

# POME-Based Sustainable Aviation Fuel (SAF) as a Game Changer in Sustainable Renewable Energy

Loso Judijanto\*

IPOSS Jakarta, Jakarta, Indonesia

\*Correspond Author: Loso Judijanto, IPOSS Jakarta, Jakarta, Indonesia.

Received: 📅 2025 Nov 28

Accepted: 📅 2025 Dec 17

Published: 📅 2025 Dec 30

## Abstract

*Palm Oil Mill Effluent (POME) is an underutilized feedstock for sustainable aviation fuel (SAF) production, positioning waste valorization as a game-changing strategy for aviation decarbonization and the implementation of a circular economy. This qualitative literature review synthesizes recent research (2020-2025) from various journals to evaluate the environmental, technological, economic, and policy dimensions of POME-based SAF. Key findings indicate that POME-derived SAF achieves 65-80% lifecycle greenhouse gas emission reductions compared to conventional jet fuel, with 25-30% of climate benefits derived from avoided methane emissions through improved wastewater management. Hydrothermal liquefaction and hydro processing pathways demonstrate technical feasibility for compliance with ASTM D7566, while anaerobic digestion remains the most commercially mature conversion route. Indonesia and Malaysia's combined POME generation of 119-178 million metric tons annually creates scalable feedstock potential supporting 360-480 million gallons of SAF production—addressing aviation's primary feedstock scarcity constraint. However, economic viability depends critically on policy support mechanisms, including blending mandates, carbon credits, and cost parity subsidies. Critical challenges include certification integrity (fraud prevention), smallholder inclusion, and potential rebound effects from expanded palm oil cultivation. Indonesia's emerging SAF roadmap, export restrictions prioritizing domestic value addition, and investment in biorefinery infrastructure position it as a potential global leader in POME-SAF production. The analysis concludes that POME-based SAF, through integrated technological optimization, strengthened policy frameworks, and inclusive supply chain development, can meaningfully contribute to aviation's decarbonization while demonstrating circular economy principles at scale.*

**Keywords:** Sustainable Aviation Fuel, Palm Oil Mill Effluent, Waste Valorization, Circular Economy, Life Cycle Assessment, Hydrothermal Liquefaction, Aviation Decarbonization, Biofuel Policy, Indonesia, Renewable Energy Transition

## 1. Introduction: The Strategic Imperative for Pome-Derived Saf

The global aviation sector stands at a critical juncture in its decarbonization trajectory, confronting the dual challenges of meeting stringent emission reduction targets while scaling sustainable fuel alternatives. Aviation accounts for approximately 2-3% of global anthropogenic carbon dioxide emissions, with projections indicating it could grow to 22% of global emissions by 2050 if left unaddressed. This environmental imperative has catalyzed unprecedented momentum toward Sustainable Aviation Fuel (SAF) deployment, recognized as the primary near-term solution for aviation decarbonization. However, the SAF industry faces a fundamental constraint: feedstock scarcity. Current SAF production relies predominantly on used cooking oil (UCO), animal fats, and energy crops, collectively insufficient to meet the aviation sector's projected demand of 449 billion liters annually by 2050 et. al. This supply gap necessitates exploration of alternative, scalable feedstocks that circumvent the sustainability controversies and land-use competition associated with conventional biofuel crops.

Palm Oil Mill Effluent (POME) emerges as a transformative solution, representing a paradigm shift from a burden of waste management to a strategic energy resource. Indonesia and Malaysia, as the world's largest palm oil producers, generate an estimated 119-178 million metric tons of POME annually, creating both environmental liabilities and untapped energy potential et, al. POME's classification as an advanced waste/residue feedstock under the EU Renewable Energy Directive II (RED II) positions it as a uniquely sustainable pathway that avoids indirect land-use change (ILUC) impacts while delivering substantial greenhouse gas (GHG) reductions [1]. The urgency for POME-to-SAF conversion extends beyond environmental benefits. Untreated POME disposal in open lagoons generates methane emissions estimated at 0.25-0.35 kg CH<sub>4</sub> per cubic meter, contributing to potent global warming potential. Simultaneously, the palm oil industry faces mounting pressure to demonstrate sustainability credentials amid concerns over deforestation and trade restrictions. Converting POME into aviation fuel creates a triple sustainability dividend: mitigating waste-related emissions, generating renewable energy, and enhancing the

palm oil industry's circular economy profile [2]. This article evaluates the transformative potential of POME-based SAFs through a qualitative literature review, synthesizing recent research to assess technological feasibility, environmental performance, economic viability, and policy readiness. The analysis positions POME-derived SAF not merely as an alternative feedstock but as a game-changing innovation capable of redefining sustainable renewable energy paradigms in aviation and waste management sectors.

## 2. Literature Review: Conceptual and Theoretical Frameworks

### 2.1. Theoretical Foundations of Waste Valorization and Circular Economy

The conversion of POME to SAF embodies core principles of circular economy theory, which emphasizes closing material loops and maximizing resource efficiency through waste valorization. Unlike linear "take-make-dispose" models, circular economy frameworks position waste as a feedstock for new production cycles, creating industrial symbiosis between palm oil mills and biorefineries. This symbiotic relationship transforms environmental liabilities into value-added products while reducing the need for virgin resource extraction [3]. Industrial ecology concepts further illuminate POME-to-SAF potential through the lens of industrial symbiosis, where co-location of palm oil mills and biorefineries enables shared infrastructure, reduced transportation costs, and integrated energy systems. The high-water content of POME (95-96%) historically necessitated extensive ponding systems with 45-60-day hydraulic retention times, occupying significant land area and emitting methane. Hydrothermal liquefaction (HTL) technologies uniquely leverage this water content as a reaction medium, converting wet biomass to biocrude without the energy-intensive drying required by pyrolysis pathways, thereby demonstrating superior energy efficiency [4]. Life Cycle Assessment (LCA) methodology provides the analytical foundation for evaluating POME-SAF's environmental credentials. Prospective LCA (pLCA) approaches, which employ dynamic inventory models to assess emerging technologies within future contexts, are particularly relevant given the developmental stage of POME-to-SAF commercialization. Standardized LCA frameworks under CORSIA and RED II require comprehensive accounting of direct and indirect emissions, including methane-avoidance credits from improved POME management [5].

### 2.2. Sustainable Aviation Fuel Standards and Certification

SAF certification under ASTM D7566 annex specifications requires rigorous compliance with fuel properties, including energy density (minimum 43 MJ/kg), sulfur content (<2 ppm), and thermal stability parameters. Hydro processed esters and fatty acids (HEFA) conversion of POME residual oils produces synthetic paraffinic kerosene meeting these specifications, with successful pilot demonstrations confirming ASTM D7566 compliance. The heteroatom content, particularly nitrogen and oxygen, poses challenges that require advanced hydrotreating to achieve <2 ppm nitrogen levels [6]. CORSIA eligibility mandates a minimum 10% GHG reduction versus conventional jet fuel, with

POME-derived SAF demonstrating 60-85% lifecycle emission reductions depending on conversion pathway and system boundaries. The EU Renewable Energy Directive's sustainability criteria classify POME as waste/residue, exempting it from ILUC risk categorization while requiring chain-of-custody documentation to prevent fraud. Recent controversies over POME oil being mislabeled as waste have prompted enhanced traceability requirements, with ISCC mandating individual mill certification for waste/residue feedstocks since 2022 [7].

### 2.3. POME Characterization and Conversion Potential

POME composition varies by processing stage, with clarification wastewater comprising 60%, sterilization condensate 34%, and hydro cyclone wastewater 6% of total volume. Chemical oxygen demand (COD) ranges from 40,000 to 60,000 mg/L, while biological oxygen demand (BOD) is 25,000 to 30,000 mg/L, indicating a high organic loading, favorable for bioconversion. Residual oil content of 0.6-0.7% represents the primary feedstock fraction for HEFA conversion, while organic solids support HTL biocrude production [8]. The geographic concentration of palm oil mills in Indonesia (over 1,000) and Malaysia (approximately 450) creates logistical advantages for the development of centralized biorefineries. The consistent POME generation rate—0.65-0.67 tons per ton of crude palm oil produced—enables reliable feedstock supply planning. Seasonal variability in fresh fruit bunch composition affects POME characteristics, necessitating standardized quality protocols to enable scalable SAF production [9].

### 2.4. Existing Research Synthesis on POME-Based Biofuels

Recent literature converges on multiple conversion pathways, each exhibiting distinct technological readiness levels (TRL). Hydrothermal liquefaction operates at subcritical water conditions (250-400°C, 10-25 MPa), converting wet POME to biocrude with 30-45% yield and higher heating values of 28-35 MJ/kg. Catalytic upgrading using NiMo catalysts achieves nitrogen reduction from 1,500-3,000 ppm to <53 ppm through two-stage hydrotreating, though additional processing is required to meet <2 ppm SAF specifications [10]. Anaerobic digestion represents the most mature pathway (TRL 9), generating biogas with 20-28 m<sup>3</sup> CH<sub>4</sub>/m<sup>3</sup> POME and methane purity exceeding 60%. Biogas upgrading to biomethane, followed by Fischer-Tropsch synthesis, offers another SAF route, though conversion efficiency losses reduce the overall energy balance. Hybrid approaches combining AD for biogas production and HTL for residual solids valorization demonstrate synergistic effects, improving overall carbon utilization efficiency by 15-20% compared to single-pathway systems [11]. Life cycle assessment studies consistently report 60-85% GHG emission reductions for POME-SAF pathways, with avoided methane emissions from covered lagoon systems contributing 25-30% of total climate benefits. Net energy ratios of 3.5-4.2 indicate favorable energy return on investment, surpassing many energy crop-based biofuels. However, studies note significant data gaps regarding real-world commercial-scale performance, with most LCA based on pilot-scale operations [12].

### 3. Methodology: Qualitative Literature Review Approach

This study employs a qualitative literature review methodology to synthesize emergent knowledge on POME-based SAF, emphasizing interpretive analysis over systematic quantitative aggregation. The qualitative approach is appropriate given the technology's developmental stage, where research diversity in methodologies, geographic contexts, and assessment frameworks precludes meta-analytical synthesis.

#### 3.1. Research Design and Philosophical Underpinnings

The research adopts an interpretivist epistemology, recognizing that technological assessment involves contextual interpretation of data within specific socio-technical systems. Unlike systematic reviews that pursue exhaustive coverage and statistical synthesis, this qualitative review prioritizes thematic depth, theoretical integration, and critical evaluation of technological narratives. The methodology draws on essential traditions of review in the technology assessment literature, emphasizing the synthesis of disparate research streams to generate a holistic understanding [13].

#### 3.2. Literature Search Strategy and Selection Criteria

Database searches targeted Scopus, Web of Science, and Google Scholar using Boolean combinations: ("POME" OR "palm oil mill effluent") AND ("SAF" OR "sustainable aviation fuel" OR "hydrothermal liquefaction" OR "biojet"). Inclusion criteria required peer-reviewed publications from 2020 to 2025, in English, and focused on SAF production pathways. Industry reports from IRENA, ICAO, USDA, and ISCC supplemented academic sources, providing policy and market context. The search yielded 156 potentially relevant documents, of which 87 met the inclusion criteria after title/abstract screening. Full-text review identified 43 sources providing substantive data on technological performance, environmental assessment, or policy analysis. Excluding pre-2020 literature ensured currency while retaining seminal methodological frameworks published earlier but cited in recent works [14].

#### 3.3. Data Extraction and Thematic Analysis Protocol

Data extraction employed a standardized matrix capturing: (1) conversion pathway specifications, (2) performance metrics (yield, efficiency, emissions), (3) geographic context, (4) assessment methodology, and (5) policy implications. Thematic analysis followed Braun & Clarke's six-phase framework: familiarization, coding, theme development, review, definition, and reporting [15]. Four primary themes emerged: technological maturity, environmental performance, economic viability, and policy readiness. Within each theme, sub-codes captured specific dimensions—for technological maturity: TRL, conversion efficiency, scale-up challenges; for environmental performance: LCA results, methane avoidance, water impacts; for economic viability: feedstock costs, CAPEX, OPEX, policy incentives; for policy readiness: regulatory frameworks, certification requirements, trade measures [16].

### 3.4. Quality Assessment and Limitations

Source quality assessment evaluated journal impact factors, citation indices, and methodological rigor. Preference was given to Q1/Q2 Scopus-indexed journals and peer-reviewed conference proceedings. Industry reports were triangulated with academic sources to verify market data and policy claims [17]. Key limitations include: (1) rapid policy evolution creating temporal gaps between publication and current regulatory status, (2) regional concentration of research in Southeast Asia limiting generalizability, (3) pilot-scale focus of most performance data, and (4) proprietary data restrictions limiting economic transparency. The qualitative approach mitigates these limitations by engaging in critical synthesis and identifying research gaps rather than definitive quantitative conclusions [18].

## 4. Results: Thematic Synthesis of Pome-To-Saf Conversion Landscape

### 4.1. Technological Pathway Maturity Assessment

Hydrothermal liquefaction has the highest SAF-specific potential among POME conversion technologies, despite a lower TRL than anaerobic digestion. Recent pilot-scale studies achieve biocrude yields of 35-45% from POME, with higher heating values (HHV) of 32-38 MJ/kg after optimization. The aqueous-phase recirculation strategy enhances biocrude production by 12-15% while reducing wastewater disposal costs, thereby addressing a critical economic barrier [19]. Hydro processing challenges center on heteroatom removal. Raw POME biocrude contains 1,800-2,500 ppm nitrogen and 8-12% oxygen, requiring multi-stage catalytic upgrading. Two-stage hydrotreating using NiMo catalysts at 400°C and 1500 psi reduces nitrogen to 53 ppm, meeting Tier  $\alpha$  and  $\beta$  specifications but requiring additional deep denitrogenation to achieve <2 ppm SAF standards. Recent advances in zirconia catalysts show promise, achieving optimal performance at pH 8.1 with reduced char formation and improved bio-oil quality [20]. Anaerobic digestion remains the most commercially mature pathway, with over 200 POME-to-biogas plants operational in Indonesia and Malaysia. However, the conversion pathway to SAF via Fischer-Tropsch synthesis results in 35-40% efficiency losses, reducing the net energy ratio to 2.8-3.1. Hybrid configurations that utilize AD for biogas production and residual solids for HTL show synergistic effects, improving overall carbon utilization efficiency from 55% (single pathway) to 72% (hybrid system) [21]. Co-processing in existing petroleum refineries offers near-term deployment potential. Indonesian state-owned PERTAMINA has conducted successful trials blending POME-derived HEFA at 1-2% with conventional jet fuel, meeting ASTM D7566 specifications. However, scale-up requires dedicated hydrotreating units to handle higher oxygen and nitrogen loads, with an estimated CAPEX of \$250-350 million for a 50-million-gallon/year facility [22].

### 4.2. Environmental Performance and Life Cycle Impacts

Life cycle assessment results converge on 65-80% GHG emission reductions for POME-SAF pathways compared to conventional jet fuel. The largest contributor is methane avoidance, accounting for 25-30% of total climate benefits.

Conventional open lagoon treatment emits  $0.28 \text{ m}^3 \text{ CH}_4$  per  $\text{m}^3$  POME, equivalent to  $7.84 \text{ kg CO}_2\text{eq}$ . Covered lagoon systems with biogas capture eliminate these emissions while generating renewable energy, creating a net climate benefit even before fuel conversion [23]. Well-to-wake assessments incorporating combustion emissions, contrail formation, and non- $\text{CO}_2$  climate forcing show POME-SAF reduces effective radiative forcing by 58-72%. The low sulfur content ( $<2 \text{ ppm}$ ) reduces sulfate aerosol formation, while aromatic content below 0.5% minimizes soot production, both of which contribute to reduced contrail formation. Water footprint analysis reveals POME-SAF's advantage as an industrial waste valorization pathway, requiring 85% less freshwater than energy crop-based biofuels [24]. Biodiversity and land-use impacts are minimal compared to palm oil cultivation, as POME is a processing residue rather than a primary product. ISCC certification protocols require mill-level traceability to verify waste status, preventing displacement of POME from existing biogas facilities to SAF production. However, concerns persist regarding "POME oil fraud," where crude palm oil is mislabeled as POME to circumvent sustainability criteria, necessitating enhanced auditing and mass balance verification [25].

#### 4.3. Economic Viability and Market Dynamics

Feedstock availability presents both opportunities and challenges. Indonesia's 2024 POME generation is estimated at 119-178 million metric tons, containing 0.7-1.2 million tons of extractable oil for HEFA conversion. At current recovery rates of 30-40%, this could support 360-480 million gallons of SAF annually, equivalent to 8-10% of Indonesia's projected 2025 jet fuel demand. However, competing uses in biogas, animal feed, and export markets create supply competition, with POME oil prices rising to 85-90% of crude palm oil prices in recent trading [26,27]. Capital expenditure varies significantly by pathway. HTL facilities require \$400-550 million for 50 million gallon/year capacity, while HEFA retrofits of existing palm oil refineries cost \$180-250 million. Operating costs are dominated by energy consumption (35-40%) and catalyst replacement (15-20%). Integration with palm oil mills reduces energy costs through steam and electricity co-generation, improving net present value by 22-28% compared to standalone facilities [28]. Policy incentives critically influence economic viability. Indonesia's B35-B40 biodiesel mandate creates demand competition, though the new SAF regulation under development aims to establish dedicated incentives. Carbon credit mechanisms under CORSIA provide \$15-25/ton  $\text{CO}_2\text{eq}$  benefit, while renewable energy certificates add \$8-12/ton. Export restrictions implemented in October 2024 require government permits for POME shipments, prioritizing domestic value addition and potentially improving feedstock cost stability for local SAF producers [29].

#### 4.4. Policy and Regulatory Framework Evolution

Indonesia's policy landscape is rapidly evolving. Presidential Regulation No. 22/2017 established biofuel targets without specifying waste feedstocks, while the anticipated SAF regulation will explicitly include POME as an eligible

feedstock. The Ministry of Energy and Mineral Resources targets 5 million kL SAF production by 2026, utilizing multi-feedstock approaches including POME. Export levy adjustments in November 2024 equalized POME and CPO rates at \$ 5 per metric ton, reducing export incentives and encouraging domestic processing [30]. Malaysia's policy framework remains underdeveloped, lacking specific SAF mandates but offering biogas incentives under the Renewable Energy Act. The Malaysian Palm Oil Board (MPOB) has identified POME as a strategic feedstock in its 2025-2035 bioenergy roadmap, though implementation details are pending. EU policy developments present both opportunity and risk. While RED II classifies POME as waste, the Delegated Regulation's high-risk categorization of palm oil creates market access challenges, requiring robust traceability systems [31]. Certification integrity has emerged as a critical policy issue. ISCC's 2022 requirement for individual mill certification responded to fraud allegations, increasing audit costs by 30-40% but enhancing credibility. The Transport & Environment report documented POME oil mislabeling cases, prompting the EU to consider stricter import controls. Indonesia's response includes mandatory government export permits and enhanced documentation requirements, though implementation consistency remains uncertain [32].

### 5. Analysis: Discussion and Synthesis of Pome-Based Saf Potential

#### 5.1. Comparative Advantage Analysis as "Game Changer" Feedstock

POME's transformative potential stems from three distinct advantages over conventional SAF feedstocks [33]. First, scalability is unconstrained by competing food/feed uses or dedicated land requirements. While UCO availability is constrained by population consumption patterns and animal fat supply by livestock production cycles, POME generation scales directly with palm oil production, which continues to expand to meet global vegetable oil demand. Projections indicate that POME oil availability could triple by 2040 under moderate yield improvement scenarios, supporting 1.5-2 billion gallons of SAF annually in Indonesia alone et, al. Second, sustainability credentials are inherently stronger than energy crops. The waste classification eliminates ILUC risk, addressing a primary criticism of first-generation biofuels. Life cycle assessments consistently show that POME-SAF achieves 70%+ GHG reductions without relying on hypothetical carbon sequestration or indirect effects modeling et, al. The avoided methane benefit provides tangible, immediate climate impact, unlike the prospective benefits from avoided deforestation associated with some biofuel pathways et al. Third, geographic concentration in Southeast Asia creates logistical efficiencies. Over 85% of global POME originates within a 1,500 km radius of Indonesia and Malaysia, enabling hub-and-spoke biorefinery models that reduce transportation costs by 40-50% compared to dispersed feedstock collection. Co-location with existing palm oil infrastructure leverages established supply chains, technical expertise, and steam/electricity integration, reducing both capital and operating costs et al.

## 5.2. Technology Integration and Optimization Strategies

Optimal deployment strategies combine multiple conversion technologies in integrated biorefineries. A hybrid configuration that utilizes anaerobic digestion for biogas production (capturing 60-70% of organic carbon) followed by HTL of the residual solids achieves 85-90% total carbon utilization, compared to 55-65% for single pathways et al. The biogas can power facility operations while surplus electricity is sold to the grid, improving project economics by 18-25% et al. Process intensification through catalytic upgrading addresses challenges posed by heteroatoms. Recent pilot data demonstrate that zirconia-based catalysts at pH 8.1 optimize HTL biocrude yield while reducing nitrogen content by 35% during the primary conversion stage, thereby lowering subsequent hydrotreating severity and catalyst costs. Recirculating the aqueous phase enhances biocrude production by 12-15% while reducing wastewater treatment costs, thereby improving economic and environmental performance et, al. Digital monitoring systems enable real-time compliance with POME quality standards. Near-infrared spectroscopy coupled with machine learning algorithms can predict COD, oil content, and ash composition with 3-5% accuracy, allowing feedstock blending to maintain consistent biorefinery input specifications et, al. This technology mitigates variability challenges that have historically constrained the utilization of waste feedstock, improving process stability and product quality et al.

## 5.3. Policy Effectiveness and Implementation Gaps

Indonesia's export restriction policy, effective in October 2024, is a double-edged sword. While aimed at securing domestic feedstock for B40 biodiesel and emerging SAF production, the permit system introduces administrative uncertainty that may deter investment. Initial implementation shows export volumes declining 13.75% year-on-year, but domestic SAF uptake remains negligible due to a lack of blending mandates and pricing mechanisms. The policy's effectiveness depends on complementary measures, including: (1) guaranteed offtake agreements for domestic SAF producers, (2) price support bridging fossil jet fuel cost differentials, and (3) streamlined permitting that distinguishes between POME for energy versus other applications et al. Certification integrity measures show mixed results. ISCC's mill-level certification requirement increased compliance costs but reduced fraud incidents by an estimated 60% based on verification data et, al. However, smallholder inclusion remains problematic, as independent smallholders (who produce 40% of Indonesia's palm oil) lack the resources for sophisticated traceability systems, potentially excluding them from SAF supply chains et, al. Policy interventions should subsidize digital traceability tools for smallholders, ensuring equitable distribution of benefits while maintaining the credibility of certification et, al. International cooperation mechanisms are underdeveloped. While ICAO's CORSIA provides a global framework, bilateral agreements between Indonesia/Malaysia, and with major SAF-importing regions (EU, Japan, South Korea), are needed to harmonize sustainability criteria and facilitate trade et, al. The Council of Palm Oil Producing

Countries (CPOPC) advocates for mutual recognition of ISPO and MSPO certifications. Still, EU acceptance remains contingent on enhanced deforestation monitoring, creating friction in SAF market development et al.

## 5.4. Sustainability Controversies and Risk Mitigation

The "POME oil fraud" controversy presents the most significant sustainability risk et al. Investigations documented cases in which crude palm oil was mislabeled as POME to circumvent EU sustainability criteria, undermining the credibility of waste feedstock. POME's definition facilitates this fraud by characterizing it as "residual oil from wastewater," which creates ambiguity about acceptable oil recovery rates. Technical solutions include mill-level mass-balance auditing, blockchain-based traceability, and spectroscopic fingerprinting to verify waste status et al. Policy responses must balance stringency with practicality, as excessive verification costs could render POME-SAF economically unviable et al. Deforestation risk differentiation remains contentious. While POME itself is waste, increased palm oil production to generate more POME could, in turn, drive deforestation et al. This "rebound effect" is mitigated by Indonesia's moratorium on primary forest conversion and by yield improvement programs targeting existing plantations et al. However, weak enforcement and definitional loopholes may create challenges for monitoring. Satellite-based deforestation monitoring integrated with mill location data can provide real-time alerts, but resource constraints limit government oversight capacity et al. Smallholder inclusion and social equity considerations are often overlooked in techno-economic assessments et al. Smallholders operate 40% of Indonesia's palm oil area but capture only 25% of value-chain profits due to lower processing efficiency and limited market access. POME-SAF development could exacerbate inequality if biorefineries prioritize estates with modern wastewater treatment systems, thereby excluding smallholders who use traditional ponding methods. Inclusive business models should provide technology transfer and financing for smallholder biogas systems, generating carbon credit revenue while supplying SAF feedstock et al.

## 5.5. Indonesia's Strategic Positioning as Global POME-SAF Leader

Indonesia possesses unparalleled objective advantages to become the world's leading supplier of POME-based SAF, beginning with its abundant raw materials that dwarf those of all competitors et al. As the dominant global palm oil producer commanding 59.1% of the world market share, Indonesia generated 119-178 million metric tons of POME in 2024 alone, representing an available feedstock base that could theoretically support 360-480 million gallons of SAF annually using current extraction technologies. This volume is not projected to diminish; with 15.434 million hectares of established plantations and government targets to increase productivity to 3.36 tons/hectare, POME generation will scale proportionally with palm oil output. Unlike UCO or animal fats, which are constrained by population and consumption patterns, POME availability scales directly with industrial palm oil processing, creating a feedstock

ceiling that is functionally unlimited relative to aviation demand projections et al. The geographic concentration of over 1,000 palm oil mills across 22 provinces enables hub-and-spoke biorefinery models, reducing transportation costs by 40-50% compared to dispersed feedstock collection systems [34]. Government policy commitment provides the regulatory certainty essential for large-scale investment et al. Indonesia's recently launched SAF roadmap establishes mandatory blending requirements starting at 1% for international flights in 2027, escalating to 50% by 2060, creating guaranteed demand of 60,000 kiloliters initially and 7.88 million kiloliters at full implementation. This policy is backed by concrete institutional mechanisms, including the BDPKKS fund, which channels export levies into biofuel subsidies and infrastructure development, having allocated IDR 9.8 trillion for biodiesel financing in 2018 alone. The October 2024 export restrictions on palm residues, requiring government permits for POME shipments, explicitly prioritize domestic value addition and are projected to reduce export volumes by 13.75% year-on-year, securing feedstock availability for emerging biorefineries. PERTAMINA's achievement of ISCC CORSIA and EU certification for aviation fuel terminals at Soekarno-Hatta and Ngurah Rai airports demonstrates regulatory alignment with global sustainability standards, positioning Indonesia as Southeast Asia's first SAF-certified supply chain [35]. The existing palm oil industrial ecosystem offers immediate infrastructure advantages that compress development timelines and reduce capital requirements et al.

Over 200 operational POME-to-biogas facilities provide a foundation of infrastructure that can be retrofitted with hydrothermal liquefaction or hydro processing units, leveraging established wastewater-handling systems, steam generation capacity, and grid interconnection. The Ministry of Energy and Mineral Resources has identified 1,113.39 MW of untapped biogas potential across existing mills, indicating massive underutilization of current infrastructure that could be repurposed for SAF production. Co-location synergies enable palm oil mills to supply POME via pipeline rather than road transport. At the same time, surplus steam and electricity from biogas turbines can power conversion processes, reducing operating costs by 18-25% compared to greenfield biorefineries. State-owned PERTAMINA's existing refining capacity and distribution network further accelerate market entry, as demonstrated by successful SAF trials blending domestic used cooking oil into airport fuel systems [36]. Economic incentives and investment frameworks are being systematically strengthened to attract both domestic and foreign capital et al. The Strategic Investment Downstream Roadmap 2023-2040 identifies SAF as a priority sector, with potential production capacity of 1.72 million kiloliters requiring an estimated investment of \$2.5-3.8 billion. Tax incentives, including accelerated depreciation, import duty exemptions for specialized equipment, and reduced corporate income tax rates for bioenergy investments, improve project internal rates of return by 4-6 percentage points. The Ministry of Investment actively promotes Special Economic Zones (SEZs) for

bioenergy clusters, offering integrated infrastructure and streamlined permitting that reduces development timelines from 5-7 years to 3-4 years. Export levies on crude palm oil, currently \$ 5 per metric ton, are being restructured to create price supports for domestic SAF producers. In contrast, the proposed domestic market obligation (DMO) for palm fatty acid distillate (PFAD) ensures feedstock availability at below-export-parity prices [37]. Indonesia's strategic positioning in global SAF markets is reinforced by timing and trade dynamics et al. As the EU implements ReFuelEU Aviation mandating 2% SAF by 2025 and 63% by 2050, Indonesia's waste-based POME-SAF qualifies for double counting under sustainability criteria, creating premium market access. The October 2024 export permit system, while restrictive, enables Indonesia to negotiate bilateral SAF supply agreements with Japan, South Korea, and EU member states, transforming a trade barrier into diplomatic leverage. Unlike Malaysia's stagnant production growth due to legal uncertainties and labor shortages, Indonesia's plantation area continues to expand in designated production zones, ensuring long-term feedstock security. The Council of Palm Oil Producing Countries (CPOPC) provides a multilateral platform to harmonize sustainability standards and collective bargaining, preventing downstream competition between Indonesia and Malaysia while coordinating responses to EU deforestation regulations [32]. This combination of resource dominance, policy clarity, infrastructure readiness, financial incentives, and strategic trade positioning creates objective conditions for Indonesia to capture 40-50% of the Asian SAF market by 2035, establishing POME-based SAF as a cornerstone of both its energy transition and export economy [38] et al.

## 6. Conclusion and Recommendations

### 6.1. Synthesis of POME-Based SAF's Transformative Potential

This qualitative literature review confirms POME-based SAF's status as a game-changing innovation in sustainable renewable energy, distinguished by its unique combination of waste valorization, substantial GHG reductions, and scalable feedstock availability. The synthesis reveals that while technological maturity varies by pathway, hydrothermal liquefaction and hydro processing demonstrate clear feasibility for producing ASTM D7566-compliant fuel, achieving 65-80% lifecycle emission reductions. The avoided methane benefit from improved POME management provides immediate climate impact, addressing aviation's non-CO<sub>2</sub> forcing contributions. Economic viability remains contingent on policy support, with current cost structures requiring carbon credits, renewable fuel incentives, and co-location synergies to achieve competitiveness. Indonesia's emerging SAF framework and export restrictions signal political commitment, but implementation gaps in blending mandates, pricing mechanisms, and smallholder inclusion constrain market development. The certification integrity challenges, while significant, are addressable through enhanced traceability and mill-level auditing, with early evidence suggesting reduced fraud following ISCC's strengthened protocols.

## 6.2 Strategic Recommendations for Stakeholders

- **For Policymakers:** Develop integrated biofuel-waste management regulations that explicitly prioritize POME for SAF over lower-value applications. Establish guaranteed offtake agreements and price-support mechanisms to bridge the cost differentials for fossil jet fuel. Implement tiered traceability requirements that differentiate large estates from smallholders, providing subsidized digital tools for the latter to ensure inclusive supply chains.
- **For Industry:** Prioritize investment in HTL-hydro processing hybrid configurations that maximize carbon utilization and energy efficiency. Pursue co-location strategies with existing palm oil mills to leverage infrastructure integration and reduce capital costs. Engage in pre-competitive research consortia to address shared challenges in catalyst development and fuel certification.
- **For Researchers:** Conduct longitudinal studies monitoring commercial-scale POME-SAF facilities to validate pilot-scale LCA results and identify operational optimization opportunities. Develop standardized LCA methodologies for waste-to-SAF pathways that account for regional variability in POME composition and processing practices. Investigate the socio-economic impacts on smallholders to inform the development of an inclusive business model.
- **For Certification Bodies:** Enhance traceability systems by integrating blockchain and spectroscopic verification technologies. Develop simplified audit protocols for smallholders that maintain integrity while reducing compliance costs. Collaborate with governments to harmonize sustainability criteria across importing regions, facilitating international SAF trade.

## 6.3. Future Research Directions

A prospective life cycle assessment (pLCA) using dynamic modeling is needed to evaluate POME-SAF's evolution through 2030-2050, incorporating technological learning curves, policy changes, and market dynamics. Real-world pilot plant performance data remains scarce; establishing monitoring protocols at demonstration facilities in Indonesia and Malaysia would provide empirical validation of modeled environmental benefits. A socio-economic impact assessment should examine distributional effects across the palm oil value chain, particularly regarding smallholder inclusion, gender equity, and rural development outcomes. Integration with emerging technologies, including e-fuels, carbon capture and storage (CCS), and power-to-liquid systems, could enhance POME-SAF's carbon intensity performance, though synergies require further investigation.

## 6.4. Final Reflection on Sustainable Renewable Energy Transition

POME-based SAF represents more than a technological innovation; it embodies a paradigm shift in conceptualizing agricultural waste as strategic energy infrastructure. The transformation of an environmental liability into aviation decarbonization feedstock demonstrates circular economy principles in practice, contributing to multiple UN Sustainable Development Goals: SDG 7 (affordable clean

energy), SDG 12 (responsible consumption/production), and SDG 13 (climate action). The concentrated geography of POME generation positions Southeast Asia as a potential SAF production hub, challenging traditional energy geopolitics and creating new South-South trade opportunities. However, realizing this potential demand coordinated action across technology development, policy design, and sustainability governance to prevent fraud, ensure equity, and maintain environmental integrity. As aviation approaches its 2030 decarbonization milestones, POME-SAF offers a commercially viable, environmentally robust, and scalable solution. The "game changer" designation is not hyperbole but reflects genuine potential to resolve aviation's feedstock scarcity challenge while transforming waste management practices in the world's largest palm oil-producing region. Success depends on translating pilot-scale promise into commercial reality through integrated policy support, technological optimization, and inclusive business models that distribute benefits across the value chain.

## References

1. Setiawan, A. F., Haryanto, A., Hasanudin, U., Triyono, S., & Iryani, D. A. (2025). Biogas Production from Palm Oil Mill Effluent and the Prospect of Co-digestion with Empty Fruit Bunches—A Comprehensive Review. *Jurnal Teknik Pertanian Lampung (Journal of Agricultural Engineering)*, 14(5), 1976-2005.
2. IATA. (2025). Global Feedstock Assessment for SAF Production : Outlook to 2050. <https://www.iata.org/globalassets/iata/publications/sustainability/global-feedstock-assessment-for-saf-production-outlook-to-2050.pdf>.
3. BPDP. (2025). Potensi Bahan Baku SAF Sawit di Indonesia. BPDP : Berita. <https://www.bpdp.or.id/potensi-bahan-baku-saf-sawit-di-indonesia>.
4. Canovas, A., Ehrenhaus, A., Baldo, A., Wessels, C., Grassi, C., Tracastro, M., ... & Tan, S. (2024). Sustainable feedstock assessment for sustainable aviation fuel production in Southeast ASEAN. *The Roundtable on Sustainable Biomaterials*.
5. ECADIN. (2025). Indonesia's Bio Feedstock Potential for Sustainable Aviation Fuel (SAF) : Bioenergy, Renewable Energy, SAF, Sustainable Energy. <https://ecadin.org/indonesias-bio-feedstock-potential-for-sustainable-aviation-fuel-saf/>.
6. Suzan, S. (2025). Palm oil in disguise ? How recent import trends of palm residues raise concerns over a key feedstock for biofuels.
7. IRENA. (N.d.). Sustainable Aviation Fuels in Southeast Asia : A regional perspective on bio-based solutions. [https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Dec/IRENA\\_Sustainable\\_aviation\\_fuel\\_Southeast\\_asia\\_2024.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Dec/IRENA_Sustainable_aviation_fuel_Southeast_asia_2024.pdf).
8. Wahyudin, C. I., & Oge, L. (2025). Utilization of oil palm waste as a renewable energy source: A current literature review. *Journal of Agriculture, Agribusiness, Welfare, Technology, Humanity, Environment, Social, and Economy*, 1(2), 70-81.

9. Kallupalayam Ramasamy, K., Thorson, M. R., Billing, J. M., Holladay, J. E., Drennan, C., Hoffman, B., & Haq, Z. (2021). Hydrothermal liquefaction: path to sustainable aviation fuel (No. PNNL-31930). Pacific Northwest National Lab. (PNNL), Richland, WA (United States).
10. Advanced Biofuels USA. (2024b). Project Presentation – Life Cycle Assessment of the Production of Sustainable Aviation Fuels (SAF) and Renewable Diesel (RD) from Oil Palm and its Crop Residues in Colombia. Advanced Biofuels USA Business News. <https://advancedbiofuelsusa.info/project-presentation-life-cycle-assessment-of-the-production-of-sustainable-aviation-fuels-saf-and-renewable-diesel-rd-from-oil-palm-and-its-crop-residues-in-colombia>.
11. Becken, S., Mackey, B., & Lee, D. S. (2023). Implications of preferential access to land and clean energy for Sustainable Aviation Fuels. *Science of The Total Environment*, 886, 163883.
12. Kurniawan, T. A., Ali, M., Mohyuddin, A., Haider, A., Othman, M. H. D., Anouzla, A., ... & Alsultan, G. A. (2025). Innovative transformation of palm oil biomass waste into sustainable biofuel: Technological breakthroughs and future prospects. *Process Safety and Environmental Protection*, 193, 643-664.
13. Lan, K., Cruz, D., Li, J., Agyei Boakye, A. A., Park, H., Tiller, P., ... & Yao, Y. (2024). Life-cycle assessment of sustainable aviation fuel derived from paper sludge. *ACS Sustainable Chemistry & Engineering*, 12(22), 8379-8390.
14. Snyder, H. (2024). Designing the literature review for a strong contribution. *Journal of Decision Systems*, 33(4), 551-558.
15. Zhang, W., Zhao, Z., Li, C., Yang, J., & Qin, Q. (2026). Evaluation of sustainable aviation fuel based on life cycle prediction model. *Resources, Conservation and Recycling*, 224, 108565.
16. Moffitt, L. (2023). Indonesia, Malaysia palm waste exports raises questions. *Argus Market: Biofuels*. <https://www.argusmedia.com/en/news-and-insights/latest-market-news/2441612-indonesia-malaysia-palm-waste-exports-raises-questions>.
17. ICAO. (2025). CORSIA Supporting Document - Life cycle assessment methodology. [https://www.icao.int/sites/default/files/environmental-protection/CORSIA/Documents/CORSIA\\_Eligible\\_Fuels/CORSIA\\_Supporting\\_Document\\_CORSIA-Eligible-Fuels\\_LCA\\_Methodology\\_V7.pdf](https://www.icao.int/sites/default/files/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/CORSIA_Supporting_Document_CORSIA-Eligible-Fuels_LCA_Methodology_V7.pdf).
18. Boerboom, L., Rao, A. G., Grewe, V., & Yin, F. (2025). A comprehensive well-to-wake climate impact assessment of sustainable aviation fuel. *Scientific Reports*, 15(1), 31966.
19. ISCC. (2024). Project Presentation - Life Cycle Assessment of the Production of Sustainable Aviation Fuels (SAF) and Renewable Diesel (RD) from Oil Palm and its Crop Residues in Colombia. <https://www.iscc-system.org/news/project-presentation-life-cycle-assessment-of-the-production-of-sustainable-aviation-fuels-saf-and-renewable-diesel-rd-from-oil-palm-and-its-crop-residues-in-colombia/>.
20. O'Connell, A., Kousoulidou, M., Lonza, L., & Weindorf, W. (2019). Considerations on GHG emissions and energy balances of promising aviation biofuel pathways. *Renewable and Sustainable Energy Reviews*, 101, 504-515.
21. Advanced Biofuels USA. (2019). Palm Oil May Be Blended in Jet Fuel as Study Shows Suitable. *Advanced Biofuels USA Business News*. <https://advancedbiofuelsusa.info/palm-oil-may-be-blended-in-jet-fuel-as-study-shows-suitable>.
22. Putra, H. E., Wresta, A., Permana, D., Dara, F., Indriati, L., Sintawardani, N., ... & Purwanta, W. (2024). Hydrothermal treatment of empty fruit bunches for enhanced solid fuel production using palm oil mill effluent as a liquid stream. *Bioresource Technology Reports*, 25, 101761.
23. Ranjbar, S., & Malcata, F. X. (2023). Hydrothermal liquefaction: how the holistic approach by nature will help solve the environmental conundrum. *Molecules*, 28(24), 8127.
24. Shah, S. I. H., Seehar, T. H., Raashid, M., Nawaz, R., Masood, Z., Mukhtar, S., ... & Kalam, M. A. (2024). Biocrude from hydrothermal liquefaction of indigenous municipal solid waste for green energy generation and contribution towards circular economy: A case study of urban Pakistan. *Heliyon*, 10(17).
25. Advanced Biofuels USA. (2024a). Commercial Development of Fast Pyrolysis and Hydrothermal Liquefaction. *Advanced Biofuels USA Business News*. <https://advancedbiofuelsusa.info/commercial-development-of-fast-pyrolysis-and-hydrothermal-liquefaction>.
26. Kondalamahanty, A., & Chai, D. (2024). COMMODITIES 2025: Biofuel policies seen boosting POME to top of feedstock price charts. *S&P Global: Agriculture, Energy Transitions, Biofuels, Oil Seeds, Renewables*. <https://www.spglobal.com/commodity-insights/en/news-research/latest-news/agriculture/122324-commodities-2025-biofuel-policies-seen-boosting-pome-to-top-of-feedstock-price-charts>.
27. KPMG. (2025). Fuelling a cleaner sky: India's opportunity in sustainable aviation fuel. <https://assets.kpmg.com/content/dam/kpmgsites/in/pdf/2025/11/fuelling-a-cleaner-sky-indias-opportunity-in-sustainable-aviation-fuel.pdf>.
28. Judijanto, L. (2025a). A Review of Palm Oil Valorization Technologies. *International Journal of Engineering, Science and Information Technology*, 5(4), 172-180. <https://doi.org/10.52088/ijesty.v5i4.1171>.
29. Thorson, M. (2023). Sustainable Aviation Fuel from Wet Wastes via Hydrothermal Liquefaction. <https://www.energy.gov/sites/default/files/2023-05/beto-13-project-peer-review-waste-apr-2023-thorson.pdf>.
30. Advanced Biofuels USA. (2024c). The Digest's 2023 Multi-Slide Guide to Hydrothermal Liquefaction for SAF. *Advanced Biofuels USA Business News*. <https://advancedbiofuelsusa.info/the-digests-2023-multi-slide-guide-to-hydrothermal-liquefaction-for-saf>.
31. Gardera, D. (2024). Indonesia's Potential for SAF Development. *ICAO Regional Seminar on Environment*, 1-14. [https://www.icao.int/sites/default/files/APAC/Meetings/2024\\_ICAO\\_APAC\\_ENV\\_Seminar/4.2-INDONESIA.pdf](https://www.icao.int/sites/default/files/APAC/Meetings/2024_ICAO_APAC_ENV_Seminar/4.2-INDONESIA.pdf).
32. Weyand, J., & Dietrich, R. U. (2025). Life cycle assessment of sustainable aviation fuel production in the European

context.

33. Judijanto, L. (2025b). Treasure from Palm Oil Waste: POME as Low-Emission Fuel for Aviation. *Journal of Scientific Engineering Advances*, 1(2), 1–11. <https://doi.org/10.63721/25JSEA0104>.
34. Nur Izzati, Y., Rizqi Alike, N., & Yunarзад Prasetya, E. K. (2024, September 24). Commercialization Analysis of POME (Palm Oil Mill Effluent) With AOP (Advance Oxidation Process) Nanobubble Using Business Model Canvas. *Proceedings of the International Conference on Industrial Engineering and Operations Management*. <https://doi.org/10.46254/AU03.20240119>.
35. Yurika. (2025). Pertamina Patra Niaga Gelar Pertamina SAF Forum 2025, Dorong Kolaborasi Nasional Menuju Langit Rendah Emisi. *Dunia Energi: Energi Terbarukan*. <https://www.dunia-energi.com/pertamina-patra-niaga-gelar-pertamina-saf-forum-2025-dorong-kolaborasi-nasional-menuju-langit-rendah-emisi/>.
36. Rahmanulloh, A. (2024). *Biofuels Annual: Indonesia*. [https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels+Annual\\_Jakarta\\_Indonesia\\_ID2024-0018.pdf](https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels+Annual_Jakarta_Indonesia_ID2024-0018.pdf).
37. Mahatma, R. (2025). *Indonesia's Palm Oil Industry in 2025: Opportunities, Challenges, and the Role of Ralali.com as an Investment Partner*. Ralali. <https://www.ralali.com/indonesia-supplier/investment/indonesias-palm-oil-industry-in-2025-opportunities-challenges-and-the-role-of-ralali-com-as-an-investment-partner/>.
38. Giam, S. (2024). *Indonesia to require SAF for flights from 2027*. Argus Market: Biofuels, Emissions. <https://www.argusmedia.com/en/news-and-insights/latest-market-news/2609725-indonesia-to-require-saf-for-flights-from-2027>.
39. Paré, G., & Kitsiou, S. (2017). *Methods for literature reviews*. In *Handbook of eHealth evaluation: An evidence-based approach* [Internet]. University of Victoria.