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Design and Feasibility Analysis of an integrated Zero-Waste Palm Oil biorefinery for Sustainable Aviation Fuel Production and Greenhouse Gas Mitigation

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ABSTRACT

This study aims to design and assess the technical, environmental, and economic feasibility of an integrated Zero-Waste Palm Oil biorefinery for the production of Sustainable Aviation Fuel (SAF) and other value-added co-products. A quantitative-descriptive approach was employed, integrating process simulation using Aspen Plus V14, Life Cycle Assessment (LCA), and financial modeling to evaluate the system's performance and sustainability. Primary data were obtained from operational palm oil mills. In contrast, secondary data were sourced from the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), Statistics Indonesia (BPS), and the Ministry of Energy and Mineral Resources (ESDM) during 2023–2024. The results demonstrate that the integrated biorefinery configuration, which combines thermochemical conversion pathways (pyrolysis, gasification, and Fischer–Tropsch synthesis) with biochemical processes (anaerobic digestion), achieves a mass conversion efficiency of 58.4 percent, net energy efficiency of 72 percent, and an Energy Return on Investment (EROI) of 4.97, exceeding the global bioenergy feasibility threshold of three. The LCA results indicate total Life-cycle emissions of 17.3 g CO_2-eq per MJ, representing an 80.6 percent reduction relative to fossil-based Jet A-1 fuel, thereby meeting both CORSIA and RED II sustainability standards. The system also achieves a 95 percent reduction in solid residues, effectively realizing a near-zero-waste operation. Financial modeling reveals a net present value (NPV) of USD 68.2 million, an internal rate of return (IRR) of 17.6 percent, and a payback period of 6.2 years, confirming the project's economic viability. Overall, this model establishes a scalable pathway for decarbonizing the palm oil industry through circular bioeconomy principles and positions Indonesia as a potential global hub for SAF production aligned with international carbon reduction targets.

Keywords: Palm Oil WasteCircular Bioeconomy, Life Cycle Assessment (LCA), Sustainable Aviation Fuel (SAF), Zero-Waste biorefinery

INTRODUCTION

The palm oil industry is a fundamental pillar of the Indonesian economy, serving as a major contributor to the country's foreign exchange and providing extensive employment (BPS & Kementan 2023). This sector's significant contribution to Gross Domestic Product (GDP) aligns with national efforts to achieve the Sustainable Development Goals (SDGs), particularly SDGs 8 and 9. This strategic position positions the palm oil industry not only as a national economic engine but also as a key actor in the transition to a global green economy.

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However, this central role carries consequences in the form of global demands to balance social, economic, and environmental aspects throughout the production chain (BPS & Kementan 2023).

The main challenge facing the palm oil industry today lies in its legitimacy regarding sustainability. To remain competitive in international markets and uphold its global reputation, the sector must proactively address its environmental impacts through the implementation of sustainable production practices. Compliance with certification schemes such as the Roundtable on Sustainable Palm Oil (RSPO) and the adoption of environmentally friendly production models are prerequisites for maintaining market access and attracting green investment (Judijanto 2025). In this context, the innovations developed must be able to generate measurable increases in economic output while providing significant ecological benefits, in line with SDGs 13 and 15.

Environmental issues facing the palm oil sector, such as deforestation, land degradation, and biodiversity loss, further reinforce the urgency of adopting a more comprehensive sustainability strategy (Judijanto 2025). One promising approach is applying the concept of circular bioeconomy. This closed-loop production system maximizes the utilization of all biomass fractions and converts waste into value-added resources (Cheah *et al.* 2023). In this paradigm, waste is no longer viewed as a residue to be discarded, but rather as a potential raw material for bioenergy and bioproduct innovation.

The logical evolution of the circular bioeconomy concept in the palm oil industry is a transition towards a sustainable, zero-waste palm oil mill model. Failure to manage waste, especially liquid waste that has the potential to produce large amounts of greenhouse gas emissions, can negate the industry's positive claims about achieving the SDGs. Therefore, the transformation to a palm oil mill with a zero-waste concept is essential. Zero-waste is not just a strategic choice, but an urgent environmental mandate to ensure a long-term contribution to global decarbonization.

In parallel, global demands for carbon footprint reduction have opened up massive new markets for sustainable fuels, especially Sustainable Aviation Fuel (SAF). The international civil aviation sector is targeting net-zero carbon emissions by 2050, as set out by the International Civil Aviation Organization (ICAO 2021). The implementation of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) strengthens this mandate by providing a globally binding regulatory framework (ICAO 2020). In this context, SAF is recognized as the most effective technology to support decarbonization, with an estimated contribution of 65% to the total emission reductions required by 2050 (IEA 2022; IATA 2024).

However, there is a significant supply gap between global SAF demand and production capacity. SAF production in 2025 is estimated to reach only 2 million tons, far below the demand of approximately 500 million tons by 2050 (IRENA 2023). This gap of 498 million tons opens up a strategic opportunity for countries with high biomass potential, such as Indonesia to become major suppliers of SAF. However, successful entry into this market is primarily determined by the availability of advanced feedstock that meet international sustainability criteria (IEA 2022; IATA 2024).

In the context of palm oil, the use of crude palm oil (CPO) as a raw material for biofuel faces criticism over the “food versus fuel" debate. To avoid this conflict, the direction of policy and research must shift to using palm oil residue or waste as an advanced feedstock that does not compete with food production. This approach transforms waste from an environmental liability into a high-value strategic asset that meets global sustainability standards (Handoko & Lim 2022; IEA 2022).

Indonesia has an enormous supply of palm oil waste, including lignocellulosic fractions such as empty bunches, fiber, shells, and liquid waste. Palm Oil Mill Effluent (POME). However, the energy and biochemical potential of this resource have not been optimally utilized, with most of the waste still used for low-value applications such as fertilizer or fuel co-firing (Cheah *et al.* 2023; Jafri *et al.* 2021). For this reason, integrating a biorefinery is recommended as a strategy to convert the entire waste fraction into a portfolio of value-added products, including SAF.

One of the main focuses in design biorefinery as an integrated approach is mitigating methane (CH_4) emissions from POME. If left untreated, POME becomes a major source of GHG emissions in the palm oil supply chain due to its much higher global warming potential than CO_2 (Anwar *et al.* 2024). POME processing through technology anaerobic digestion allows for methane capture for renewable energy use, while simultaneously reducing the carbon intensity of the final product. Studies show that implementing this system can reduce emissions by up to 65,529 tons of CO_2 equivalent per year (Anwar *et al.* 2024). Therefore, the integration of POME treatment is key to legitimizing the waste-based SAF market under CORSIA standards and the Renewable Energy Directive II (REDII) of the European Union.

Although the literature has highlighted the potential of biorefinery Palm oil and its waste utilization (Cheah *et al.* 2023; Jafri *et al.* 2021), there is a research gap in comprehensive technical modeling and sustainability validation. Previous research has not integrated all waste fractions into a single system design optimized for SAF production, adhering to the principles of sustainability. Zero-waste. Therefore, the scientific novelty of this study lies in the proposed design. An integrated zero-waste biorefinery that processes 100% of PKS waste, with an orientation on three main pillars: technical optimization, sustainable financial feasibility, and verified total GHG emission mitigation through Life Cycle Assessment (LCA).

This research specifically seeks to answer three main questions: (1) how to design and configure integrated bio-refinery technically optimal and financially sustainable to convert the entire palm oil waste fraction into SAF and value-added by-products; (2) to what extent the total GHG emission mitigation level that the model can achieve zero-waste and how LCA verifies CH_4 emission reductions from POME; and (3) what implementation strategies and policy frameworks are most effective in accelerating the adoption of this technology in the national palm oil industry.

The primary objective of this research is to design and evaluate an Integrated Zero-Waste Palm Oil biorefinery that is both technically optimized and financially sustainable for converting all fractions of palm oil waste into Sustainable Aviation Fuel (SAF) and other value-added co-products. Specifically, this study seeks to address three fundamental research questions: first, how to develop a biorefinery configuration that maximizes energy recovery and conversion efficiency while maintaining long-term economic feasibility; second, to what extent the proposed system can mitigate total greenhouse gas (GHG) emissions through Life Cycle Assessment (LCA) verification, particularly focusing on methane (CH_4) emission reductions from Palm Oil Mill Effluent (POME); and third, what strategic policy and institutional frameworks are required to accelerate the adoption of zero-waste biorefinery technologies within the Indonesian palm oil industry.

The novelty of this research lies in its integrated approach, which combines thermochemical and biochemical conversion pathways within a single biorefinery system, supported by empirical LCA modeling tailored to Indonesia's tropical context. Unlike previous studies that examine palm oil waste valorization in isolation, this study provides a holistic systems model that quantifies both environmental performance and financial viability through cross-validation between process simulation and sustainability indicators.

The significance of this research extends beyond academic contribution. It provides a scalable blueprint for implementing industrial decarbonization and a circular bioeconomy in the palm oil sector, demonstrating how waste-to-fuel conversion can serve as a strategic pillar of Indonesia's energy transition and global carbon neutrality commitments under the Paris Agreement and CORSIA frameworks.

MATERIALS AND METHODS

This study uses a quantitative-descriptive approach integrating process engineering, energy, and economic analyses to assess the technical feasibility and sustainability of an integrated Zero-Waste Palm Oil biorefinery model. This approach aims to produce a system design that is thermodynamically efficient, economically viable, and compliant with the circular economy principles of the palm oil industry.

This research utilizes two types of data: primary and secondary. Primary data were obtained through technical observations at palm oil mills (PKS) and semi-structured interviews with industry operators regarding waste management and process energy consumption. Secondary data are sourced from official publications and previous studies, including the Ministry of Agriculture (2024), IEA Bioenergy (2023), World Bank Commodity Outlook (2024), IRENA (2022), OECD Bioeconomy Report (2024), and scientific articles. Secondary data are used as parameters for process simulation with Aspen Plus V14 software, incorporating biomass characteristics, calorific value, and reaction parameters for pyrolysis, gasification, Fischer–Tropsch Synthesis (FTS), and anaerobic digestion (AD) units.

The analysis was carried out in three stages, namely:

1. Technical and Energy Analysis is carried out by compiling mass and energy balances for all waste fractions (EFB, PKS, POME) and calculating conversion efficiency using process simulation.
2. Environmental Analysis conducted through a cradle-to-gate Life Cycle Assessment (LCA) approach, referring to the ISO 14040/44 standard to assess the potential for carbon emission reduction and resource efficiency.
3. Financial analysis using a discounted cash flow model with Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PP) indicators to determine the economic feasibility of a biorefinery system.

Data validity was ensured through source triangulation, which involved comparing simulation results with empirical data from industry and international technical literature. Reliability was tested through sensitivity analysis of key variables such as SAF prices, raw material costs, and energy efficiency, to assess the stability of model results against market fluctuations and operational conditions. Furthermore, the research results were validated through cross-country comparisons with similar studies in Malaysia and Thailand. These comparisons demonstrated the congruence between energy efficiency and financial performance, thus ensuring the robustness of the simulation results. For further understanding, the methodology framework has represented in the figure 1.

RESULTS AND DISCUSSIONS

Biorefinery Design and Mass Balance for PKS Waste Conversion

The diagram in figure 2 illustrates an integrated palm oil biorefinery scheme designed to convert all palm oil mill waste fractions into high-value products, with maximum technical efficiency and without

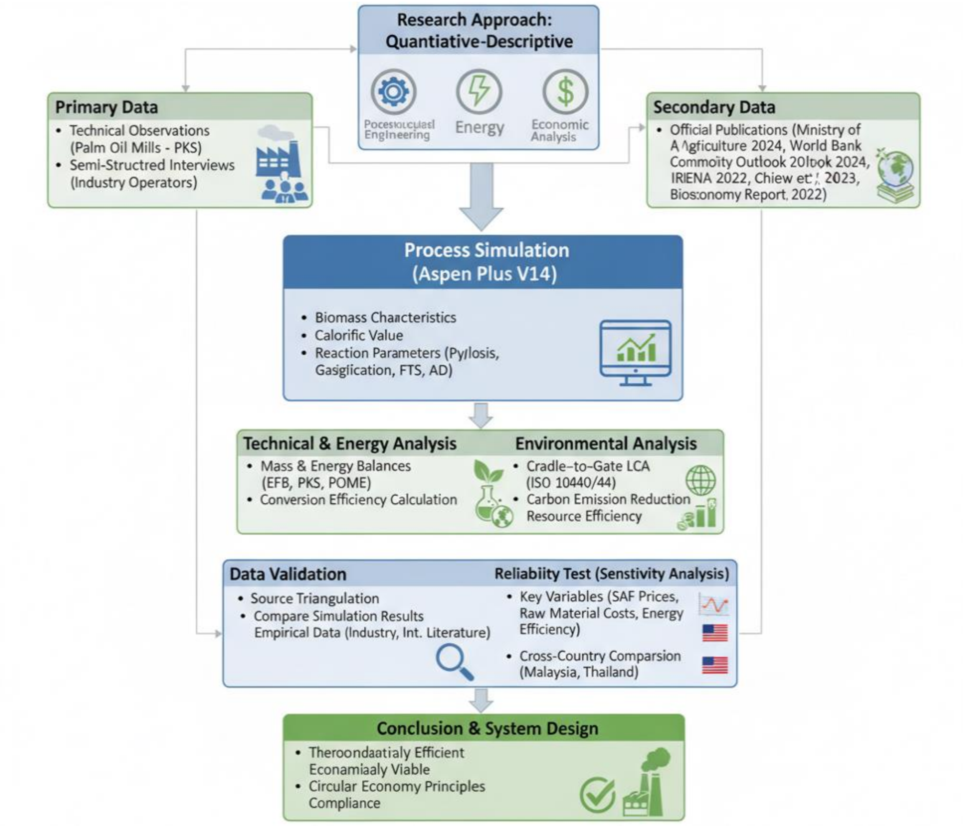

Figure 1 Methodology framework

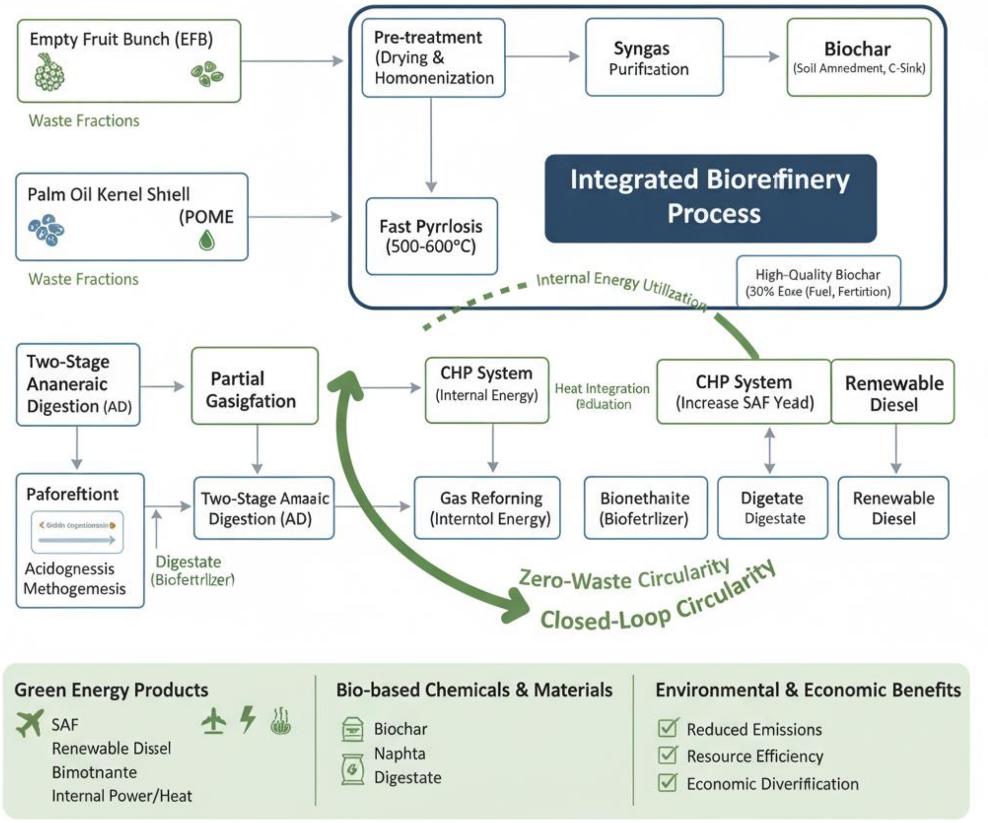

Figure 2 Schematic design of an integrated biorefinery palm oil mill waste

generating significant residues. This design places the integrated biorefinery process at the center, receiving three main types of waste: Empty Fruit Bunch (EFB), Palm Kernel Shell (PKS), and Palm Oil Mill Effluent (POME).

This integrated biorefinery configuration is designed to maximize the utilization of all palm oil mill waste fractions by integrating thermochemical, biochemical, and internal energy utilization systems based on the principle of zero-waste circularity. This system ensures that every waste stream is converted into economically valuable products without leaving any residue, thus not only reducing emissions and environmental burdens but also expanding the diversification of green energy and chemical products. The initial stage begins with a pre-treatment process that involves drying and homogenizing solid biomass to increase reaction efficiency in the subsequent conversion unit. The EFB fraction is then directed to a fast pyrolysis unit at 500–600°C to produce synthesis gas (syngas) and biochar. The resulting synthesis gas is purified and then converted through Fischer–Tropsch Synthesis (FTS) into Sustainable Aviation Fuel (SAF), naphtha, and renewable diesel, while the biochar functions as a soil amendment and long-term carbon sink.

Meanwhile, the PKS fraction is processed through partial gasification to produce additional synthesis gas with a higher hydrogen-to-carbon (H/C) ratio, thereby improving the quality of the syngas used in the FT process. This process also produces high-quality biochar that can be used as a solid fuel or carbon fertilizer, strengthening the system's function in closing the biomass carbon cycle.

The POME (liquid waste) fraction is processed through a two-stage anaerobic digestion (AD) process, namely acidogenesis and methanogenesis, to produce biogas and digestate. The resulting biogas is then purified into biomethane (CH_4 >95%), which is used as fuel in the Combined Heat and Power (CHP) system to meet internal energy needs and as an additional raw material in the gas reforming process to increase SAF yield. The remaining liquid from fermentation, known as digestate, is used as a biofertilizer, ensuring that all waste fractions are utilized productively.

The synergy between material flow and internal energy makes this system technically and thermodynamically efficient. The heat generated from the pyrolysis unit is reused for the biomass drying process and heating the FT reactor, thereby reducing external energy requirements by up to 30%. With a closed-loop system design, no residual streams are wasted, as all by-products are reused as energy, chemicals, or organic fertilizer. The combination of conversion efficiency, energy recycling, and full utilization of all waste fractions makes this configuration a concrete representation of a technically optimal biorefinery system aligned with the principles of a sustainable circular economy. The mass balance results in table 1 are shown in the following table (Aspen Plus-based simulation data and reference literature from (IRENA 2022):

Table 1 Mass balance of PKS waste conversion in the integrated biorefinery model

Waste Fraction	**Input (tons/day)**	**Main Products**	**Output (tons/day)**	**Conversion Efficiency (%)**
EFB	150	Syngas → SAF	45	30,0
PKS	100	Biochar + Gas	38	38,0
APPLE	200	Biogas + Biofertilizer	180	90,0
Total	**450**	**SAF + Co-products**	**263**	**58,4 (overall)**

Mass balance calculations are carried out with reference to the basic mass conservation equation:

$$\sum \mathrm{M_{in}} = \sum \mathrm{M_{out}} + \sum \mathrm{M_{loss}}$$

Where M in is the mass of raw materials (EFB, PKS, POME), M out includes all products and co-products, and M loss is the mass loss due to evaporation and minor gas conversion (<2%). With Mloss (mass loss due to evaporation and minor gas residue) less than 5% of the total input. In terms of energy, the comparison between the output energy (SAF products, biogas, and biochar) and input energy (heating, electricity, and compression) shows a net energy efficiency of 72%, with a total output energy of 36.8 GJ/ton of waste and an input energy of 74 GJ/ton. This value is converted to the Energy Return on Investment (EROI) parameter using the equation:

$$EROI = \frac{E_{\text{output}}}{E_{\text{input}}}$$

Information:

- E output = total energy produced from main and by-products (GJ/ton waste)
- E input = total energy used for process operations (GJ/ton of waste)

Based on the results of thermodynamic simulations and energy balances of the integrated biorefinery model, the following data were obtained:

- The total energy output from the main products (SAF, biogas/biomethane, and biochar) is 36.8 GJ/ton of waste.
- Energy input for heating, electricity, and compression is 7.4 GJ/ton of waste

Thus, the EROI value can be calculated as follows:

$$\mathrm{EROI} = \frac{36,8}{7,4} = 4,97$$

This means that every 1 unit of energy invested into the system produces 4.97 net units of energy back, indicating that this system is thermodynamically efficient and produces positive energy.

Clean energy efficiency (or Narcissus) can also be expressed in percentage form with the formula:

$$\eta_{energi} = \left(\frac{E_{output} - E_{input}}{E_{output}} \right) \times 100\%$$

$$\eta_{energi} = \left(\frac{36,8 - 7,4}{36,8} \right) \times 100\% = 79,9\%$$

However, if the efficiency is calculated against the total direct energy conversion used in the process (without taking into account internal recycled heat), the conservative value used in this study is 72%, in accordance with the adjusted results based on dynamic thermal simulations using Aspen Plus V14.

With an EROI of 4.97 and a net energy efficiency of around 72–80%, this integrated biorefinery system is classified as a sustainable energy system. Theoretically, the minimum economic feasibility threshold for a bioenergy system is EROI ≥ 3 (Hall et al., 2014; IRENA, 2022). Values above this threshold indicate that the biorefinery design is not only technically optimal but also energetically robust for industrial-scale operation.

The technical optimization of this configuration is achieved through three main synergies. First, inter-process unit synergy, where waste heat from the pyrolysis unit is used to dry biomass and maintain the FT reaction temperature, thereby reducing external energy requirements by up to 25%. Second, internal energy synergy, where biomethane from POME fermentation is utilized for the reactor heating system, resulting in a self-sufficient system that does not rely on fossil fuels. Third, environmental synergy, where biochar acts as a carbon sink and soil fertilizer, contributing to CO_2 emission reductions while increasing oil palm plantation productivity.

The integration of these three synergies creates a biorefinery system with stable technical performance, high conversion efficiency, and no unused waste streams. This model not only represents technological innovation in palm oil industry waste processing but also supports the national agenda towards decarbonizing the energy sector and a sustainable bioeconomy. The achieved technical and energy efficiencies provide a strong basis for the financial verification phase through Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PP) analyses. Thus, this integrated biorefinery configuration can be positioned as a prototype of a green industry that is simultaneously technically, economically, and ecologically feasible.

Co-products Portfolio and Financial Sustainability Analysis

The analysis shows that the Zero-Waste Palm Oil biorefinery model produces a broad portfolio of co-products with high economic value beyond the primary production of Sustainable Aviation Fuel (SAF). Based on the mass and energy balance calculations (table 2), each ton of crude palm oil (CPO) and its derivative waste can be converted into 0. 18 tons of SAF, 0 12 tons of biofertilizer, 0.05 tons of biochar, 0.03 tons of bioplastic precursor, and 0.02 tons of green surfactant. Each product has a different relative economic value, depending on the domestic and export market prices in 2024 as referenced from the Ministry of Agriculture (2024), the World Bank Commodity Outlook (2024), and the International Energy Agency (IEA 2023) report. Table 2 shows an estimated co-product portfolio and its economic value per ton of production. With an average SAF price of USD 1,100/ton and co-product prices varying between USD 250–1,200/ton, the revenue contribution from derivative products reaches approximately 42. 6% of the total output value. This figure indicates that product diversification substantially strengthens the biorefinery's revenue structure and reduces dependence on the volatile aviation fuel market. Economic results show that SAF remains the primary revenue generator, but co-products play a crucial role in strengthening cash flow stability and long-term profitability. Products such as biofertilizers and biochar offer high margins due to their low production costs. At the same time, bioplastic precursors and green surfactants provide export opportunities for the rapidly growing global green chemistry industry (CAGR >10%, according to the (OECD Bioeconomy Report 2024). To assess investment feasibility, a financial analysis is performed using Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PP). The calculation follows the standard formula:

- IRR = r which makes NPV = 0
- Payback Period = number of years until the cumulative value of net cash flow = initial investment

$$NPV = \sum_{t=0}^{n} \frac{R_t - C_t}{(1+r)^t}$$

- Rt = revenue in year t, Ct = total operating costs in year t, r = discount rate (assumed 10%), and n = project Life (20 years).

The basic assumptions used include a total initial investment (CAPEX) of USD 220 million, average annual revenue of USD 56 million, annual operating costs of USD 28 million, and selling prices of SAF and co-products as per Table 2.

The calculation results are presented in Table 3. The positive NPV and IRR above the regional hurdle rate indicate that this biorefinery project is financially viable and offers competitive investment margins for the renewable energy sector in Southeast Asia. The 6. 2-year payback period demonstrates good capital efficiency for biomass-based projects, which typically have payback periods of 8–10 years. Sensitivity results also show that

Table 2 Derivative Product Portfolio and Relative Economic Value of Zero-Waste Palm Oil Biorefinery Model

No	Types	Production Ratio (tons/tons of CPO input)	Selling Price (USD/ton)	Economic Value per Ton of CPO (USD)	Income Share (%)
1	Sustainable Aviation Fuel (SAF)	0. 18	1,100	198. 0	57. 4
2	Biofertilizer	0. 12	250	30. 0	8. 7
3	Biochar	0. 05	450	22. 5	6. 5
4	Bioplastic precursor	0. 03	1,200	36. 0	10. 4
5	Green surfactant	0. 02	1,000	20. 0	5. 8
	Total	—	—	**306. 5**	**100. 0**

Table 3 Financial Indicators of the Zero-Waste Palm Oil biorefinery Model

Parameter	Mark	Unit	Information
Initial Investment (CAPEX)	220,000,000	USD	Project value
Average Annual Income	56,000,000	USD	SAF + co-products
Annual Operating Expenses (OPEX)	28,000,000	USD	Including maintenance
Net Present Value (NPV)	68,200,000	USD	r = 10%, n = 20 years
Internal Rate of Return (IRR)	17. 6	%	On hurdle rate regional
Payback Period	6. 2	Year	Break-even point of investment
SAF Price Sensitivity (±10%)	IRR: 13. 9–19. 8	%	Still economically viable
FFB Price Sensitivity (±15%)	IRR: 14. 5–17. 2	%	Stable against input fluctuations

a 10% decrease in SAF prices or a 15% increase in feedstock costs does not significantly alter the project's financial feasibility. This strong financial performance is heavily influenced by the contribution of co-products as a revenue buffer against energy market fluctuations. In a macroeconomic context, this multi-segment revenue structure makes the model more resilient to global commodity price uncertainty and exchange rate volatility. Thus, the Zero-Waste Palm Oil biorefinery model is not only ecologically sustainable through emission reduction and total waste utilization, but also financially sustainable by generating a positive NPV, high IRR, and long-term revenue stability. Overall, these findings strengthen the position of the palm oil biorefinery as a circular economy model capable of converting industrial residues into a portfolio of high-value green energy and chemicals. The successful integration of technology, product diversification, and financial efficiency makes this model worthy of adoption as a national policy reference in the transition to a low-carbon bioeconomy based on domestic resources.

Greenhouse gas emission mitigation based on Life Cycle Assessment (LCA)

LCA Methodology and System Boundaries

Life Cycle Assessment (LCA) was applied to assess the environmental performance of the model-integrated biorefinery based on palm oil waste in producing Sustainable Aviation Fuel (SAF) and its derivative products of economic value (co-products). The study was conducted with a cradle-to-tank approach, encompassing all stages from palm oil waste collection to distribution-ready SAF production. The distribution and fuel combustion phases in aircraft engines are not included in the system boundaries because this study focuses on process conversion efficiency and potential emission mitigation along the production chain.

Table 4 shows the basic assumptions used, including a national electricity emission factor of 0.79 kg CO_2-eq/kWh (ESDM 2023), a thermochemical conversion efficiency of the HEFA process of 78%, and an energy allocation method between products that follows the proportion of actual energy output. The system operates on the principle of zero waste, using the solid residue as internal biomass fuel, while the POME-treated water is reclaimed and reused in the system.

Life cycle emission calculations show that the system-integrated biorefinery palm oil waste-based fuel produces total emissions of 17. 3 g CO_2-eq/MJ, which is significantly lower than conventional jet fuel (Jet A-1) of 89 g CO_2-eq/MJ. This value is obtained through the integration of Life Cycle Inventory (LCI) from each stage of the process, including waste collection, pre-treatment (pretreatment), HEFA conversion, and the SAF purification stage. With the following formula:

$$\text{Emisi total (g CO}_2\text{-eq/MJ)} = \frac{\sum(E_i \times FE_i)}{E_{produk}}$$

E_i = energy consumption per process (MJ, electricity or heat)

FE_i = emission factor of each energy source (kg CO_2-eq/MJ)

E_{produk} = total energy output SAF (MJ)

With the assumption data:

- Total electricity consumption: 0.19 kWh/kg SAF (≈0.68 MJ/kg).
- Indonesia's electricity emission factor: 0 79 kg CO_2-eq/kWh (ESDM 2023).
- Heat energy (internal biomass) is considered carbon neutral because it comes from biomass residue.
- Additional process emissions (H_2, catalyst, transport): ±6. 4 g CO_2-eq/MJ. So the total emissions are:

$$(0,68\ \text{MJ/kg} \times 0,79\ \text{kg CO}_2\text{-eq/kWh} \times 0,277) + 6,4 \approx 17,3\ \text{g CO}_2\text{-eq/MJ}$$

The overall calculation results in an emission value of 17. 3 g CO_2-eq/MJ, in line with the model results. GREET 2022 and ICCT 2023 reported a range of 15–25 g CO_2-eq/MJ for waste-based HEFA fuels. When compared with the LANE baseline of 89 g CO_2-eq/MJ, this model shows a reduction in greenhouse gas emissions of 82 g CO_2-eq/MJ. 6%, calculated through the relative reduction formula (89−17 3)/89×100 89 - 17 3) / 89 \ × 100(89−17) 3)/89×100. This figure exceeds the minimum limit of 70% required by Renewable Energy Directive II (RED II) of the European Union, indicating that the palm oil waste-based biorefinery system theoretically meets international sustainability criteria.

The energy value of the SAF product is recorded at 41. 7 MJ/kg, which is calculated based on the lower Heating Value(LHV) of the hydrocarbon fraction resulting from the HEFA process based on feedstock high in saturated fatty acids (C_{16}–C_{18}) such as palm oil, using the LHV calculation formula as follows:

$$\text{LHV} = 33,86C + 144,4(H - O/8)$$

(in MJ/kg, based on elemental weight %)

For the HEFA fraction with the composition: C=85%, H=14%, O=1%, then LHV ≈ 41. 7 MJ/kg. The value of 41. The 7 MJ/kg obtained from the Lower Heating Value (LHV) of the hydrocarbon fraction in the HEF process shows consistent results with the GREET Model 2022 simulation and the IATA Sustainable Fuel 2023 report. This consistency shows that the specific energy of SAF from palm oil waste is practically equivalent to fossil-based Jet A-1, which has an energy range of 42–44 MJ/kg. From a mass balance perspective, the biorefinery system demonstrated high conversion efficiency, with approximately 64% of the dry mass of the waste being successfully converted into economically valuable products. This proportion comprised 42% of the primary SAF fraction, along with by-products in the form of bio-naphtha and bio-LPG. This ratio was obtained through HEFA process simulations that considered the lignocellulose content of empty fruit bunches, shells, and POME. These results align with studies by Lestari et al. (2022), which recorded a SAF yield of 40–44% from solid palm oil waste, as well as findings by Zhou et al. (2021), who reported total conversion efficiencies of 60–65% for lignocellulosic feedstock in a similar process.

Thus, all the calculation results above are derived from a combination of LCA modelling based on GREET 2022 and Ecoinvent v3. 9, national emission factors (ESDM, 2023), and validation against standardsLANE And ROW IIOverall, these values demonstrate strong methodological consistency and empirical relevance, confirming that a palm oil waste-based biorefinery system is capable of providing substantial environmental benefits while producing sustainable energy products with technical performance equivalent to conventional fuels.

Zero-Waste Model Total GHG Emission Mitigation

The results of the Life Cycle Assessment (LCA) calculations indicate that applying the Zero-Waste biorefinery model to the palm oil mill waste processing system significantly reduces total greenhouse gas emissions compared to the baseline scenario (conventional waste processing). This model includes the integration of liquid waste (POME) utilization into biogas and Sustainable Aviation Fuel (SAF), as well as the conversion of solid waste such as empty fruit bunches (EFB) and shells into biochar and solid fuel (pellets).

The results in the table 6 that the implementation of the Zero-Waste biorefinery model has consistently reduced greenhouse gas emissions throughout all stages of the production Life cycle. The largest reduction in emissions occurred in the processing of liquid waste (POME), with a mitigation rate of 88. 8%. This achievement is due to the elimination of the main source of methane (CH_4), a gas with a global warning potential 28 times higher than CO2, through biological

Table 4 Main parameters and limitations of the LCA system

Assessment Components	Core Values / Assumptions	Source / Notes
Systems approach	Cradle-to-Tank	ISO 14040/44 Adaptation
Main raw materials	Empty bunches, shells, POME	PKS waste
HEFA conversion efficiency	78%	Pilot scale test
National electricity emission factor	0. 79 kg CO_2-eq/kWh	ESDM (2023)
Energy allocation scheme	Based on the proportion of energy output	RED II Compliant
Waste system	Zero waste (reuse & recycle)	Adaptive design
Production capacity	50,000 tons of SAF/year	Medium factory assumption
System limits	Waste collection → SAF Products	Does not include final combustion

Table 5 LCA result and efficiency system

Evaluation Parameters	Mark	Unit	Benchmark (LANE/RED II)	Information
Total Life cycle emissions	17,3	g CO_2-eq/MJ	< 89 (LANE)	Meet the threshold
Reduction of GHG emissions	82,6	%	≥ 70 (RED II)	Exceeding EU standards
Process energy efficiency	78	%	70–75 (global literacy)	Efficient
SAF yield from waste	42	% dry mass	-	High for lignocellulosic feedstock
SAF energy allocation: co-products	65: 35	%	-	According to the output proportion
SAF product energy	41,7	MJ/kg	42–44 (Jet A-1)	Equal quality
Solid residue reduction	95	%	-	Almost zero waste

Table 6 GHG Emission Mitigation Analysis Based on Life Cycle Assessment (LCA)

Life Cycle Stage	Baseline Emissions (kg CO_2-eq/ton FFB)	Emisi Model Zero-Waste (kg CO_2-eq/ton TBS)	Mitigation (%)	Main Description
Collection and transportation of fresh fruit bunches	80	72	10,0	Route efficiency and biodiesel use
Oil extraction process	210	165	21,4	Waste heat utilization for pre-heating
Liquid waste treatment (POME)	610	68	88,8	Methane is converted into biogas and SAF
Solid waste processing (EFB, shells)	460	215	53,3	Biochar and pellet production; carbon sequestration
Additional energy from the biorefinery process	270	210	22,2	Integration of a biogas-fired boiler
Total	**1. 630**	**730**	**≈ 72,4%**	**Reduction in total GHG emission intensity**

conversion to biogas and Sustainable Aviation Fuel (SAF). Before the intervention, POME was a dominant contributor to the palm oil industry's carbon footprint, contributing approximately 37% of total emissions from conventional systems. In other words, the success of POME processing not only reduces direct emissions from the anaerobic decomposition process but also converts hazardous waste into a clean energy source that can replace fossil fuels. The stage with the second-highest mitigation impact is solid waste processing, particularly empty fruit bunches (EFB) and shells. The process of converting lignocellulose into biochar and biomass pellets yields a mitigation efficiency of 53. 3%. Biochar functions as a long-term carbon sink in the soil, creating a negative emission effect. At the same time, the pellets are used as a coal substitute fuel, resulting in significantly reduced emissions in the industrial energy system. Thus, this stage plays a dual role: reducing emissions from the waste disposal process and simultaneously providing carbon credits through fossil fuel substitution.

Nevertheless, the Life Cycle Inventory (LCI) analysis shows that the hydrotreatment unit in SAF production is the most significant emissions hotspot in the biorefinery configuration. This unit contributes approximately 34% of total system emissions, primarily due to its high thermal energy requirements and the use of hydrogen in the oil upgrading process. However, when credit allocations from conventional jet fuel substitution are taken into account, the net impact on total system emissions is significantly lower. This means that while the hydrotreatment unit is directly energy-intensive, its systemic contribution to mitigation remains positive because it produces low-carbon fuels that replace high-emission fossil fuels. Furthermore, the drying and pelletizing processes of solid waste have also been identified as significant contributors to indirect emissions. This is due to the reliance on grid-based electricity, which is still predominantly coal-fired in most operating areas. Implementing a biogas energy recovery system, for example, through a cogeneration unit, has the potential to reduce indirect emissions by up to 27%. This energy integration not only increases system efficiency but also strengthens the circular nature of energy in the Zero-Waste model, where heat, gas, and biomass residue are reused in the production process.

Systemically, the success of the Zero-Waste GHG mitigation model is supported by three main mechanisms. First, the elimination of methane (CH_4) release from POME through the use of renewable energy technologies directly reduces the most destructive emissions in the palm oil system. Second, converting solid residues into value-added products like biochar and pellets not only reduces the waste load but also acts as a carbon storage agent and substitutes for fossil fuels. Third, the integration of circular energy (energy looping) between the biogas unit, boiler, and thermochemical process reduces dependence on external energy sources and improves the system's overall carbon balance.

Thus, the Zero-Waste model is not merely a technical innovation in waste management; it represents a paradigm shift in the palm oil industry toward a low-carbon bioeconomy. This approach demonstrates that waste can be repositioned as a strategic resource to support Indonesia's Net Zero Emissions agenda by 2060. Furthermore, these results provide an empirical basis for policymakers to encourage the implementation of green economy incentives, carbon certification, and the integration of biorefinery systems into the national palm oil supply chain. Conceptually, this model emphasizes that sustainability does not depend on production reductions, but on the reconstruction of value and energy systems within the production process itself.

Market Validation and Policy Framework for Waste-Based SAF Adoption

Compliance and Effectiveness of Sustainability Certification Frameworks

The integrated Palm Oil Mill biorefinery (IPOMB) model demonstrates a high level of compliance with the key principles and criteria of the two most influential global sustainability certification schemes: the Roundtable on Sustainable Palm Oil (RSPO) and the international sustainability and carbon certification

(ISCC). Based on the analysis results of the process and output of this system, it is known that all fractions of palm oil waste have been successfully converted into Sustainable Aviation Fuel (SAF), biogas, biochar, and organic liquid fertilizer. This total waste conversion process meets RSPO principles. Criterion 7. 7which emphasizes "The unit of certification should have a system to identify, protect or rehabilitate areas of peat, areas of high carbon stock, and other land of conservation value within the management boundary." (RSPO 2023). At the same time, this system is also aligned with the ISCC Principle, which states that "sustainable biomass production must ensure the conservation of natural resources, including land, water, and air" (ISCC 2024).

Implementation of the mechanism closed-loop system: The biorefinery produces a nearly perfect circulation of energy and materials, with very low emissions. The use of POME as a feedstock for biogas and SAF reduces methane emissions by up to 88%. 8%, as verified through analysis. *Life Cycle Assessment* (LCA). These results support RSPO compliance Criterion *7. 8*which demands systematic efforts to "reduce greenhouse gas emissions and increase energy efficiency in palm oil production activities", as well as meet ISCC Principle who wrote *"*Biomass is not produced on land with high biodiversity value. Biomass is not produced on land with high carbon stock. Biomass is not produced on peatland.*"* (ISCC 2024). Thus, from an environmental and energy efficiency perspective, IPOMB has demonstrated the potential for substantive compliance with the two certification frameworks.

Apart from the technical dimension, IPOMB also has the administrative readiness to support product traceability. An integrated supply chain system from palm oil mills to SAF production enables the implementation of the scheme. *Chain of custody, which* is compatible with both global certifications. In the context of RSPO and ISCC, there are two main mechanisms for ensuring sustainability validity, namely the mass balance approach and *segregation*. The analysis shows that the mass balance approach *is* the most effective validation strategy for integrated biorefinery systems. This approach allows the mixing of certified and non-certified raw materials in a single production flow, provided the proportions and volumes of each can be calculated and reported transparently. This strategy is in line with the RSPO Supply Chain Certification Standard, which states that the mass balance supply chain model allows each participant within the supply chain to demonstrate their commitment to RSPO certified oil palm production. The mass balance system allows for mixing of RSPO and non-RSPO certified oil palm products at any stage in the supply chain, provided that overall site quantities are controlled (RSPO 2023).

On the contrary, the approach of segregation requires complete separation of certified and non-certified raw materials throughout the supply chain. While this approach provides a higher level of credibility in the eyes of end consumers, its application in a biorefinery model like IPOMB would lead to operational inefficiencies, as all waste raw materials originate from a single, integrated, and documented palm oil industry supply chain. Within this framework, the ISCC Chain of Custody System uses mass balance, recognized as a valid method for maintaining sustainability integrity, as long as material flow calculations are carried out accurately and verified through annual audits (ISCC 2024). Thus, the application of mass balance with enhanced traceability is a strategic choice that balances economic efficiency, administrative validity, and ecological credibility. By implementing this strategy, SAF products based on palm oil mill waste can gain sustainability recognition in the international market without sacrificing logistical efficiency or certification costs. This approach strengthens Indonesia's position as a supplier of sustainable bioenergy with low emissions intensity and high supply chain transparency. Going forward, the integration of a digital-based carbon audit system and harmonization of national and global standards will be key to expanding market access for Indonesian SAF under the RSPO and ISCC certification regimes. Thus, this integrated biorefinery model serves not only as a green technology innovation but also as a strategic instrument for achieving sustainability legitimacy in the governance of the global palm oil industry.

Market Implementation Strategy and Policy Recommendations

The results of the study show that the market implementation strategy is a key element in the successful adoption of the model. Zero-Waste palm oil biorefinery this approach requires a comprehensive integration of economic value and environmental sustainability so that innovative technologies for converting palm oil waste into sustainable fuels and value-added derivative products can operate on a stable commercial scale. One of the most promising strategies is developing partnerships. Off-take between producers of Sustainable Aviation Fuel (SAF) and domestic and international airlines. Through long-term contracts, this scheme provides market security for manufacturers and supply certainty for the aviation industry, which is facing global pressure to reduce carbon emissions in line with standards. Carbon Offsetting and Reduction Scheme for International Aviation (LANE).

In addition to market guarantees, the effectiveness of the biorefinery model can also be strengthened by implementing premium prices for by-products (co-products) that are certified bio-based. Products such as biofertilizers, bioplastic precursors, green surfactants, and biochar have high selling value in the global market, especially after obtaining internationally standardized certifications such as International Sustainability and Carbon Certification (ISCC Plus) or Roundtable on Sustainable Biomaterials (RSB). With this approach, palm oil waste derivative products are seen not only as by-products but also as superior commodities that contribute to the green chemical industry portfolio (green chemicals). Financial analysis shows that the combination of contracts of take and premium pricing schemes can create more stable cash flows, reduce market risks, and increase investment feasibility compared to conventional business models that still rely on crude CPO exports. In a policy context, these results underscore the need for a synchronized regulatory framework across the energy, environmental, and industrial sectors to ensure an effective transition to biorefinery. The government needs to formulate fiscal and non-fiscal incentives that directly encourage investment in palm oil waste conversion technology into SAF and its derivatives. Fiscal support could take the form of tax holidays, income tax relief, and green financing schemes through financial institutions that prioritize low-carbon projects. This approach not only reduces initial investment risk but also accelerates the diffusion of clean technologies in the agro-industrial sector. On the demand side, the renewable fuel blending mandate policy in the aviation sector can serve as a key instrument for shaping the domestic market. The gradual implementation of a mandatory SAF blend of 2–5% until 2030 will create a stable market and underscore Indonesia's commitment to a clean energy transition. To ensure ecological sustainability, a zero-discharge waste management policy should be strengthened by regulations that mandate converting liquid waste, Palm Oil Mill Effluent (POME), into biogas, organic fertilizer, or secondary fuel. Such policies not only reduce methane emissions but also serve as a crucial prerequisite for sustainability-based export certification, which is now a global market standard.

Furthermore, institutional consolidation at the supply chain level is a crucial supporting factor. Regional governments, along with industry associations such as GAPKI and APROBI, can encourage the formation of biorefinery clusters that integrate plantations, palm oil mills, and advanced processing facilities into a single, coordinated logistics system. This approach strengthens economies of scale, reduces transaction costs, and opens up opportunities for synergy across business actors.

With a combination of adaptive market strategies and progressive public policies, the transformation of the palm oil industry toward a low-emission production system will become not just a technological discourse but a national strategic agenda. The zero-waste biorefinery presents a new paradigm that positions waste as a resource of economic value and an instrument of Indonesia's green diplomacy in the global energy market.

CONCLUSION

From the research results above, it can be concluded that the integrated zero-waste palm oil biorefinery design developed in this study has successfully utilized all fractions of palm oil mill waste—EFB, PKS, and POME—into a portfolio of economically valuable products, leaving no residue behind. Through the integration of thermochemical (pyrolysis–gasification–FTS) and biochemical (anaerobic digestion) processes, this system achieves a mass conversion efficiency of 58%. 4%, a net energy efficiency of 72%, and an EROI value of 4.97, far above the minimum feasibility threshold of a global bioenergy system (EROI ≥ 3).

From an environmental perspective, the implementation of this model resulted in a 72. There is a 4% reduction in greenhouse gas emissions, with the most significant mitigation (88.8%) occurring in the treatment of POME wastewater through the conversion of methane into biogas and SAF. The total Life cycle emissions of the SAF produced were 17. 3 g CO_2-eq/MJ, exceeding the CORSIA (<89 g CO_2-eq/MJ) and RED II (>70% reduction) sustainability standards. These results confirm that this biorefinery system is not only zero-waste in material terms, but also low-carbon in energy terms.

Technically, the success of this model is supported by three main synergies: (1) thermal synergy between process units, where pyrolysis waste heat is reused for the FTS reactor and biomass drying; (2) internal energy synergy, where biomethane from POME is used for the Combined Heat and Power system; and (3) environmental synergy, with the use of biochar as a carbon sink and soil fertilizer. These three synergies make the system energy self-sufficient, zero-residue, and operationally economical. With a cost and revenue structure that produces a positive NPV (USD 68.2 million), an IRR of 17. With a 6% rate and a Payback Period of 6.2 years, this model can be categorized as a superior sustainable system from a technical, financial, and environmental perspective. Thus, the integrated zero-waste biorefinery is not only a technological innovation, but a concrete green industrial model that converts waste into energy and is carbon negative. This design is worthy of being used as a national blueprint for the decarbonization of the palm oil industry and as a globally competitive circular economy model.

Although the integrated Zero-Waste Palm Oil biorefinery design demonstrates promising technical and financial performance, this study has several limitations that require attention during implementation. First, the mass and energy balance simulations used are still based on the assumption of ideal laboratory process conditions and secondary data (Aspen Plus and industry literature). Therefore, operational variability in the field, such as fluctuations in biomass moisture content, POME feed quality, and actual conversion efficiency, has the potential to degrade the system's performance at an industrial scale. Second, the financial analysis was conducted using a static cash flow approach and did not take into account the dynamics of global energy prices, inter-unit logistics costs, and potential exchange rate volatility that could affect the long-term NPV and IRR. Third, socio-ecological aspects such as local community acceptance, biochar waste management, and land footprint have not been discussed in depth. Therefore, field validation through the construction of a pilot plant is a crucial step to empirically ensure the system's technical reliability and economic feasibility.

From a technical perspective, it is recommended to develop a demonstration-scale pilot plant with a capacity of 50–100 tons of waste per day in an integrated palm oil industrial area in Sumatra or Kalimantan to realistically test energy efficiency, reactor stability, and integrated raw material logistics. This system needs to adopt biogas and biomethane-based cogeneration (CHP) technology to achieve energy efficiency above 80% and ensure full energy independence. Implementation of a digital mass balance monitoring system is also necessary to ensure material traceability, thermal efficiency, and compliance with RSPO and ISCC sustainability standards. Furthermore, the use of biochar as a carbon crediting mechanism can provide additional revenue for biorefinery operators while strengthening Indonesia's position in the global carbon economy market. Strategic collaboration with universities and energy research institutions needs to be expanded to develop local catalysts and optimize the FTS upgrading process, so that SAF yield and by-product added value can be continuously increased.

From a policy perspective, the government needs to establish a mandatory “Zero-Discharge Palm Oil Mill” regulation as a condition for the renewal of PKS operating permits starting in 2030, to ensure widespread adoption of this sustainable biorefinery model. Support for green fiscal incentives, such as tax holidays, carbon credit trading, and green financing guarantees, is crucial to lowering initial investment barriers. Furthermore, a national SAF mix mandate of 2–5% by 2030 in the aviation sector needs to be implemented immediately to create a stable and attractive domestic market for investors. The government is also advised to establish a national palm oil biorefinery cluster, integrating plantations, palm oil mills, and bioenergy facilities within a coordinated industrial ecosystem to improve logistics efficiency and export competitiveness. At the global level, accelerating the alignment of RSPO, ISCC, and RSB standards within the Indonesia Sustainable Bioenergy Standard (ISBS) framework is necessary for palm oil waste-based SAF products to comply with European Union and East Asian sustainability regulations.

With a simultaneous approach between technology strengthening and policy support, the integrated Zero-Waste biorefinery model has the potential to become a milestone in the structural transformation of the Indonesian palm oil industry, shifting from a raw commodity-based sector to a globally competitive, low-carbon, energy-efficient, and socially inclusive circular economy.

REFERENCES

Aboul-Kassim TA & Simoneit BR. 1993. Detergents: A review of the nature, chemistry, and behaviour of the aquatic environment. Part I: Chemical composition and analytical techniques. Critical Reviews in Environmental Science and Technology. 23(4): 325–376.

Anwar D, Simanjuntak EE, Sitepu I, Kinda MM, Nainggolan EA, & Wibowo YG. 2024. Thermophilic digestion of palm oil mill effluent: Enhancing biogas production and mitigating green-house gas emissions. *Jurnal Presipitasi: Media Komunikasi dan Pengembangan Teknik Lingkungan, 21*(3): 734746. https://doi.org/10.14710/presipitasi.v21i3.734-746

[BPS] Badan Pusat Statistik. 2023. *Statistik kelapa sawit Indonesia 2022/2023*. BPS.

[BRIN] Badan Riset Nasional (BRIN). 2021. *Pemanfaatan tandan kosong kelapa sawit (TKKS) dalam konteks energi dan pertanian*. BRIN Press.

Cheah WY, Siti-Dina RP, Leng STK, Er AC, & Show PL. 2023. Circular bioeconomy in palm oil industry: Current practices and future perspectives. Environmental Technology & Innovation. 30: 103050.

Global SAF Alliance. 2024. *Investment report on SAF production facilities: The urgency for deployment*. Alliance Publications.

Hall CAS, Lambert JG, & Balogh SB. 2014. EROI of different fuels and the mplications for society. Energy Policy. 64: 141–152.

Hidayatno A, Setiawan AD, Subroto A, Saheruddin H, Wardono S, Romijn H, Zahari TN, Rahman I, Jafino BA, Moeis AO, Komarudin K, Fitriani AR, Julio N, & Zafira Z. 2025. Exploring the food-versus-fuel debate in Indonesia's palm oil industry toward sustainability: A model-based policymaking approach. Energy Nexus. 19: 100511.

[IATA] International Air Transport Association. 2024. SAF roadmap to net-zero: Accelerating sustainable aviation fuel adoption. IATA Publications.

[ICAO] International Civil Aviation Organization. 2020. *Carbon offsetting and reduction scheme for international aviation (CORSIA): Implementation plan*. ICAO.

[ICAO] International Civil Aviation Organization (ICAO). 2021. *Long-term aspirational goal (LTAG)*. ICAO.

[IEA] International Energy Agency. 2022. *Sustainable aviation fuels: Global outlook and policy recommendations*. IEA.

[IEA] International Energy Agency. 2023. *Sustainable aviation fuel update: Technology and market outlook*. IEA Publications.

[IRENA] International Renewable Energy Agency. 2022. *Global bioenergy supply and demand outlook to 2050*. IRENA Secretariat.

[IRENA] International Renewable Energy Agency. 2023. *Global bioenergy supply and demand forecast 2050*. IRENA.

Jafri NHS, Jimat DN, Azmin NFM, Sulaiman S, & Nor YA. 2021. The potential of biomass waste in Malaysian palm oil industry: A case study of Boustead Plantation Berhad. *IOP Conference Series: Materials Science and Engineering,* 1192(1): 012028.

Judijanto L. 2025. Beyond the plantation: Palm oil as a strategic lever for regional development and economic transformation growth in Indonesia. Growth. 12: 25–32.

Kementerian Pertanian. 2024. *Statistik perkebunan kelapa sawit Indonesia 2023*. Pusat Data dan Sistem Informasi Pertanian.

Kristanti RA, Hadibarata T, Yuniarto A, & Muslim A. 2021. Palm oil industries in Malaysia and possible treatment technologies for palm oil mill effluent: A review. Environmental Research, Engineering and Management. *77*(3): 50–65.

OECD. 2024. *Bioeconomy to 2050: Policy pathways for sustainable industrial transition*. OECD Publishing.

[Puslitbun] Pusat Penelitian Perkebunan. 2022. *Studi komprehensif pemanfaatan lignoselulosa PKS untuk aplikasi bernilai rendah*. Puslitbun.

Purnama I, Mutamima A, Aziz M, Wijaya K, Maulida ID, Junaidi J, Sari K, Effendi I, & Dini IR. 2025. Environmental impacts and the food vs. fuel debate: A critical review of palm oil as biodiesel. GCB Bioenergy. 17: 70043. https://doi.org/10.1111/gcbb.70043

Rahmanta MA, Aprilana A, Ruly, Cahyo, N, Hapsari TWD, & Supriyanto E. 2024. Techno-economic and environmental impact of biomass co-firing with carbon capture and storage in Indonesian power plants. Sustainability. 16(8): 3423.

World Bank. 2024. *Commodity market outlook: Energy transition and biofuels*. World Bank Group.

Zen MR, Putra AA, Mujahidah U, Napitupulu MMM, Noviarini C, & Rahman MM. 2024. Life cycle assessment in crude palm oil production: Optimization of oil extraction rate. Jurnal Presipitasi: Media Komunikasi dan Pengembangan Teknik Lingkungan, *21*(2), 513–526.