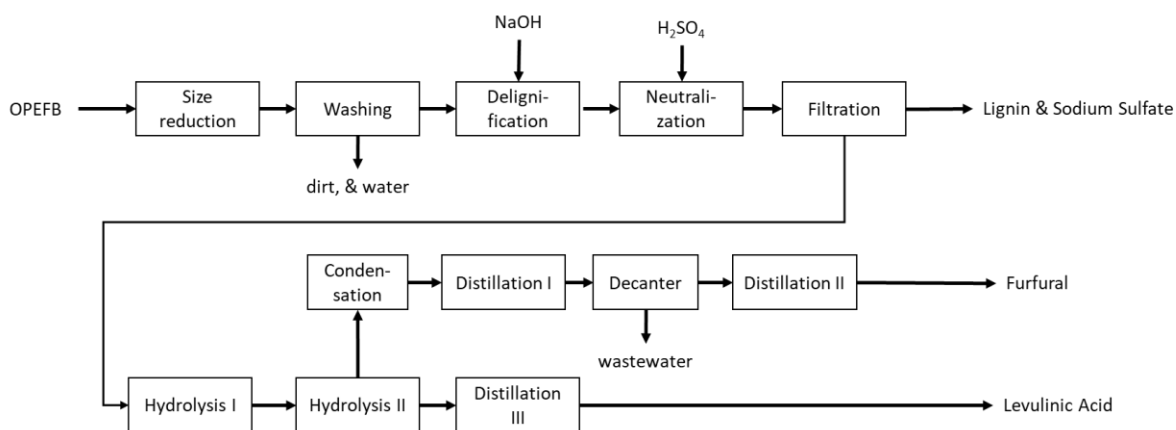

Figure 1.   Block Flow Diagram (BFD) by Superpro Designer for the base case (modified from Kapanji *et al*., 2021)

Gambar 1.   Diagram Alir Kotak (BFD) dengan Superpro Designer untuk kasus dasar (dimodifikasi dari Kapanji et al., 2021)

Table 1. Alternative scenario configuration
Tabel 1. Konfigurasi Skenario alternatif

	Alternative I *Alternatif ke-I*	Alternative II *Alternatif ke-II*	Alternative III *Alternatif ke-III*
Pretreatment *Perlakuan awal*	No treatment	Aqueous Ammonia Soaking (AAS)	Ammonia Fiber Explosion (AFEX)
Alkaline Composition *Komposisi alkali*	-	30%,	
Condition *Kondisi*	-	12 h at 35°C	
Reference *Referensi*	-	(Gozan *et al*., 2020)	(Hassan *et al*., 2020)

Table 2. OPEFB Composition
Tabel 2. Komposisi Tandan Kosong Sawit

Component *Komposisi*	Composition [%] *Komposisi [%]*	Characterization Method *Metode Karakterisasi*
Ash	2.00	SNI 7460
Lignin	23.20	SNI 0492-2008
Cellulose (Alfa)	40.30	SNI 0444:2009
Hemicellulose	31.18	SNI 14-1304-1989

parameters. The IRR (Internal Rate of Return) was negative (-7.7%). It certainly does not meet the predefined parameters. From some trials with an increase in production capacity, it was found that the capacity met the economic parameters (IRR> 14%, the maximum PBP in productive age of the plant), and the plant capacity was calculated to be 12,425 tonnes/year levulinic acid. The estimation capacity was considerable compared to global capacity following the potential market share. However, levulinic acid production meets the needs of global levulinic acid, but it would be used for domestic needs as biodiesel fuel additives.

Indonesia's biodiesel demand is targeted at 20% of the national diesel consumption, which amounted to 10.22 million KL in 2016-2025 (APEC, 2009). As an additive in biodiesel production, levulinic acid will be converted into ethyl levulinate. The use of ethyl levulinate as an additive is used to improve the performance of biodiesel at low ambient temperatures (low-temperature flow properties), especially the cloud point (CP) and pour point (PP). Ethyl levulinate as additives can improve stability and thermal oxidation (Mohan *et al.*, 2021). Determining the ethyl levulinate market in Indonesia can be studied with ethyl levulinate needs themselves. Knowing the biodiesel consumption data predicted in the year 2016-2025 amounted to 2.04 million kL, the calculation was made by following several assumptions:

a. The composition of biodiesel and additives used, namely ethyl levulinate (20%), biodiesel (79%), and co-additive (1%).
b. The esterification process used a homogeneous acid catalyst to convert levulinic acid into ethyl levulinate amounts to 85.2%.
c. Conversion of 2.04 million kL equivalent to 720,419 tonnes. It could be seen that ethyl levulinate demand is as follows.

$$\frac{100}{79} \text{ x } 720,419 \text{ ton} = 911,922.78 \text{ ton}$$

$$\frac{20}{100} \text{ x } 911,922.78 \text{ ton} = 182,384.5 \text{ ton}$$

From the above calculation, ethyl levulinate is required following biodiesel consumption of 182,384.5 tons. Using conversion as previously assumed, if the entire production of levulinic acid was used as a raw material in ethyl levulinate production, it obtained 10,561.25 tons of ethyl levulinate. The calculation results concluded that the levulinic acid production capacity that has been determined was following the demands of predicted ethyl levulinate.

Mass balance

The total mass balance of the integrated levulinic acid plant is depicted in Table 3. The efficiency was estimated to be up to 98% from the mass balance calculation. The total product mass's efficiency to the amount of raw material was relatively high (75.5%). Reversely the mass conversion of OPEFB to levulinic acid was still relatively small (29.1%). The process is caused by quite a process used to produce levulinic acid, including the pretreatment process, which can dissolve cellulose as the primary raw material for levulinic acid formation due to sodium hydroxide in the delignification process (Barlianti *et al.*, 2015). Also, the cellulose composition in lignocellulose material was only around 35-40%, and in the study, the cellulose content in the raw materials used was about 40.3%. The above calculation appeared that the furfural generated more weight than levulinic acid as the top product, and hemicellulose content (31.18%) contained in OPEFB was lower than cellulose (40.3%). It happened because, on the furfural formation, the produced intermediate product was hydrolyzed further as xylose into furfural. While the reaction levulinic acid formation, through the formation of intermediate glucose hydrolysis into hydroxymethylfurfural and further hydrolyzed to levulinic acid and formic acid as a final product.

Based on the activation energy required in the hydrolysis process, cellulose had higher activation energy (188.9 kJ/mol) compared to the hydrolysis of hemicellulose (107.9 kJ/mol) (Dussan *et al.*, 2013). The yield of levulinic acid obtained in the plant design was about 44.7% mol. The plant design's primary process adopted the patent US 5.608.105 (Biofine[TM] Technology) (Kapanji *et al.*, 2021).

Table 3. Total mass balance for the base case
Tabel 3. Neraca massa total untuk kasus dasar

Component *Komponen*	In *Masuk*	Out *Keluar*
Hydroxymethyfurfural	0	8.89
Ash	90.72	90.72
Cellulose	1,827.98	160.67
Formic Acid	0	532.12
Furfural	0	1,724.74
Glucose	0	62.16
Hemicellulose	1,414.3	132.5
Humine	0	550.29
Levulinic Acid	0	1,349.22
Lignin	1,052.33	1,052.33
Sodium Hydroxide	3,265.22	326.52
Sodium Sulfate	0	5,217.94
Sulfic Acid	4,551.94	949.08
Water	439,830,19	430,586
Xylose	0	5.59
TOTAL	452,032.68	442,478.73
Overall Error	2.05%	

Based on the published patent, levulinic acid yield was about 59.01% mol with reactor configuration using PFR-CSTR, a feedstock used wood flour with 42% cellulose and 10% biomass intake composition. In comparison, the yield of levulinic acid produced by the study (44.7 mol %) was lower than the value that should be contained in patents (59.1% mol). Several things might cause it:

a. The cellulose composition in the raw material used in the study (40.3%) was lower than the patent (42%). It affected the amount of levulinic acid formed in the final product.

b. Biomass intake used in the study has a considerable value (18.62 wt%) compared to those used in the patent (max. 10% wt). Biomass intake affects the cellulose concentration during the reaction of levulinic acid formation. The high concentration of cellulosic substrate provided abundance for the formation of intermediate hydrolysis products glucose hydroxymethylfurfural. Under conditions of excess glucose provided, it can potentially not completely react and form a condensation product in the form of humin—the cause of lower levulinic acid yield. The higher yield of levulinic acid (60 mol%) was obtained with 1.7 wt% lower cellulose concentration or by 1.7 wt% addition of cellulose periodically (Ahlkvist, 2014).

Energy balance

The energy balance conducted in the study was based on the material energy balance involved in every equipment (equipment) process. As the mass and energy balance results, energy efficiency was obtained only by 52.67% due to mass losses, hence energy losses, during the process.

Energy analysis was also conducted based on the energy required in the process (energy required) and the product's energy value. Utilities such as electric energy needs and energy content owned raw materials used are not included in calculating the input energy. The energy input calculated for the plant design was 15.19 GJ/h (Table 4), based on the amount of OPEFB per tonnes treated. The energy output was calculated and shown in Table 5.

From the calculation of energy input and output at the plant design, it was found that the energy balance was positive (5.78 GJ) to the energy ratio of 1.38. So, it is classified as a positive energy balance. From the energy analysis results, the production process generates more energy than the energy needed. The parameter is an essential requirement in second-generation biofuels economically (Hayes, 2013).

Table 4. Energy input value for the base case
Tabel 4. Nilai energi asupan untuk kasus dasar

Equipment *Peralatan*	Energy Required (GJ/h) *Energi yang dibutuhkan (GJ/jam)*
Delignification Tank	33.7
Pre-Hydrolysis Tank (PFR)	7.2
Hydrolysis Tank (CSTR)	14.4
Reboiler I	20.3
Reboiler II	69.1
Reboiler III	0.3
Total	**75.9**
OPEFB processed (ton/h) *TKKS yang diproses (ton/jam)*	5
Energy required/h/ton OPEFB (GJ/h) *Energi yang dibutuhkan/jam/ ton TKKS (GJ/jam)*	15.19

Table 5. Energy output value for the base case
Tabel 5. Nilai energi keluar untuk kasus dasar

Product *Produk*	Amount (ton/ton OPEFB) *Jumlah (ton/ton TKKS)*	Energy Content (GJ/ton) *Jumlah Energi (GJ/ton)*	Energy output (GJ) *Energi keluar (GJ)*
Levulinic Acid	0.292	21.89	6.39
Furfural	0.35	25.97	9.09
Formic Acid	0.114	5.24	0.597
Lignin	0.21	23.02	4.83
Energy output/h/ton OPEFB (GJ/h) *Energi keluar/jam/ton TKKS (GJ/jam)*			20.97

Economic evaluation

Calculating the total capital investment required computing several components in it, such as the Total Direct Permanent Investment (DPI), Total Depreciable Capital (TDC), and Total Permanent Investment (TPI). Using Guthrie's cost estimation method, reference Cost Index 394 (D'Angelo *et al.* 2015). The equation for the Total Capital Investment (C_{TCI}) by the Guthrie method stated as:

$$C_{TCI} = C_{TPI} + C_{WC} = 1.18 \left(C_{TBM} + C_{site} + C_{buildings} + C_{offsite\ facilities} \right) + C_{WC} \quad (1)$$

$$C_{BM} = C_{Pb} + \left(\frac{I}{I_b} \right) \left[F_{BM} + (F_d F_p F_m - 1) \right] \quad (2)$$

where,

F_{BM} = bare-module factor
F_d = equipment design factor
F_p = pressure factor
F_m = material factor

Total Capital Investment or Capital Expenditure (CAPEX) obtained from the plant design was the US $ 233,659,876. Based on the calculation of the components of operational costs, such as the cost of raw material (utility costs), salaries of workers, depreciation, maintenance, insurance cost, also safety and environmental cost, the estimated value of operational cost per year on integrated levulinic acid production plant was US$ 7,625,178.

Economic value determination of the plant design was conducted by profitability analysis of three standard economic parameters, which were Internal Rate Return (IRR), Net Present Value (NPV), and Payback Period (PBP). The IRR was calculated by following the trial-and-error method equation.

$$\sum_{t=0}^{T} \frac{X_t}{(1+IRR)^t} = 0 \quad (3)$$

For the NPV parameter, the equation is

$$NPV = \sum_{t=0}^{T} \frac{X_t}{(1+i)^2} \quad (4)$$

Where,

- X_t : cash flow in n-years
- i : discount rate (MARR is used)

Thus,

$$PBP = \sum_{t=0}^{PBP} X_t = 0 \qquad (5)$$

The calculation resulting IRR, NPV and PBP is 24.75%, US$ 548.850.764, and 6 years with an annual income of US$ 126.63 million/year. Based on the profitability analysis of economic parameters, IRR, NPV and PBP concluded that the plant design was economically feasible because the IRR value was more than the sum of calculated MARR with Indonesia's risk-free rate. Besides, positive NPV and PBP are less than half-productive ages of the plant. From this overview, the plant design fulfilled the criteria for the economically feasible project. However, economic feasibility conditions were achieved within a large production capacity of up to 12,425 tonnes/year for levulinic acid production as the main product. Even though the production cost (net production cost) is high, the underlying levulinic acid global production capacity is still small, with high production costs. Still, a low levulinic acid yield was produced (max. 50% of the theoretical yield).

Sensitivity analysis was conducted to determine the uncertainty of the project caused by several factors. The study used two parameters that assumed more affected the profit, i.e., product selling price and capital expenditure (CAPEX), as shown in Figure 2 (A, B, C).

Based on the sensitivity analysis results, the selling price significantly influenced the revealed NPV value as a factor of change. The result has occurred because NPV indicated the absoluteearning power during economic life. The product selling price directly affected the total revenue per year, affecting the value of the benefits. Later. The underlying effect of changes in selling prices was more significant to the NPV. From the calculation, changes in selling prices of products could be tolerated up to 30% with only a parameter IRR of 14% with a reduction in NPV of nearly 50% of the initial value and the longer the PBP, which was ten years old.

Changes in capital investment significantly influenced the value of IRR. As a result, the IRR indicated a relative value earning power of capital invested in the project. Thus, the amount of IRR greatly influenced the amount of initial capital invested in a project. From the calculation, increasing capital investment value is inverse to IRR. Increased capital investment is the maximum that could be tolerated by + 40% with a 15% IRR, NPV of US $ 364,943,410, and PBP increased in 10 years.

Economic evaluation of alternative scenarios

The calculations presented above are calculations for the base case. Calculations were then developed for the 3 scenarios. Figure 3 shows a comparison between the calculated capital and operating cost of the base case with the 3 scenarios. Table 6 shows economic parameters (IRR, NPV, PBP) of various scenarios.

From Figure 3 and Table 6 it is shown that the Alternative I (no pretreatment on biomass) had the lowest capital investment and operational cost compared to the primary case. This is quite expected as in this alternative I, the number of equipments and chemicals are much less than other case or alternatives. However, the alternative I only process biomass at 3 tonnes/h with a relatively low biomass loading rate (5%) of the base case and other scenarios (10-15%).
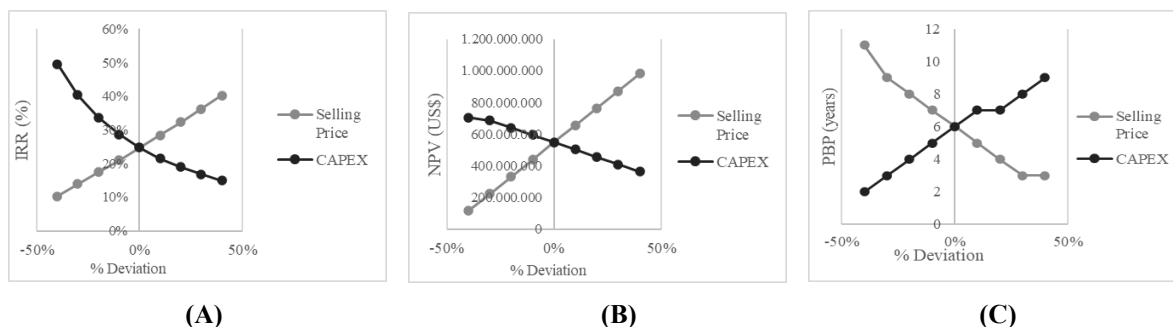

(A)   **(B)**   **(C)**

Figure 2.   Sensitivity analysis of (A) Internal Rate of Return (IRR); (B) Net Present Value (NPV); and (C) Payback Period (PBP)

Gambar 2.   Analisis sensitivitas (A) Internal Rate of Return (IRR); (B) Nilai Bersih Saat ini (NPV); (C) Waktu Balik modal (PBP)
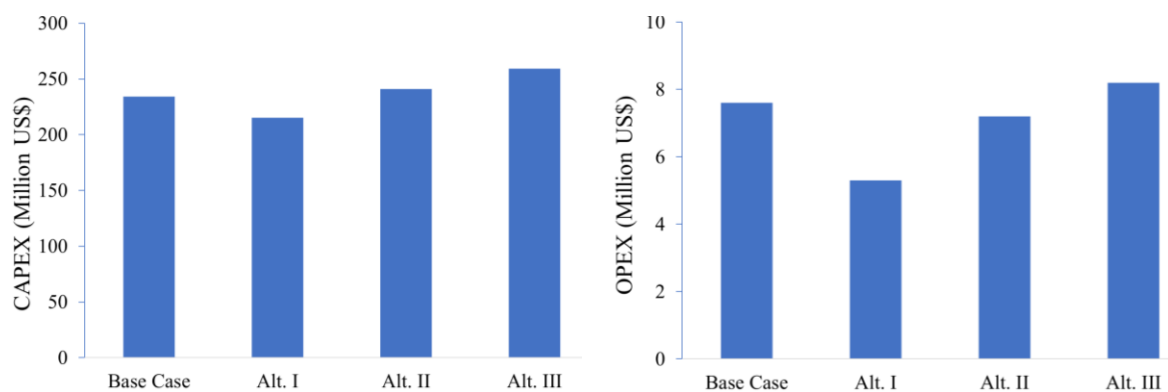
Figure 3. (A) Capital Expenditure (CAPEX); and (B) Operating Expenditure (OPEX) of various Alternatives
Gambar 3. (A) Biaya Modal (CAPEX); dan (B) Biaya Operasi (OPEX) berbagai Alternatif

Table 6. Calculation of economic parameters of various scenarios
Tabel 6. Perhitungan parameter ekonomi berbagai skenario

Economic parameters	Scenarios			
	Skenario			
Parameter ekonomi	Base case	Alternative I	Alternative II	Alternative III
	Kasus dasar	*Alternatif ke-I*	*Alternatif ke-II*	*Alternatif ke-III*
IRR (%)	24.75	4.62	23.87	21.42
ROI (%)	30	9	29	27
NPV (Million US$)	548.9	-48.0	539.2	499.0
PBP (year)	6	15	7	7

The capital investment and operational cost value are relatively more extensive in alternatives II and III than in the base case. Alternative II has a higher value due to the extended operation time for the AAS method (12 h/cycle) that requires enhanced delignification reactor capacity to 5 times greater than the base case to meet the biomass processing capacity of 5 tonnes/h. These conditions resulted in increased capital investment. However, the operational cost of alternatives tends to decrease due to the lower price of ammonium hydroxide used in the delignification process than the base case's sodium hydroxide. In alternative III, the increased capital investment and operational cost value are the largest among other scenarios. The AFEX method requires an ammonia recovery unit with a moderate complex system. These conditions increase capital investment and operational cost by increasing the type and number of devices operating. The same thing also happened to Alternative II. The OPEFB pretreatment using the AFEX method keeps the plant economically feasible.

Based on the results (Figure 3 and Table 6) it can be concluded that pretreatment methods and the overall system used in the base case remain the most efficient system.

Conclusion

Integrated levulinic acid plant design based on oil palm empty bunches (OPEFB) consists of three main stages: pretreatment, hydrolysis, and purification. Based on techno-economic evaluation results, alkaline pretreatment (base case) is the most effective method in the pretreatment stage biomass to produce an integrated levulinic acid plant based on OPEFB. MARR value of 6.1% was used to determine the optimal production capacity of 5 tonnes OPEFB per hour. The integrated levulinic acid plant has total mass efficiency of 75.5%, with the mass conversion of OPEFB to levulinic acid of 29.01%. The yield obtained from acid hydrolysis of cellulose into levulinic acid was 44.7%. The feasibility study of the integrated levulinic acid plant showed economically feasible with levulinic acid production capacity of 12,425 tonnes/year, furfural 15,105 tonnes/ year and formic acid 6,074.5 tonnes/ year. The product price of levulinic acid, furfural and formic acid sold at US$ 8,000/ton, US $ 1,500/ton, and US $ 750/ton would generate IRR, NPV, and payback period calculated 24.75%, US $ 548,850,764, and 6 years.

References

Ahlkvist J (2014) Formic and levulinic acid from cellulose via heterogeneous catalysis, Umeå universitet.

Barlianti V, D Dahnum, H Hendarsyah & H Abimanyu (2015) Effect of alkaline pretreatment on properties of lignocellulosic oil palm waste, Procedia Chemistry, 16, 195-201.

Chin SX, CH Chia, & S Zakaria (2013) Production of reducing sugar from oil palm empty fruit bunch (EFB) cellulose fibres via acid hydrolysis, *BioResources,* 8(1), 447-460.

Climent MJ, A Corma & S Iborra (2014). Conversion of biomass platform molecules into fuel additives and liquid hydrocarbon fuels. *Green Chemistry* 16(2), 516-547.

D'Angelo SC, A Dall'Ara, C Mondelli, J Pérez-Ramírez, & S Papadokonstantakis (2018) Techno-Economic Analysis of a Glycerol Biorefinery, *ACS Sustainable Chemical Engineering*, 6(12), 16563–16572.

Dussan K, B Girisuta, D Haverty, J Leahy & M Hayes (2013) Kinetics of levulinic acid and furfural production from Miscanthus giganteus, Bioresource Technology 149, 216-224.

Gozan M, Abdurrachman, AFP Harahap, AA Rahman, B Prasetya, JRH Panjaitan, MYA Ramadhan, NC Natsha, Rahmayetty, SZ Amraini, M Samsuri, S Setyahadi, Sukirno (2020) Emas Hitam dari tandan Kosong Sawit, UI Press.

Gozan M, JRH Panjaitan, D Tristantini, R Alamsyah & YJ Yoo (2018) Evaluation of separate and simultaneous kinetic parameters for levulinic acid and furfural production from pretreated palm oil empty fruit bunches, *International Journal of Chemical Engineering*, 2018, ID 1920180.

Harahap AFP, AA Rahman, IN Sadrina & M Gozan (2019a) Optimization of Pretreatment Conditions for Microwave-assisted Alkaline Delignification of Empty Fruit Bunch by Response Surface Methodology, *International Journal of Technology*, 10(8). 1479-1487.

Harahap AFP, AA Rahman, IN Sadrina & M Gozan (2019b) Production of formic acid from oil palm empty fruit bunch via dilute acid hydrolysis by response surface methodology, in *IOP Conference Series: Materials Science and Engineering*, 673 (1), 012004.

Hassan N, NAKK Anwar, & A Idris (2020) Strategy to enhance the sugar production using recyclable inorganic salt for pre-treatment of oil palm empty fruit bunch (OPEFB). *BioResources*, 15(3), 4912-4931.

Hayes D (2013) Report on Optimal Use of DIBANET Feedstocks and Technologies.'," EU's Seventh Framework Programme.

Kapanji KK, KF Haigh, & JF Görgens (2021) Techno-economics of lignocellulose biorefineries at South African sugar mills using the biofine process to co-produce levulinic acid, furfural and electricity along with gamma valeractone. *Biomass and Bioenergy*, 146, 106008.

Mayasari F, R Dalimi, WW Purwanto (20Projection of Biodiesel Production in Indonesia to Achieve National Mandatory Blending in 2025 using System Dynamics Modeling, *International Journal of Energy Economics and Policy*, 2019, 9(6), 421-429.

Mohan A, S Dutta, S Balusamy. & V Madav (2021). Liquid fuel from waste tires: novel refining, advanced characterization and utilization in engines with ethyl levulinate as an additive. *RSC Advances*, 11(17), pp.9807-9826.

Mordor I (2022). Levulinic Acid Market - Growth, Trends, Covid-19 Impact, And Forecasts ((2022 - 2027) [Online]. *Mordor Intelligence*, Available: https://www.mordorintelligence.com/industry-reports/levulinic-acid-market.

NREL (2020) Data and Tools [Online]. *National Renewable Energy Laboratory,* Available: https://www.nrel.gov/bioenergy/data-tools.html

Panjaitan JHR, S Monica & M Gozan (2017) Production of furfural from palm oil empty fruit bunches: kinetic model comparison, in *IOP Conference Series: Earth and Environmental Science*, 65(1), 012042.

Panjaitan JRH & M Gozan (2017) Formic acid production from palm oil empty fruit bunches, International *Journal of Applied Engineering Research*, 12(14), 4382-4390.

Purnomo H, B Okarda, A Dermawan, QP Ilham, P Pacheco, F Nurfatriani, & E Suhendang, (2020) Reconciling oil palm economic development and environmental conservation in Indonesia: A value chain dynamic approach. *Forest Policy and Economics*, 111, 102089.

Sadrina, AFP Harahap, A Rahman & M Gozan (2019) Effect of microwave-assisted

sodium hydroxide pretreatment on hemicellulose content of oil palm empty fruit bunch for furfural production, in *IOP Conference Series: Materials Science and Engineering*, 673(1), 012008.

Samsuri M, M Gozan, H Hermansyah, B Prasetya, M Nasikin & T Watanabe (2008) Ethanol production from bagasse with combination of cellulase-cellubiase in simultaneous saccharification and fermentation (SSF) using white-rot fungi pretreatment, *Journal of Chemical and Natural Resources Engineering*, 3, 20-32.

Statista (2020) Production volume of palm oil in Indonesia 2012-2021 [Online] *Statista Research Department*, Mar 8, 2022. Available:

https://www.statista.com/statistics/706786/production-of-palm-oil-in-indonesia/#:~:text=Indonesia%20is%20the%20world's%20top,the%20beginning%20of%20the%20year.

Ya'aini N, NAS Amin & M Asmadi (2012) Optimization of levulinic acid from lignocellulosic biomass using a new hybrid catalyst, *Bioresource Technology*, 116, 58-65.

Zulkiple N, MY Maskat & O Hassan (2016) Pretreatment of Oil Palm Empty Fruit Fiber (OPEFB) with Aquaeous Ammonia for High Production of Sugar. *Procedia chem.* 18, 155-161.