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Techno-Economic Analysis of Biorefinery from Oil Palm Frond Petiole for Bioethanol and Electricity Production in Indonesia

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Abstract

Indonesia faces challenges in increasing the share of renewable energy, while large amounts of oil palm biomass remain underutilized. Oil palm frond (OPF) petiole is an abundant non-food residue with strong potential as a feedstock for bioethanol-based biorefineries. This study aims to evaluate the techno-economic feasibility of OPF petiole utilization by comparing three biorefinery configurations integrated with an existing palm oil mill processing 45 tons of fresh fruit bunches per hour. The assessment was conducted through process modelling, mass and energy balance analysis, and economic evaluation. Scenario 1 utilizes OPF juice to produce first-generation ethanol, and the remaining bagasse is burnt for electricity. In Scenario 2, both OPF juice and saccharified bagasse are converted to first- and second-generation ethanol through Separate Hydrolysis and Fermentation (SHF). Scenario 3 combines alkaline pretreatment and Simultaneous Saccharification and Fermentation (SSF). The residual fiber in all scenarios is used as solid fuel in the cogeneration system. The results show that Scenario 3 provides the highest ethanol yield at 9.65 million L/year. Although this scenario requires more external electricity than the other scenarios, it provides the most profitable pathway with an ROI of 7.91%, IRR of 14.93%, NPV of 24.97 million USD, and POT of 5.58 years. Thus, the SSF conversion of OPF petiole is identified as the most attractive scheme to optimize the palm oil biorefinery system in Indonesia.

Keywords: *techno-economic analysis, oil palm frond petiole, biorefinery, bioethanol, cogeneration system*

Abstrak

Indonesia menghadapi tantangan dalam meningkatkan porsi energi terbarukan, sementara biomassa kelapa sawit yang melimpah belum dimanfaatkan secara optimal. Tangkai pelepah sawit merupakan residu non-pangan yang berpotensi besar sebagai bahan baku biorefinery berbasis bioetanol. Penelitian ini bertujuan untuk mengevaluasi kelayakan tekno-ekonomi pemanfaatan tangkasi pelepah sawit melalui perbandingan tiga konfigurasi biorefinery yang terintegrasi dengan pabrik kelapa sawit berkapasitas 45 ton tandan buah segar per jam. Metode penelitian meliputi pemodelan proses, analisis neraca massa dan energi, serta evaluasi ekonomi. Skenario 1 memanfaatkan nira pelepah sawit untuk produksi etanol generasi pertama, sementara ampasnya dibakar untuk menghasilkan listrik. Pada Skenario 2, nira pelepah sawit dan ampas yang telah disakarifikasi diubah menjadi etanol generasi pertama dan kedua melalui Hidrolisis dan Fermentasi Terpisah (SHF). Skenario 3 mengombinasikan pra-perlakuan alkali dengan proses Sakarifikasi dan Fermentasi Serentak (SSF). Residu serat pada seluruh skenario dimanfaatkan sebagai bahan bakar padat dalam sistem kogenerasi. Hasil penelitian menunjukkan bahwa Skenario 3 menghasilkan etanol tertinggi sebesar 9,65 juta L/tahun. Meskipun memerlukan pasokan listrik eksternal lebih besar dari skenario lainnya, skenario ini merupakan jalur yang paling menguntungkan dengan ROI 7,91%, IRR 14.93%, NPV 24,97 juta dolar AS, dan POT 5,58 tahun. Dengan demikian, konversi tangkai pelepah sawit dengan SSF merupakan skema paling menarik untuk mengoptimalkan sistem biorefinery kelapa sawit di Indonesia.

Kata Kunci: *analisis tekno-ekonomi, tangkai pelepah sawit, biorefinery, bioetanol, sistem kogenerasi*

1. Introduction

Fossil fuels continue to dominate Indonesia’s national energy mix despite the country’s growing energy demand. With 42% coal, 31% oil, 14% natural gas, and just 12.3% new and renewable energy, the primary energy supply reached 246 million TOE in 2022—much less than the required 23% renewable share by 2025 [1]. According to the national energy roadmap [2] and the Long-Term Strategy for Low Carbon and Climate Resilience 2050 [3], Indonesia has likewise pledged to achieve Net Zero Emissions by

2060 or sooner. All energy-consuming sectors must undergo significant changes in order to meet these objectives.

However, current evaluations show sluggish growth. According to the Indonesia Energy Transition Outlook 2024, installed capacity is dominated by coal-fired power plants, with renewable penetration contributing to final energy demand remaining below 10% [4]. Through ESDM Regulation No. 4/2025, which requires the production and blending of biofuels, including bioethanol, the Indonesian government reinforced its regulatory framework in order to expedite the deployment of biofuels [5]. The national biofuel roadmap identifies the development of lignocellulosic feedstock as a major medium-term objective [6], and plans to blend E10 gasoline countrywide have also been affirmed [7].

Indonesia, the world's top producer of crude palm oil (CPO), has an abundance of biomass resources that can be used to produce chemicals and bio-based fuels. With 15.93 million hectares of oil palm plantations, Indonesia produced more than 47 million tons of CPO in 2023 [8], making up about 58% of the world's total [9]. Oil palm frond (OPF), oil palm trunk (OPT), empty fruit bunch (EFB), mesocarp fiber (MF), palm kernel shell (PKS), and palm oil mill effluent (POME) are among the significant biomass residues that this production system produces from both plantation and mill operations. Of these, OPF makes up the most—roughly 52% of the country's palm biomass, or 299 million tons per year [10]. As a practice in the field, OPF is always available because two fronds must be cut down every time a fresh fruit bunch (FFB) is picked. But OPF is still not used very much because it is usually left on the plantation floor to decompose naturally, which doesn't bring in much money. Because of this, its market value and collection cost are among the lowest in the industry, at just USD 19.4 per ton [11].

The leaflet, stem, and petiole parts of OPF all have different biochemical properties. The petiole is especially appealing because it has a lot of fermentable carbohydrates and a fiber structure that enzymes and microbes can easily work with [12][13]. It is more likely to be useful in a biorefinery because it is not food and is available all year. Previous studies have demonstrated the conversion of OPF-derived substrates into bioethanol [13][14], succinic acid [11][15], bio-solvents [16], bioplastic [17], and biobutanol [18]. Fresh petioles can be broken down into juice, which is full of sugars that can be easily fermented, and fiber, which is a second source of carbohydrates after hydrolysis [19][20]. OPF juice ferments well without adding any nutrients [19], but the fiber needs to be pretreated to make it easier for enzymes to get to it. But the energy needed for pretreatment is still a big problem [18]. Making ethanol from OPF can be done using either Separate Hydrolysis and Fermentation (SHF) or Simultaneous Saccharification and Fermentation (SSF). SSF usually makes more ethanol because it stops the product from stopping yeast from using glucose right away [14]. This has made people more interested in using SSF to process fresh OPF petiole directly, which makes things easier and less harsh.

There have been many experimental studies, but techno-economic assessments are still not very common. The most important study looked at an integrated biorefinery that made first- and second-generation ethanol from OPF using an SHF framework [13]. Nevertheless, comparative analyses of alternative pathways—such as whole petiole SSF versus the combined utilization of juice and fiber—have yet to be conducted. This knowledge gap is very important because differences in how juice is extracted, how much it is pretreated, how it is hydrolyzed, and how energy is integrated can all have a big effect on how much bioethanol is made and whether or not it is worth the money.

To fill this gap, the current study looks at three biorefinery setups that turn OPF petiole into bioethanol and electricity in a palm oil mill (POM): (1) OPF juice for first-generation ethanol; (2) OPF juice for first-generation ethanol mixed with SHF-based second-generation ethanol from OPF fiber; and (3) direct SSF of whole fresh OPF petioles. In every case, the fiber leftovers are used to make steam and electricity, along with MF and PKS from the POM. This study determines the optimal strategy for valorizing OPF petiole as a sustainable feedstock to facilitate Indonesia's renewable energy transition through a comparative analysis of production performance, energy balance, and economic viability.

2. Materials and Method

Design Basis

This study evaluated the techno-economic viability of an integrated biorefinery utilizing OPF petiole as feedstock for the concurrent production of bioethanol and electricity. The biorefinery is meant to work with an existing POM in Indonesia that can handle 45 tons of FFB per hour. This study presumes that the mean weight of a single FFB is 25 kg [13] and that the mean weight of a single OPF petiole is 2.5 kg [12]. For every FFB that is picked, it is thought that two OPF petioles are cut off. Researchers who look at biorefineries that use OPF often use this ratio as an upper-bound estimate. The evaluation takes place every year, based on 330 operational days each year. The mill can use more steam and electricity from its cogeneration system by connecting to the POM. This makes the whole process more efficient and cuts down on the need for outside utilities.

Process Flowsheet

The simplified flowsheet in this study only shows the most important steps. It is a block diagram. After that, design specifications for each scenario are gathered using information from the literature. Some of the things that go into these specifications are temperature, pressure, chemical reactions, types of materials, and any other information needed to make a process happen. Next, a mass balance analysis is done to figure out the material flow rates for each process by figuring out how many tons of material come in and go out each year (t/y). **Figure 1** shows what each situation includes as well as the scope of this study.

Energy Performance Analysis

The Net Energy Ratio (NER), which is defined in Equation (1), is the main thing that is used to compare each scenario in the analysis of energy performance. The total amount of energy used in the biorefinery process is called the energy input. The total amount of energy that can be made from biorefinery products, like bioethanol and electricity, is called energy output.

$$NER = \frac{Energy\ Output}{Energy\ Input} \tag{1}$$

If the NER is greater than one, it means that the situation can happen with energy, which means that the energy return is likely to be good. Higher NER values may also mean that energy is used more efficiently, which can lead to lower emissions depending on where the energy comes from. Bioethanol has a lower heating value (LHV) of 21.20 MJ/L [21], while OPF fiber has a lower heating value (LHV) of 15.72 MJ/kg [22].

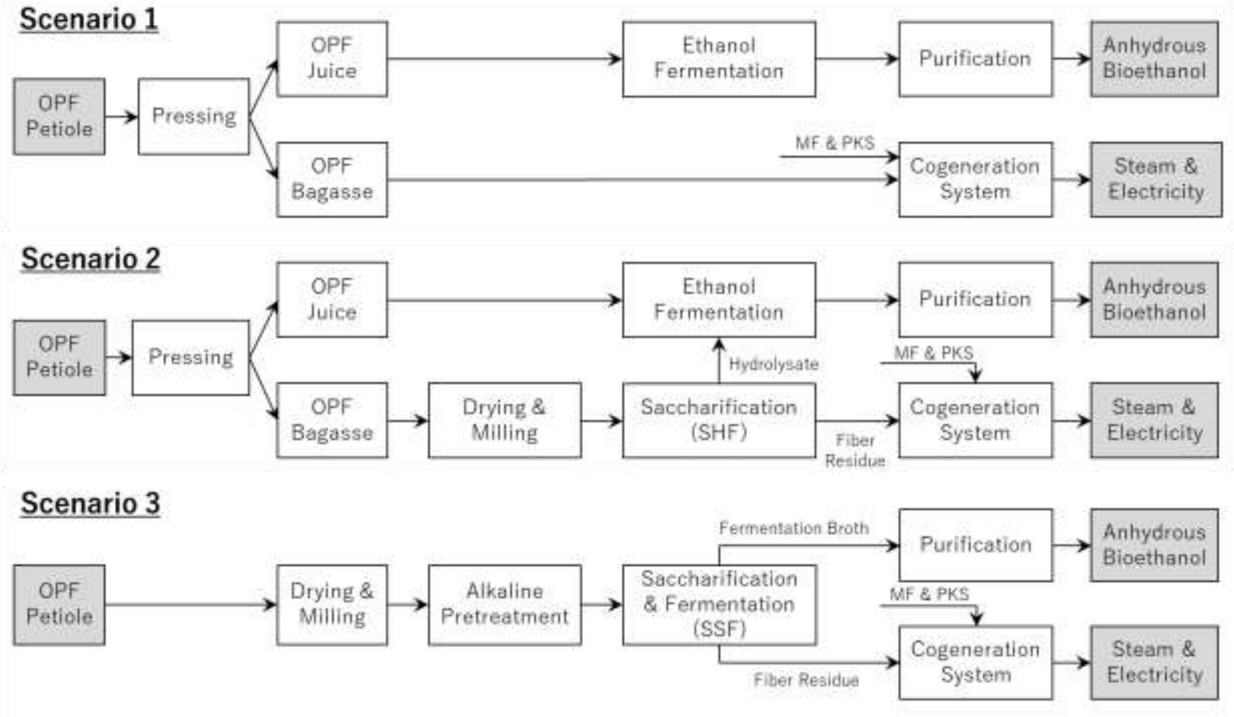

Fig. 1: Research Scope

Economic Evaluation

The economic evaluation looks at the Total Capital Investment (TCI), the costs of running the project, the income it will bring in, and whether it is possible to pay for it. The main parameters that were used are shown in **Table 1**. The TCI is calculated using the Purchased Equipment Cost (PEC). The PEC is based on the Chemical Engineering Plant Cost Index (CEPCI) and the base cost of the equipment. We get the base cost data from quotes from suppliers and a report by Abdullah et al. [13]. The financial feasibility analysis includes the return on investment (ROI), the pay-out time (POT), the net present value (NPV), and the internal rate of return (IRR).

Table 1. Parameters used in economic performance analysis

Parameter	Value	Unit	Reference
Base Year	2025	-	Assumption
Plant lifetime	20	years	Assumption
Depreciation (linear)	10	years	Assumption
Discount rate	5	%	[23]
Enzyme price	0.13	USD/L	[24]
Anhydrous ethanol price	1	USD/L	[25]
Feed-in-tariff	9.24	cent USD/kWh	[26]

3. Results and Discussions

The biorefinery that was looked at in this study processes 71,280 tons of fresh OPF petioles per year. This is the same amount of mass that a POM with a capacity of 45 tons of FFB can make in a year. According to the mass balance reported by Zahari et al. [19], about half of the OPF petiole can be turned into juice, which makes 35,640 tons of OPF juice and the same amount of OPF bagasse. The bagasse fraction is made up of 21,384 t/y of dry fiber and 14,256 t/y of moisture, which is based on the fact that fresh petioles have a moisture content of 70% [19]. These numbers are used to analyze the flow of the process for three different biorefinery setups.

Process Flow Diagram for Scenario 1: First-Generation Ethanol from OPF Juice

In Scenario 1, OPF juice is turned into bioethanol, and the rest of the OPF bagasse is burned to make steam and electricity, as shown in **Figure 2**. About 35,640 t/y of juice and 35,640 t/y of bagasse are made from the 71,280 t/y of fresh OPF petiole that is fed each year. After being pressed, the juice is filtered and concentrated to 50% before being fermented with *Saccharomyces cerevisiae* at 32 °C. According to Zahari et al. [20], ethanol fermentation yields 0.49 g/g of consumed sugar with urea supplementation. Abdullah et al. [27] also found that approximately 86.39% of total sugars are consumed.

Centrifugation, distillation, rectification, and molecular sieve dehydration are used to clean up the fermented broth. The final product is 99.60% anhydrous ethanol, which is what Dias et al. [28] said it would be. The mill's cogeneration boiler burns and dries OPF bagasse, MF, and PKS at the same time. The boiler is 80% efficient, and the turbine is 77% efficient [29]. They make electricity and high-pressure steam for both the biorefinery and the POM. The grid gets any extra power. This pathway is simple to follow and does not use a lot of energy, especially since it does not need any steps for pretreatment or enzymatic saccharification.

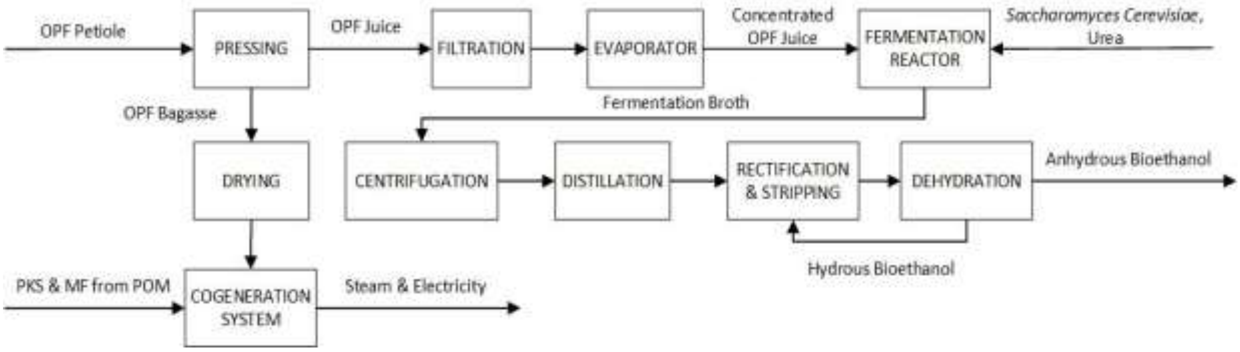

Fig. 2: Flowchart of Scenario 1

Process Flow Diagram for Scenario 2: First-Generation and Second-Generation Ethanol (SHF Process)

The SHF process is used to mix first-generation ethanol from OPF juice and second-generation ethanol from OPF bagasse in Scenario 2, as shown in **Figure 3**. In this case, bagasse is not burned directly. Instead, it is dried and ground up to break up its fibers. During saccharification, cellulose and hemicellulose are broken down into sugars at 50 °C for 48 hours. This is done with 20 Filter Paper Units (FPU) per gram of substrate, which can turn up to 60% of the sugar conversion. [14][20].

The hydrolysate is concentrated and combined with OPF juice before entering the fermentation reactor. Following ethanol separation and dehydration, the remaining fiber residue from saccharification is directed to the cogeneration system. Although this pathway yields significantly more ethanol than Scenario 1, it requires considerably higher energy input for pretreatment and enzymatic hydrolysis, aligning with previous studies reporting that OPF pretreatment and enzyme production are the dominant energy hotspots in lignocellulosic bioethanol systems [30][31]. Despite this, Scenario 2 benefits from internal electricity production and produces a substantial amount of fermentable sugars compared to Scenario 1.

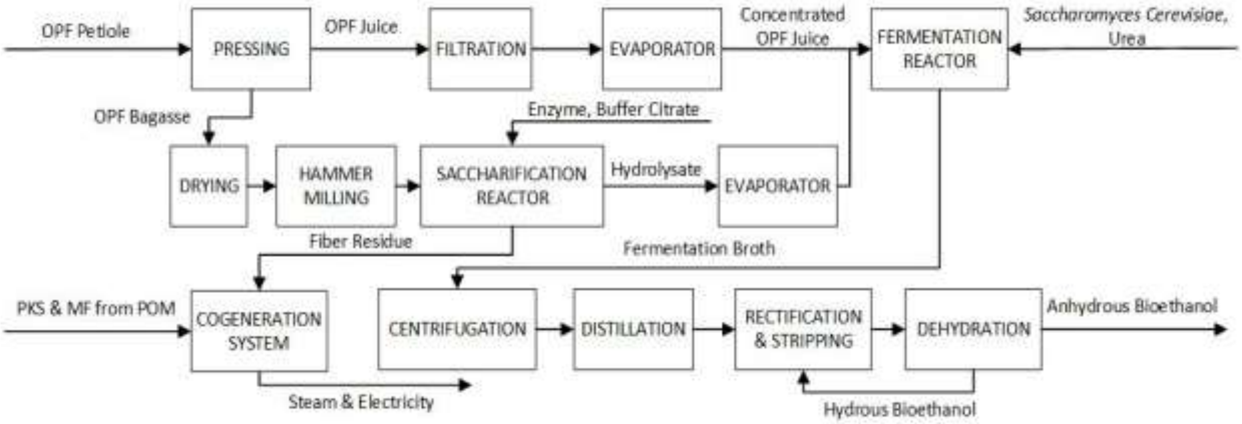

Fig. 3: First-Generation and Second-Generation Ethanol (SHF Process) Flowchart

Process Flow Diagram for Scenario 3: Whole-OPF Petiole Conversion via SSF

Figure 4 shows that Scenario 3 uses a whole-biomass conversion method that uses fresh OPF petiole without extracting juice. The petioles are chopped up, dried, ground up, and then soaked in a 10% NaOH alkaline solution at 150 °C for half an hour. This step breaks up the lignocellulosic structure, making it easier for enzymes to get to it. This is what Triwahyuni et al. [14] and Abubakar et al. [18] found.

After washing to a neutral pH, the pretreated slurry (15% w/v) goes into an SSF reactor with 30 FPU/g substrate of enzymes and 1% yeast. Triwahyuni et al. [14] showed that SSF lowers end-product inhibition and can produce up to 95.95% ethanol after 96 hours. This high conversion rate is why Scenario 3 produces the most ethanol of the three scenarios. The remaining solids go to the cogeneration system, but there are a lot fewer of them than in Scenarios 1 and 2, so not enough electricity is generated inside. Because of this, the scenario needs electricity from outside, which is a common problem with high-yield lignocellulosic SSF systems [32]. The grid provides this electricity deficit, which is included in the cost of running the business.

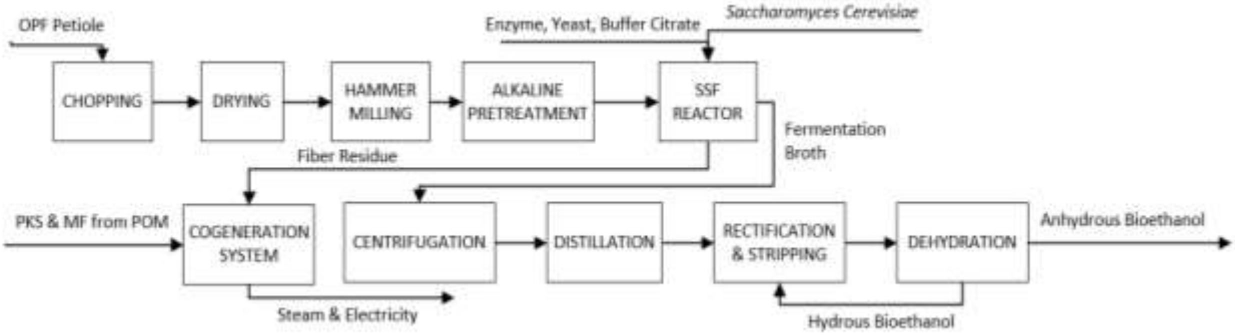

Fig. 4: Whole-OPF Petiole Conversion via SSF

Comparison

To enable a systematic comparison of the three biorefinery configurations, the overall performance of each scenario was evaluated based on key technical, energy, and economic indicators. **Table 2** summarizes the calculation results for all scenarios, including bioethanol production capacity, energy balance, capital and operating costs, as well as economic returns. These parameters were selected to capture the trade-offs between product yield, energy efficiency, and financial feasibility arising from differences in process integration, conversion pathways, and energy utilization strategies. The comparative results presented in **Table 2** provide a quantitative basis for assessing the advantages and limitations of each scenario, and serve as a foundation for the subsequent discussion on bioethanol production performance, cogeneration behavior, energy efficiency, and economic viability of OPF petiole-based biorefineries in Indonesia.

Bioethanol Production

The mass balance analysis shows that Scenario 3 produces the most ethanol, at 9.65 million L/y, followed by Scenario 2, at 6.52 million L/y, and Scenario 1, at only 1.22 million L/y. This order makes sense with the biochemical processes that are going on: Scenario 1 only uses juice fermentation, Scenario 2 adds hydrolyzed fiber sugars, and Scenario 3 gets the most out of the whole petiole biomass with high SSF efficiency. As expected, Scenario 3 needs the most enzyme (1,095 t/y), buffer, and NaOH. This is because it is the most intensive stage of pretreatment. Also, Scenario 1 needs the least amount of material because it doesn't involve any chemical pretreatment or saccharification.

Table 2. Results of the calculation for all scenarios

Parameter	Unit	Scenario 1	Scenario 2	Scenario 3
Bioethanol production	ML/y	1.22	6.52	9.65
Excess electricity	TJ/y	50.11	20.41	-27.22
Energy input	TJ/y	29.67	140.10	181.42
Energy output	TJ/y	193.50	224.35	241.00
NER	-	6.52	1.60	1.33
TCI	MUSD	12.34	38.08	41.21
Operating cost	MUSD/y	2.00	4.66	6.18
Sales	MUSD/y	2.61	7.09	9.65
Profit	MUSD/y	0.46	1.82	2.61
ROI	%	4.66	5.97	7.91
IRR	%	10.20	12.21	14.93
NPV	million USD	3.48	15.71	24.97
POT	years	6.82	6.26	5.58

Cogeneration System Performance

Scenario 1 has the most biomass energy potential because all of the OPF bagasse can be used as fuel, as shown in **Table 2**. Scenarios 2 and 3 make less biomass waste because of saccharification and SSF conversion, which means less steam is made. All of the scenarios meet their steam needs and make more steam than they need. Yet only Scenarios 1 and 2 make extra electricity, while Scenario 3 has a shortfall of 27.22 TJ/y. This result is in line with the strong trade-off seen in lignocellulosic biorefineries, where high conversion efficiency often means less solid fuel is available [32].

Energy Efficiency Analysis

All of the scenarios have NER values greater than 1, which means that the energy performance is good. Scenario 1 has the highest NER (6.52) because it uses little energy and produces a lot of electricity. Scenario 3 has the lowest NER of all the possible scenarios. This is because alkaline pretreatment and SSF use a lot of energy, which is in line with the study that shows that pretreatment is the most energy-intensive stage in lignocellulosic conversion [30]. Even so, Scenario 3 still has a NER above 1 because it makes a lot of ethanol.

Economic Evaluation

The economic indicators show that the two scenarios are very different from each other. Scenario 1 has the lowest TCI and operating cost because its process setup is simpler. Scenario 3 has the highest capital and operating costs. This is mostly because of the need for pretreatment infrastructure, a lot of enzymes, and electricity from outside sources. Scenario 3, on the other hand, has the highest annual sales and profits because it makes the most ethanol.

Figure 5 shows that Scenario 3 is the best choice based on financial feasibility metrics like ROI, POT, NPV, and IRR. This result is in line with what other techno-economic studies have found: high-yield SSF systems often work better than lower-yield SHF or juice-only systems, even though they cost more [32]. Scenario 1 is safe for the economy and uses less energy, but it doesn't make enough ethanol to be as profitable as Scenario 3. So, Scenario 3—whole-petiole conversion via SSF—looks like the best biorefinery setup for OPF petiole. It has a high ethanol yield and good economic performance, even though it needs more energy and electricity from outside sources.

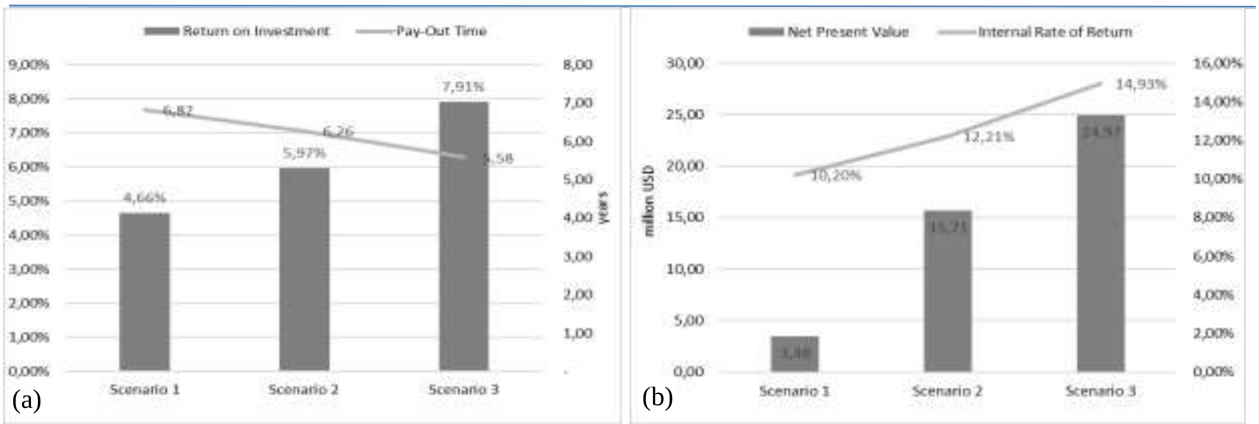

Fig. 5: Results of (a) ROI and POT and (b) cash flow analysis

4. Conclusion

OPF is the most abundant biomass from CPO production activities and has a high potential for biorefinery feedstock. This comparative study focuses on bioethanol production, energy performance, and economic evaluation for three biorefinery scenarios from OPF petiole in Indonesia. The results indicate that Scenario 3 is the most recommended plan for optimizing OPF utilization due to having more advantages from the highest bioethanol production and financial feasibility, also being energetically efficient. It means that the SSF process is a better scenario than the SHF process for large-scale bioethanol production, even more than first-generation ethanol production from OPF juice and electricity generation from OPF bagasse. Therefore, optimizing OPF petiole for bioethanol production by the SSF process is the most strategic way to support the Indonesian government's renewable energy target. For future studies, there are two recommendations. First, a life cycle assessment for evaluating the environmental performance of each scenario. Second, sensitivity analysis to know the effect of some variables, such as ethanol and electricity prices, on the economic feasibility indicators.

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