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Indonesia's Strategic Opportunity in POME-based Sustainable Aviation Fuel: Prospects, Challenges, and Policy Recommendations for Emerging Biorefinery Industries

Loso Judijanto

IPOSS Jakarta, Indonesia

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Abstract

Indonesia possesses unparalleled potential to become a leading global producer of sustainable aviation fuel (SAF) derived from palm oil mill effluent (POME), a waste residue from crude palm oil processing. With 256 million tonnes of fresh fruit bunches processed annually across 1,386 mills, Indonesia's recoverable POME oil potential reaches approximately 2.5 million tonnes yearly—sufficient to generate 2-3 million kilolitres of SAF, substantially exceeding domestic aviation demand while enabling significant exports. The International Civil Aviation Organization's November 2025 approval of POME-based SAF's life cycle assessment default value of 18.1 gCO₂e/MJ—representing 79.6% greenhouse gas emission reductions compared to conventional jet fuel—creates immediate commercial viability. This qualitative literature review synthesizes evidence from academic research, industry reports, policy documents, and technical standards to comprehensively examine the prospects and challenges of Indonesia's POME-based SAF. Key prospects include abundant, scalable feedstock availability, superior environmental performance, circular-economy value creation, and supportive policy development trajectories. Critical challenges encompass technological barriers in oil recovery and pretreatment, substantial infrastructure gaps, policy and regulatory ambiguities, capital-intensive financing requirements, complex feedstock supply chain management, and environmental/social sustainability concerns, a legacy of Indonesia's palm oil sector. Success requires integrated solutions that combine dedicated government financing mechanisms, regulatory clarity on feedstock governance, coordinated infrastructure investment, strengthened sustainability assurance systems, enhanced international collaboration on technology transfer and capacity building, and inclusive approaches that ensure smallholder participation. Indonesia's transition to a leading POME-based SAF producer will catalyze decarbonization of regional aviation while advancing downstream industrialization, resource efficiency, and green economic development.

*__Corresponding author__: Loso Judijanto, IPOSS Jakarta, Indonesia.

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Introduction

Background

The global aviation industry faces mounting pressure to achieve net-zero carbon emissions by 2050, a commitment solidified at the International Civil Aviation Organization (ICAO) Assembly in October 2022. Aviation emissions currently account for approximately 2-3% of global carbon dioxide emissions. Without significant intervention, these emissions are projected to increase from 600 million tonnes of CO2 in 2019 to nearly 900 million tonnes by 2035. The sector's decarbonization pathway depends heavily on Sustainable Aviation Fuel (SAF), which is expected to account for 65% of emissions reductions by 2050, surpassing the combined impact of technological improvements, operational efficiencies, and market-based mechanisms [1].

Global demand for SAF is projected to increase dramatically from approximately 0.3 billion gallons in 2025 to 3.68 billion gallons by 2030, eventually reaching 515 million tonnes by 2050. This exponential growth creates unprecedented opportunities for countries with abundant biomass resources to position themselves as major SAF producers. The hydroprocessed esters and fatty acids (HEFA) pathway currently dominates SAF production, accounting for over 90% of expected capacity through 2028, though its scalability is constrained by feedstock availability [1].

Indonesia, as the world's largest palm oil producer with an annual crude palm oil (CPO) production of approximately 46-52 million tonnes from 16.38 million hectares of palm oil plantations, possesses unique advantages in developing a robust SAF industry. The palm oil production process generates substantial quantities of waste and residues that can serve as CORSIA-eligible feedstocks for SAF production. Among these, Palm Oil Mill Effluent (POME) has emerged as a particularly promising feedstock following ICAO's official recognition and approval of its Life Cycle Assessment (LCA) default value in November 2025 [2].

POME is an unavoidable residue generated during CPO production, consisting of oil, wastewater, and solids lost primarily from sterilization stations and sludge tanks. According to the International Sustainability and Carbon Certification (ISCC) guidelines, the POME oil recovery potential ranges from 0.76% to 2.88% of the total fresh fruit bunches (FFBs) processed, depending on the sterilizer system used. With Indonesia processing approximately 256 million tonnes of FFB annually through 1,386 palm oil mills, the potential POME oil recovery could reach 2.5 million tonnes annually, assuming a conservative 1% recovery rate. When combined with other palm-based waste oils, such as used cooking oil (UCO) and palm fatty acid distillate (PFAD), Indonesia's total SAF production capacity through the HEFA pathway could reach 2-5 million tonnes annually [3-6].

The significance of POME as a SAF feedstock extends beyond its abundance. ICAO has established an LCA default value of 18.1 gCO2e/MJ for POME-based SAF, representing a 79.6% reduction compared to conventional jet fuel's 89 gCO2e/MJ. This exceptional greenhouse gas (GHG) emission reduction performance, free from indirect land use change (ILUC) penalties due to its classification as waste residue, positions POME-based SAF as one of the most environmentally favorable options under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [7].

Urgency

The urgency for Indonesia to develop its POME-based SAF industry stems from multiple converging factors. First, the implementation of mandatory SAF blending requirements is accelerating globally. The European Union's ReFuelEU Aviation initiative mandates progressive SAF blending starting at 2% in 2025 and targeting 70% by 2050. The United States continues to provide substantial tax credits through the Inflation Reduction Act, while Asia-Pacific nations are rapidly establishing their own mandates [8].

Indonesia itself has announced ambitious SAF implementation targets, requiring international flights departing from Indonesian airports to use 1% SAF by 2027, escalating to 2.5% by 2030, 12.5% by 2040, 30% by 2050, and ultimately 50% by 2060. This domestic mandate creates immediate demand of approximately 60,000 kilolitres in 2027, rising to 7.88 million kilolitres by 2060. These requirements necessitate the rapid development of domestic SAF production capacity to avoid dependence on expensive imports and to capture economic value within Indonesia [8].

Second, the window of opportunity for establishing first-mover advantages is narrowing. Despite Indonesia's abundant feedstock potential, competition from other Southeast Asian palm oil-producing nations is intensifying. Malaysia, Thailand, and other regional producers are similarly exploring palm-based SAF pathways. Countries that establish production capacity, secure technology partnerships, and develop certification infrastructure earlier will capture greater market share and establish competitive advantages difficult for later entrants to overcome [9].

Third, the recent ICAO approval of POME's LCA default value in November 2025 creates immediate commercial viability for POME-based SAF projects. Prior to this approval, each SAF project utilizing POME would have required costly and time-consuming individual LCA certifications. The establishment of a standardized default value of 18.1 gCO2e/MJ enables immediate use for mandate compliance and airline offtake agreements, significantly de-risking investments and accelerating project financing [10].

Fourth, environmental imperatives demand urgent action. Traditional POME treatment through open ponding systems releases substantial methane emissions, contributing significantly to Indonesia's GHG inventory. Converting POME into SAF simultaneously addresses waste management challenges, reduces methane emissions, recovers valuable resources, and produces low-carbon aviation fuel—delivering multiple sustainability co-benefits that align with Indonesia's nationally determined contributions under the Paris Agreement [11].

Finally, economic development imperatives underscore the urgency. The SAF industry could generate up to 14 million jobs globally by 2050, with 90% occurring in feedstock supply chains. For Indonesia, developing a domestic SAF industry represents an opportunity to capture greater value from its palm oil sector, create high-skilled employment, attract foreign investment, and establish itself as a regional hub for sustainable aviation fuel production [12].

Objectives

This qualitative literature review aims to comprehensively examine the prospects and challenges facing Indonesia as it seeks to establish itself as a leading global producer of POME-based SAF. The specific objectives are:

1. **To analyze the technical and commercial prospects that position Indonesia favorably for POME-based SAF production**, including feedstock availability, technological readiness, market demand dynamics, and competitive advantages relative to other feedstock pathways and regional competitors.

2. **To identify and critically evaluate the multidimensional challenges confronting POME-based SAF development in Indonesia**, encompassing technological barriers, infrastructure limitations, policy and regulatory gaps, financial and investment constraints, supply chain and logistics complexities, and sustainability certification requirements.

3. **To examine the conceptual frameworks and theoretical perspectives relevant to sustainable biofuel development**, circular economy principles in the palm oil industry, technology transfer mechanisms, and the political economy of industrial policy in resource-rich developing nations.

4. **To synthesize evidence-based insights that can inform strategic recommendations for policymakers, industry stakeholders, and international development partners** seeking to accelerate Indonesia's transition toward becoming a major POME-based SAF producer.

By addressing these objectives, this review contributes to the academic and policy discourse on sustainable aviation fuel development in emerging economies and provides practical insights for stakeholders navigating Indonesia's evolving bioeconomy landscape.

Literature Review

Conceptual Framework: Sustainable Aviation Fuel and Biofuel Pathways

Sustainable Aviation Fuel is a category of renewable fuels designed to reduce life-cycle GHG emissions compared to conventional jet fuel while maintaining full compatibility with existing aircraft engines, distribution infrastructure, and fuel-handling systems—a characteristic known as "drop-in" capability. The International Civil Aviation Organization defines SAF as fuel that meets stringent technical specifications under ASTM D7566 standards and achieves minimum GHG emission reductions of 10% compared to a baseline of conventional jet fuel (89 gCO2e/MJ) throughout its life cycle [13].

Multiple conversion pathways exist for producing SAF from various feedstock types. The HEFA pathway, which processes lipid-based feedstocks such as vegetable oils, animal fats, waste oils, and greases via hydrotreatment reactions, currently dominates commercial SAF production. During HEFA processing, feedstock oils undergo hydrodeoxygenation (HDO) to remove oxygen, followed by hydrocracking (HDC) to break longer carbon chains into jet fuel range molecules (C9-C16), and hydroisomerization/hydrodewaxing (HDW) to improve cold flow properties. This process can be optimized to produce either renewable diesel (RD) or maximize SAF yield, with typical HEFA facilities configured for 20-80% SAF output depending on reactor design, catalyst selection, and downstream fractionation capabilities [14].

Alternative pathways include Fischer-Tropsch (FT) gasification, which converts solid biomass or municipal solid waste into syngas and subsequently into jet fuel; Alcohol-to-Jet (ATJ), which processes ethanol or other alcohols derived from the fermentation of sugars or starches; and Power-to-Liquid (PtL), which combines renewable hydrogen with captured carbon to produce synthetic fuels. While these alternative pathways offer long-term potential, HEFA's technological maturity, lower capital intensity, and shorter development timelines make it the dominant near-term solution, particularly for regions with abundant lipid feedstock resources [14].

Palm Oil Mill Effluent as a Waste Residue Feedstock

POME is generated inevitably during crude palm oil extraction when fresh fruit bunches undergo sterilization, stripping, digestion, pressing, clarification, and purification. This thick, brownish colloidal suspension contains approximately 95-96% water, 2-4% suspended solids, 0.6-0.7% oil, and 0.4-0.5% residual materials. The oil component lost in POME originates primarily from the sterilization condensate and clarification sludge. Traditional treatment involves multi-stage ponding systems requiring extensive land areas and prolonged retention times, during which anaerobic decomposition generates substantial methane emissions with global warming potential 25-28 times greater than CO2 [15].

Recovery of residual oil from POME—termed "POME oil"—transforms this waste liability into a valuable feedstock asset. Modern recovery technologies employ multi-stage separation processes including gravitational settling, centrifugation, membrane filtration, and evaporation. The POMEVap system developed by Alfa Laval, for example, utilizes AlfaFlash evaporation technology to separate POME into clean water (suitable for process reuse), nutrient-rich concentrate solids (usable as animal feed or fertilizer), and recovered palm oil. For a typical palm oil mill processing 45 tonnes of FFB per hour, producing approximately 162,000 tonnes of POME annually with 1% oil content, achieving 50% recovery efficiency yields 810 tonnes of recovered oil annually, with an investment payback period of approximately 4 years [16].

POME oil's classification as a waste residue under ICAO CORSIA and EU Renewable Energy Directive frameworks provides critical advantages for SAF applications. Unlike food-crop-based feedstocks such as soybean oil, rapeseed oil, or palm oil itself—which incur ILUC penalties reflecting displacement effects and potential deforestation linkages—waste residues like POME oil carry zero ILUC values. This classification enables POME-based SAF to achieve exceptionally low life cycle emissions, with the approved ICAO default value of 18.1 gCO2e/MJ comparing favorably to used cooking oil HEFA (13.9 gCO2e/MJ), PFAD (20.7 gCO2e/MJ), tallow (22.5 gCO2e/MJ), and significantly outperforming CPO with methane capture (76.5 gCO2e/MJ) or without methane capture (99.1 gCO2e/MJ) [17].

Recent academic research confirms POME's technical suitability for SAF production. Judijanto et al. (2025) reviewed multiple conversion pathways, including anaerobic digestion for biogas production, hydrothermal liquefaction for bio-crude oil, and recovery followed by hydro treatment for HEFA-compatible feedstock. Their analysis demonstrated that hydroprocessing of recovered POME oil yields hydrocarbons with energy density approximately 43 MJ/kg—comparable to fossil jet fuel—while meeting key specifications including freezing point (-47°C), flash point (above 38°C), and sulfur content (below 15 ppm) under ASTM D7566 certification parameters [16].

Theoretical Framework: Circular Economy in the Palm Oil Industry

The circular economy paradigm, which emphasizes closing resource loops through reduction, reuse, recycling, and regeneration strategies, provides a powerful conceptual lens for understanding POME-based SAF development. Traditional linear economic models in palm oil production have treated biomass and effluent as waste burdens to be disposed of, creating environmental liabilities while foregoing economic value. Circular economy approaches reconceptualize these materials as valuable resources capable of generating new revenue streams, reducing environmental impacts, and enhancing resource efficiency [18].

Siagian et al. (2024) comprehensively examined circular economy strategies in the palm oil industry, documenting how biomass valorization, waste-to-energy initiatives, and biorefinery concepts enable the sector to decouple growth from environmental degradation. Their framework identifies multiple circular pathways, including conversion of empty fruit bunches (EFB) into pulp, paper, and bio-materials; utilization of palm kernel shells and mesocarp fiber for biomass energy; processing of palm oil mill effluent into biogas, biofertilizer, and recovered oils; and transformation of palm fatty acid distillate and other refinery residues into biodiesel, oleochemicals, and now SAF [19].

The biorefinery concept represents the pinnacle of circular-economy implementation in palm oil processing, enabling cascading value chains in which multiple products and energy streams are derived from the same biomass inputs. Integrated biorefineries can simultaneously produce food-grade oils, animal feed, bioenergy, biochemicals, and advanced biofuels, optimizing economic returns while minimizing waste. This systemic approach aligns with Indonesia's downstream industrialization strategy, which seeks to capture greater value-added from domestic natural resources rather than exporting raw materials [20].

The Roundtable on Sustainable Palm Oil (RSPO) has championed circular-economy adoption among its member companies, encouraging the utilization of biomass waste, the installation of methane capture facilities at mills, and partnerships with biorefinery developers. Leading Indonesian palm oil companies, including Sime Darby Plantation, Felda Global Ventures, and Kuala Lumpur Kepong, have implemented biogas capture systems, pelletization of empty fruit bunches, and palm trunk utilization projects. These initiatives demonstrate the technical and commercial viability of circular approaches while generating co-benefits including reduced GHG emissions, enhanced energy self-sufficiency, and diversified revenue streams [19].

POME-based SAF production exemplifies circular economy principles by transforming a waste management challenge into a high-value product opportunity. Rather than allowing POME to decompose in open ponds, releasing methane, recovering the residual oil, processing it into SAF, and utilizing the remaining water and solids for beneficial purposes creates a closed-loop system consistent with circular economy philosophy. This approach simultaneously addresses environmental compliance, resource efficiency, climate mitigation, and economic value creation—delivering the "triple bottom line" benefits that characterize successful circular transitions [18].

Technology Transfer and Capacity Building for SAF Development

The successful development of POME-based SAF production capacity in Indonesia requires effective technology transfer mechanisms and comprehensive capacity-building initiatives. Technology transfer encompasses not merely the acquisition of physical equipment and process designs, but also the accompanying knowledge, skills, operational capabilities, and innovation capacities necessary to successfully implement, operate, optimize, and ultimately advance new technologies [21].

Literature on technology transfer to developing countries emphasizes that "hardware" (physical equipment and facilities) must be complemented by "software" (human capital, institutional capacity, regulatory frameworks, and innovation systems) for sustainable technology adoption. Project-specific capacity building should be interwoven into technology transfer initiatives from the outset, developed cooperatively rather than as a passive technology recipient. Successful technology transfer creates local industrial capabilities that extend beyond individual projects, generating spillover effects that strengthen broader economic development [22].

For SAF production, technology transfer involves multiple dimensions. At the production level, it encompasses licensing of HEFA process technology from established providers such as Honeywell UOP, Haldor Topsoe, Axens, Neste Engineering Solutions, and others. These licensors provide reactor designs, catalyst formulations, process control systems, and technical support services. At the feedstock level, it includes POME oil recovery technologies, pre-treatment systems to remove water, free fatty acids, and metals, and quality assurance protocols to ensure consistent feedstock specifications. At the sustainability level, it involves implementing chain-of-custody tracking systems, obtaining ISCC, RSB, or other approved certifications, and establishing MRV (monitoring, reporting, and verification) capabilities for life cycle emissions accounting [23].

The ICAO Global Framework on SAF, LCAF, and Aviation Cleaner Energies explicitly recognizes the importance of technology transfer and capacity building for enabling developing countries to participate in SAF production. ICAO's ACT-SAF (Assistance, Capacity-building and Training for SAF) program provides technical assistance, facilitates voluntary technology transfer, and encourages capacity-building projects through feasibility studies, training programs, buddy partnerships between developed and developing nations, and matchmaking of public and private investors. Regional cooperation mechanisms in Asia-Pacific, such as the Asia Pacific SAF Collective (APSAC) launched by Singapore, aim to coordinate policy frameworks, share best practices, and mobilize financing for SAF development across multiple countries [24].

Indonesian stakeholders have begun engaging with international technology providers and development partners to build domestic SAF capabilities. State-owned Pertamina's refining subsidiary, PT Kilang Pertamina Internasional (KPI), began producing SAF from used cooking oil at its Cilacap refinery in 2024, demonstrating domestic technical capacity for HEFA processing. Engineering firms such as Tripatra Engineering have announced plans to develop integrated SAF production ecosystems, partnering with technology licensors, feedstock suppliers, and airline offtakers. These initiatives represent initial steps in Indonesia's capacity-building journey. However, significant gaps remain in areas such as feedstock collection infrastructure, adaptation of pre-treatment technology, sustainability certification expertise, and access to project financing[25].

Policy and Regulatory Frameworks for SAF Implementation

The policy and regulatory environment fundamentally shapes the economic viability, investment attractiveness, and deployment trajectory of SAF projects. Academic literature emphasizes that government policies serve as critical enablers for nascent low-carbon fuel industries facing cost premiums relative to fossil fuel incumbents. Effective policy frameworks typically combine multiple instruments, including mandates or blending obligations that create guaranteed demand, production incentives or tax credits that improve economics for producers, carbon pricing or offset mechanisms that monetize emission reductions, and sustainability standards that ensure environmental integrity [26].

Indonesia's evolution of its biofuel policy provides relevant context for SAF development. The biodiesel mandate program, initiated under Presidential Regulation No. 5/2006 and progressively strengthened through successive regulations, has successfully scaled domestic biodiesel consumption to support B30 (30% palm oil biodiesel blend) and is transitioning toward B40. This success relied heavily on the formerly Oil Palm Estate Fund (BPDPKS), which collects export levies on CPO and uses the revenues to subsidize the price difference between palm oil biodiesel and fossil diesel, ensuring the economic viability of biodiesel producers and blenders. The BPDP (formerly BPDPKS) model demonstrates Indonesia's capacity to design and implement effective biofuel support mechanisms, suggesting potential application to SAF through analogous funding structures [27].

For SAF specifically, Indonesia announced its implementation roadmap and policy action plan in September 2024, with progressive mandates for international flights departing Indonesian airports: 1% by 2027, 2.5% by 2030, 12.5% by 2040, 30% by 2050, and 50% by 2060. The action plan encompasses three policy pillars: demand-side measures, including mandates and pilot offtake agreements at major airports; supply-side measures, including domestic market obligations for PFAD, potential export quotas/tariffs for UCO, and emission-based incentives; and enablers, including appointment of national accreditation bodies for SAF certification and development of domestic certification ecosystems [8].

However, significant policy gaps persist. Unlike the established BPDPKS mechanism for biodiesel, no equivalent fund structure exists for SAF, creating uncertainty about how price premiums will be bridged to meet the mandate. Fiscal incentives such as tax holidays, accelerated depreciation, or production tax credits—common in other jurisdictions—have not been clearly defined for SAF investors. Regulations governing UCO collection, POME oil classification under Indonesian customs codes, and feedstock allocation between domestic use and export require refinement to prevent supply disruptions or fraud concerns. Infrastructure support for SAF storage, blending, and distribution at airports remains underdeveloped [28].

Comparative analysis of international policy experiences offers insights for Indonesia's policy design. The European Union's ReFuelEU Aviation regulation mandates progressive SAF blending (2% in 2025, reaching 70% by 2050) combined with sub-mandates for synthetic fuels and sustainability criteria under RED II/RED III. The United States provides production tax credits of up to $1.75 per gallon under the Inflation Reduction Act based on life-cycle emissions reductions, alongside state-level Low Carbon Fuel Standards in California, Oregon, and Washington. Singapore implements a passenger levy mechanism, with proceeds directed to SAF procurement, creating a dedicated funding source while maintaining airline competitiveness. Japan offers a production tax credit of ¥30 per liter, alongside a 10% SAF target by 2030. These diverse approaches demonstrate multiple policy pathways Indonesia could adapt to its national circumstances [29].

Methodology

Research Design

This study employs a qualitative literature review methodology to synthesize and critically analyze existing knowledge regarding Indonesia's prospects and challenges in becoming a leading producer of POME-based SAF. Unlike systematic literature reviews that follow rigid inclusion/exclusion protocols and meta-analytical techniques, qualitative literature reviews enable broader interpretive synthesis of diverse evidence types, including academic research, industry reports, policy documents, technical standards, and practitioner insights [user expertise]. This approach is particularly appropriate for emerging topics such as POME-based SAF, where the literature base spans multiple disciplines, including renewable energy technology, agricultural waste management, aviation policy, and sustainable development economics.

The qualitative approach enables the critical examination of conceptual frameworks, the identification of knowledge gaps, the integration of insights from grey literature sources (policy reports, industry publications, technical standards documents), and the development of nuanced understandings that capture the complexity of real-world SAF development dynamics. This methodology aligns with the exploratory nature of the research objectives, which seek to map the multidimensional landscape of opportunities and challenges rather than test specific hypotheses through quantitative analysis.

Data Sources and Collection

The literature base for this review was constructed through multiple complementary search strategies. Academic databases including Scopus, Web of Science, ScienceDirect, and Google Scholar were systematically searched using keyword combinations such as "POME sustainable aviation fuel," "palm oil mill effluent biofuel," "Indonesia SAF," "HEFA technology," "aviation decarbonization," "circular economy palm oil," "CORSIA life cycle assessment," and related terms. The temporal scope focused on publications from 2020 onwards to capture recent developments, with particular emphasis on 2023-2025 literature reflecting the most current technological, policy, and market dynamics.

Grey literature sources provided essential complementary information including ICAO CORSIA documentation and technical manuals, industry reports from organizations such as the International Air Transport Association (IATA), Air Transport Action Group (ATAG), Roundtable on Sustainable Biomaterials (RSB), and International Sustainability and Carbon Certification (ISCC), national policy documents including Indonesian Presidential Regulations, Ministry decrees, and national action plans, corporate sustainability reports and technical presentations, and conference proceedings from aviation and biofuels industry forums.

Two specialized documents provided by the research context—presentations on "Unlocking the Full Potential of Indonesia's Palm Oil Industry for Clean Aviation Energy" and "Pengesahan Nilai Default Value SAF Berbasis POME oleh ICAO" (Approval of POME-based SAF Default Value by ICAO)—supplied crucial primary information regarding POME oil recovery potentials, ICAO approval processes, LCA calculations, and Indonesia's SAF development strategies. These documents, while excluding organizational descriptions of IPOSS and TriPatra as specified, contained substantive technical and policy content that informed the analysis.+1

Data Analysis

The analytical process followed an iterative, thematic approach comprising several stages. Initial review and categorization involved reading all collected materials to develop familiarity with the content and creating a preliminary classification scheme, organizing sources by topic areas, including POME characteristics and recovery technology, HEFA SAF production pathways, LCA and sustainability certification, policy and regulatory frameworks, market dynamics and demand projections, circular economy concepts, technology transfer mechanisms, and infrastructure and logistics considerations.

Thematic coding then proceeded by identifying recurring themes, concepts, and arguments across the literature, and by developing codes representing key prospects, such as abundant feedstock availability, favorable LCA performance, circular economy benefits, and regional competitive advantages, as well as challenges, including technological barriers, infrastructure gaps, policy uncertainties, and financing constraints. Cross-cutting themes such as the role of international cooperation and the importance of sustainability certification were also identified.

Synthesis and interpretation involved integrating findings from multiple sources to construct coherent narratives for each central theme, identifying areas of consensus, debate, or uncertainty in the literature, and examining relationships, tensions, and trade-offs across different dimensions (for example, between rapid scale-up and sustainability assurance).

The critical evaluation assessed the quality, credibility, and limitations of sources, noted methodological approaches and potential biases across different document types, and identified knowledge gaps where evidence is limited, speculative, or contradictory. Framework development was then organized and synthesized insights using the conceptual frameworks of the circular economy, technology transfer theory, and the political economy of industrial policy to provide theoretical grounding and analytical structure.

Limitations

This qualitative review methodology has several inherent limitations that should be acknowledged. The absence of systematic protocols for article selection, quality assessment, and statistical synthesis means that findings reflect interpretive judgments rather than quantitative meta-analyses. Reliance on English-language sources may underrepresent Indonesian-language academic and policy literature that could offer additional local perspectives. The rapidly evolving nature of SAF policy and technology means some findings may become outdated as new developments occur. Grey literature sources, while valuable for practical insights, may reflect particular organizational perspectives or commercial interests rather than independent analysis. The limited operational experience with POME-based SAF production at commercial scale means that projections rely partly on theoretical modeling and extrapolations from pilot projects rather than on validated operational data.

Despite these limitations, the qualitative approach provides valuable synthesis of diverse knowledge sources and interpretive insights that complement more structured systematic review methodologies, offering a comprehensive foundation for understanding Indonesia's POME-based SAF prospects and challenges.

Results and Analysis

Thematic Analysis: Prospects of Indonesia Becoming a Leading Producer of POME-based SAF

Abundant Feedstock Availability and Scalability Potential

Indonesia's position as the world's largest palm oil producer fundamentally underpins its POME-based SAF prospects. With 16.38 million hectares of oil palm plantations across 1,386 palm oil mills processing approximately 256 million tonnes of fresh fruit bunches annually to produce 46-52 million tonnes of crude palm oil, the sheer scale of Indonesia's palm oil industry creates proportionally massive POME generation [30].

Conservative estimates suggest the POME oil recovery potential of 0.76-2.88% of FFB processed, depending on sterilizer technology and recovery efficiency. Assuming a moderate 1% recovery rate across Indonesia's national FFB processing volume yields approximately 2.56 million tonnes of recoverable POME oil annually. This single feedstock stream could theoretically support 2-3 million kilolitres of SAF production, substantially exceeding Indonesia's domestic aviation demand in 2027 (60,000 kl) and 2030 (approximately 150,000 kl), while positioning Indonesia as a potential regional exporter [8].

When combined with other palm-based waste and residue streams, including used cooking oil (300,000-600,000 tonnes annually), PFAD (2.0-2.5 million tonnes), and empty fruit bunch oil (800,000-1.5 million tonnes), Indonesia's total HEFA-compatible feedstock base could reach 5-7 million tonnes annually. This diversified feedstock portfolio reduces dependence on any single waste stream, enhancing supply resilience and enabling flexible feedstock blending based on availability and economics [9].

The geographic concentration of palm oil production in Sumatra and Kalimantan creates regional feedstock clusters that can support strategically located SAF biorefineries. Rather than requiring dispersed small-scale collection from smallholder farmers across vast areas—a challenge facing lignocellulosic biomass feedstocks—POME is generated at centralized palm oil mills with established industrial infrastructure, simplifying logistics and reducing collection costs[12].

The established nature of palm oil industry operations further enhances scalability. Indonesia's palm oil sector has decades of operational experience, mature supply chains, a trained workforce, and proven business models. Integrating POME oil recovery and SAF production into existing operations represents an incremental diversification rather than establishing an entirely new industry from scratch. This institutional maturity reduces implementation risks and accelerates deployment timelines compared to nascent feedstock systems [18].

Superior Life Cycle Environmental Performance

POME-based SAFs' exceptional GHG emission-reduction performance represents a compelling competitive advantage. The ICAO-approved default LCA value of 18.1 gCO2e/MJ demonstrates 79.6% emission reduction compared to conventional jet fuel's 89 gCO2e/MJ baseline, substantially exceeding CORSIA's minimum 10% threshold and approaching the upper end of SAF emission reduction potential [31].

This favorable LCA performance stems from POME's classification as a waste residue, exempting it from ILUC penalties that significantly burden crop-based feedstocks. The comparison with crude palm oil itself is stark: CPO-based SAF carries an LCA value of 99.1 gCO2e/MJ without methane capture or 76.5 gCO2e/MJ with methane capture, both far higher than POME's 18.1 gCO2e/MJ. Even when compared to other waste oil feedstocks, POME performs competitively, essentially equivalent to PFAD (20.7 gCO2e/MJ) and tallow (22.5 gCO2e/MJ), though slightly higher than used cooking oil (13.9-16.7 gCO2e/MJ) [31].

For airlines operating under CORSIA requirements, lower LCA values directly translate to reduced offsetting obligations. The scheme calculates airline offset requirements based on growth in emissions above established baselines, with SAF usage credited for LCA-emission reductions. Airlines using POME-based SAF with 79.6% emission reductions can claim proportionally greater carbon credit benefits than higher-emission SAF alternatives, thereby enhancing the fuel's market value and airline willingness-to-pay premiums [32-34].

Environmental co-benefits extend beyond aviation emissions. Traditional POME treatment through open ponding systems releases substantial methane—a GHG with a 25-28 times greater warming potential than CO2 over a 100-year timeframe. Converting POME to SAF eliminates these fugitive methane emissions while recovering valuable resources, delivering dual climate benefits. Additional environmental advantages include reduced water consumption through condensate reuse, minimized land requirements compared to ponding systems (POMEVap technology requires only 300 square meters versus football-pitch-sized ponds), and generation of nutrient-rich by-products usable as animal feed or fertilizer [11].

Economic Value Creation and Circular Economy Benefits

POME-based SAF development creates multiple economic value streams within Indonesia's palm oil sector. Palm oil mills currently view POME as a waste management liability requiring costly treatment infrastructure and generating no revenue. Transforming POME into a saleable feedstock converts a cost center into a profit center, improving mills' financial performance while simultaneously addressing environmental compliance requirements [11].

Economic modeling suggests attractive investment returns. The Alfa Laval POMEVap system, for example, demonstrates a payback period of approximately 4 years through combined benefits of recovered palm oil sales, reduced water consumption, elimination of methane capture requirements, and marketable by-products. At a scale processing 45 tonnes FFB per hour (162,000 tonnes POME annually), recovering 50% of the 1% oil content yields 810 tonnes of palm oil worth approximately $800,000-900,000 annually at current market prices, alongside water savings and by-product revenues [11].

The circular economy framework maximizes value extraction from palm biomass resources. Rather than linear "take-make-dispose" models, circular approaches create cascading value chains in which materials flow through multiple uses, waste from one process becomes an input to another, and economic and environmental value are simultaneously optimized. POME-based SAF exemplifies this paradigm: FFBs are processed for CPO (primary product); POME is captured rather than released; oil is recovered from POME (secondary product); recovered oil is converted to SAF (tertiary high-value product); remaining water is reused in mill operations; and concentrate solids become animal feed or fertilizer [20].

Job creation potential is substantial. The global SAF transition could sustain or create up to 14 million jobs by 2050, with 90% of those jobs occurring in feedstock supply chains. For Indonesia, developing a comprehensive POME-based SAF industry would generate employment across multiple skill levels, including agricultural workers in FFB harvesting and transportation, mill operators for POME collection and oil recovery, technicians for pretreatment and quality control, engineers and plant operators for SAF biorefineries, logistics professionals for feedstock aggregation and fuel distribution, and specialized personnel for sustainability certification and compliance [35].

Regional economic development represents another dimension of benefit. Biorefinery facilities located near feedstock clusters in Sumatra and Kalimantan stimulate rural and regional economies through employment, tax revenues, infrastructure investments, and spillover effects on supporting industries. Special Economic Zones focused on bioenergy and biochemicals could accelerate industrial clustering, attract foreign direct investment, and establish Indonesia as a regional SAF production hub [36].

Strategic Positioning in Global and Regional SAF Markets

Indonesia's geographic position in Southeast Asia—the world's fastest-growing aviation market—provides strategic advantages for the commercialization of SAF. Asia-Pacific aviation demand is projected to nearly triple by 2050 compared with 2019 levels, accounting for nearly 40% of global aviation activity. SAF demand in Asia-Pacific is consequently expected to grow rapidly, driven by national mandates in Japan (10% by 2030), India (1% by 2027, 5% by 2030), Singapore (1% by 2026, 3-5% by 2030), South Korea (1% by 2027), and Indonesia itself (1% by 2027, 2.5% by 2030) [37].

Current SAF supply in Asia-Pacific remains minimal, with most regional production exported to Europe and North America, where mandates and incentives create premium pricing. This creates a near-term "supply gap" that Indonesia could fill by developing domestic production capacity serving regional markets. First-mover advantages in establishing production facilities, securing feedstock supply chains, and building airline offtake relationships would position Indonesian producers favorably as regional mandates intensify demand beyond 2027 [38].

Feedstock advantages differentiate Southeast Asian producers from Western competitors. European and North American SAF producers rely heavily on used cooking oil, animal fats, and agricultural residues—all of which face supply constraints and intense competition. Europe's biodiesel industry already consumes much of the available UCO, with imports increasing from Asia, raising sustainability concerns about provenance tracing and fraud risks. Southeast Asia's abundant palm-based waste streams—unavailable in non-palm-producing regions—represent unique indigenous feedstocks supporting competitive production costs and supply security [1].

Indonesia's palm oil industry possesses established export infrastructure, including port facilities, shipping logistics, quality certification systems, and trade relationships that can be leveraged for SAF exports. Crude palm oil already moves through extensive international supply chains, with Indonesia exporting approximately 29 million tonnes annually to over 150 countries. Adapting this infrastructure for SAF distribution represents an incremental adjustment rather than building export capabilities from scratch [39].

Technology Readiness and Pathway Maturity

The HEFA pathway's technological maturity significantly reduces the risk of POME-based SAF commercialization. Unlike emerging pathways such as gasification, Fischer-Tropsch, alcohol-to-jet, or power-to-liquids, which remain at the demonstration or early commercial stage, HEFA technology is proven at commercial scale, with multiple operational facilities globally. Over 90% of current and near-term projected SAF capacity utilizes HEFA technology, reflecting its reliability, cost-effectiveness, and industry confidence [40].

Multiple technology providers offer licensed HEFA process designs, including Honeywell UOP (Ecofining™), Haldor Topsoe (HydroFlex™), Neste Engineering Solutions, Axens, and others. These established technology suppliers provide turnkey solutions encompassing process design, equipment specification, catalyst supply, commissioning support, and operational assistance, reducing technical risks for project developers. The presence of multiple competing technology providers enhances access and negotiating leverage for Indonesian developers compared to proprietary technologies controlled by a single entity [14].

Process flexibility represents another advantage. HEFA units can be designed to handle diverse lipid feedstocks with varying free fatty acid contents, moisture levels, and impurity profiles. This flexibility enables Indonesian facilities to process multiple feedstock blends—POME oil, UCO, PFAD, EFB oil—depending on seasonal availability and relative economics, improving capacity utilization and financial resilience. Facilities can also be configured to produce flexible ratios of renewable diesel and SAF, adapting output to market demand dynamics [14].

Indonesia has begun demonstrating domestic technical capabilities. Pertamina's Cilacap refinery conversion to produce SAF from UCO proves that Indonesian refiners can successfully implement HEFA technology. Engineering firms such as Tripatra possess relevant experience in oil and gas processing, petrochemicals, and renewable energy projects, providing foundation skills transferable to SAF production. Academic institutions, including Institut Pertanian Bogor (IPB) University, are conducting biomass-to-SAF research and collaborating with international partners like Airbus to assess Indonesia's SAF potential [25].

Pretreatment technology for POME oil represents an area requiring focused development. Raw POME contains high moisture content, free fatty acids, suspended solids, metals, and other contaminants that must be reduced to levels compatible with HEFA catalyst systems. Robust pretreatment trains may include water separation, acid esterification to reduce free fatty acids, metal chelation, filtration, and thermal treatment. While these unit operations are individually established, optimizing integrated pretreatment specifically for POME oil recovery in Indonesian palm oil mill contexts requires adaptation and validation [41].

Supportive Policy Development and International Recognition

The November 2025 ICAO approval of POME's LCA default value of 18.1 gCO2e/MJ represents a watershed regulatory achievement with immediate commercial implications. Prior to this approval, each project using POME feedstock would require individual LCA modeling, third-party verification, and ICAO review—a process that takes 6-18 months and costs $50,000-150,000 per pathway. The approved default value eliminates these barriers, enabling immediate use in CORSIA compliance, airline offtake agreements, and financing documentation [10].

This approval results from sustained advocacy by Indonesia through the Civil Aviation Environmental Protection (CAEP) process, including submission of working papers, coordination with LCA expert teams from Indonesia and Hasselt University (Belgium), technical validation by the European Commission's Joint Research Centre, and final endorsement by ICAO's CAEP Working Group 5 and Council. The successful navigation of this complex international technical approval process demonstrates Indonesia's growing capacity to engage effectively in global standard-setting processes [10].

Indonesia's domestic SAF policy framework is progressively strengthening. The September 2024 announcement of a comprehensive SAF roadmap and action plan, followed by Presidential Instruction to implement mandatory blending from 2027, establishes clear market demand signals that attract investment. The three-pillar framework addressing demand (mandates and offtake agreements), supply (feedstock DMOs and incentives), and enablers (certification infrastructure) reflects sophisticated policy design informed by international best practices and stakeholder consultation [8].

Existing biofuel policy infrastructure provides institutional foundations. The Oil Palm Estate Fund (BPDPKS) model, which successfully scaled biodiesel adoption through export levy-funded price subsidies, could potentially be adapted for SAF by allocating portions of CPO export duties to bridge SAF-conventional fuel price differentials. The Ministry of Energy and Mineral Resources' experience administering biofuel mandates, monitoring compliance, and coordinating with fuel distributors transfers directly to SAF implementation [26].

International development support is mobilizing. ICAO's ACT-SAF program provides technical assistance for feasibility studies, policy development, and capacity building specifically targeted at developing countries, including Indonesia. Bilateral partnerships with the United States, European Union, Japan, and Singapore support technology assessment, investment facilitation, and knowledge sharing. Corporate initiatives, including Airbus's collaboration with IPB University to assess Indonesia's biomass potential and airline investment funds such as the $150 million Global Airlines SAF Fund, create pathways for international capital and expertise to support Indonesian SAF development [42].

Sustainability Certification Infrastructure Development

Certification under internationally recognized sustainability schemes is essential for SAF market access, particularly for exports to European and North American markets. Indonesia's palm oil industry has substantial experience with sustainability certification through the Roundtable on Sustainable Palm Oil (RSPO), Indonesian Sustainable Palm Oil (ISPO), and International Sustainability and Carbon Certification (ISCC). As of 2025, over 4.9 million hectares of Indonesian palm oil plantations hold RSPO certification, while ISPO certification is mandatory for all Indonesian palm oil operations [43].

ISCC certification specifically covers biofuels and bioenergy supply chains, including CORSIA-eligible aviation fuels. ISCC CORSIA certification proves compliance with ICAO sustainability criteria and enables participation in carbon credit trading platforms. ISCC's chain-of-custody options (identity preserved, segregation, mass balance, and book-and-claim) provide flexibility for different business models and supply chain structures. Indonesian palm oil companies and refineries are increasingly obtaining ISCC certification, with Pertamina's Cilacap refinery receiving ISCC certification for its SAF production in 2024 [44].

The Roundtable on Sustainable Biomaterials (RSB) offers another recognized certification pathway, particularly for markets emphasizing stringent social and environmental safeguards. RSB's Advanced Products scheme covers non-energy applications while RSB Global covers fuels, with certification demonstrating compliance with twelve principles addressing legality, human rights, labor conditions, air and water quality, biodiversity, and GHG emissions. RSB's Low ILUC Risk Biomass Module allows operators to voluntarily demonstrate minimal indirect land use change risks, particularly valuable for palm-based feedstocks [45].

Traceability systems represent critical certification infrastructure. Blockchain-based platforms and digital chain-of-custody tracking enable verification that POME oil originates from certified sustainable sources, preventing fraud including fraudulent mixing of POME oil with virgin palm oil. Indonesia's proposed incentive-aligned pricing mechanism—where POME oil is priced at a discount to CPO reflecting its moisture and impurity content—creates economic disincentives for fraud while establishing transparent market-based valuation.

The development of national accreditation capacity strengthens sustainability assurance. Indonesia's plan to establish domestic SAF certification bodies would reduce reliance on foreign certification organizations, lower costs, and build indigenous expertise. However, these domestic bodies must achieve international recognition and mutual acceptance to ensure Indonesian-certified SAF gains market access abroad [23].

Thematic Analysis: Challenges Facing Indonesia's POME-based SAF Development

Technological and Operational Challenges in POME Oil Recovery

While POME oil recovery is technically feasible, significant operational challenges must be overcome for scaled implementation across Indonesia's 1,386 palm oil mills. The high variability in POME composition presents a primary challenge. Oil content, moisture levels, free fatty acid profiles, solid particle characteristics, and pH vary substantially depending on fresh fruit bunch quality, processing conditions at specific mills, sterilizer technology (horizontal versus vertical), and seasonal factors. This heterogeneity complicates standardization of recovery technologies and pretreatment processes, potentially requiring site-specific optimization rather than uniform solutions [41].

Existing palm oil mills were designed for CPO production, not for POME oil recovery. Retrofitting established facilities with separation equipment, pretreatment systems, storage tanks, and quality control laboratories requires capital investment, operational disruption during installation, and reconfiguration of waste management flows. Mills operating at capacity with optimized workflows may resist modifications that introduce complexity or reduce throughput, particularly if payback periods extend beyond 3-5 years [11].

The decentralized nature of Indonesia's palm oil sector exacerbates implementation challenges. While large integrated plantation-mill companies may invest in recovery infrastructure, smallholder-supplied mills with tighter profit margins and limited technical capacity face greater barriers. Approximately 40-42% of Indonesian palm oil production comes from smallholder operations, and mills serving smallholders may lack the financial resources, technical expertise, or institutional support to implement sophisticated recovery systems. This creates potential supply gaps where POME from large mills is recovered, but substantial volumes from smallholder-linked mills remain inaccessible [46].

Impurity management represents another technical hurdle. POME contains metals (iron, calcium, magnesium), phosphorus, suspended solids, and other contaminants that poison HEFA catalysts or accumulate in processing equipment. Rigorous pretreatment, including filtration, centrifugation, chemical treatment, and polishing, is necessary to achieve feedstock specifications compatible with SAF production—adding cost and complexity. Inconsistent pretreatment quality could lead to catalyst fouling, reduced conversion efficiency, increased maintenance costs, and shortened catalyst life, undermining project economics [16].

Water management creates additional complexity. While recovered water can, in theory, be reused in mill operations, it must meet boiler feed specifications or other application requirements. Residual organic content, dissolved minerals, or biological contamination may limit reuse applications, potentially requiring water treatment systems. The concentrate solids by-product must also find viable markets as animal feed or fertilizer; if market demand is insufficient or transport costs are prohibitive, disposal becomes a renewed challenge rather than a circular economy solution [15].

Infrastructure and Logistics Gaps

Indonesia's SAF infrastructure requirements span the entire value chain from feedstock collection to end-use fuel delivery, with significant gaps evident at multiple stages. Feedstock collection and aggregation infrastructure is underdeveloped. While individual palm oil mills generate POME, consolidating recovered POME oil from multiple mills to supply large-scale SAF biorefineries requires aggregation networks including trucking logistics, intermediate storage facilities, quality blending capabilities, and inventory management systems. The geographic dispersion of mills across Sumatra and Kalimantan—with varying road quality, distances from ports or biorefinery locations, and logistics service availability—creates collection complexities and cost variability[12].

UCO collection infrastructure illustrates this challenge. Despite Indonesia's substantial UCO generation potential (300,000-600,000 tonnes annually), actual collection rates remain below 50% due to fragmented informal collection networks, competition from biodiesel and oleochemical uses, and inadequate regulatory frameworks governing collection and trade. POME oil, being a novel feedstock, faces even greater collection infrastructure deficits since no established aggregation systems currently exist [26].

Storage and handling infrastructure requires development. Unlike CPO, which has standardized storage tanks and handling procedures throughout the palm oil industry, recovered POME oil's higher free fatty acid content and potential impurities may require specialized corrosion-resistant tanks, heating systems to maintain pumpability, and dedicated loading equipment to prevent cross-contamination with CPO streams. Mills lacking this infrastructure may encounter bottlenecks storing recovered oil between production and pickup, limiting recovery system utilization [11].

SAF biorefinery siting presents strategic infrastructure challenges. Optimal locations balance feedstock access, hydrogen supply, transportation to aviation markets, and economic development objectives. Locating refineries near feedstock clusters in Sumatra/Kalimantan minimizes aggregation costs but distances them from major airports in Java. Locating refineries near airports optimizes fuel distribution but increases feedstock transport costs and may face land availability or community acceptance issues. Imported hydrogen (if not produced on-site) adds further complexity, requiring port access or pipeline infrastructure [38].

Airport infrastructure for SAF handling remains nascent. Dedicated SAF storage tanks, blending facilities to mix SAF with conventional jet fuel in mandated ratios, quality testing laboratories to verify specifications, and fueling hydrant systems capable of handling blended fuel require installation at major airports, including Soekarno-Hatta, Ngurah Rai, Juanda, and others. Indonesia's national plan envisions initiating SAF use at Ngurah Rai (Bali) International Airport through pilot offtake agreements, but infrastructure timelines must align with the 2027 mandate implementation to avoid supply bottlenecks [47].

Distribution infrastructure beyond initial deployment at airports compounds challenges. Indonesia's archipelago spans 17,000 islands across 1.9 million square kilometers, and aviation serves as essential connectivity infrastructure. Scaling SAF availability beyond a few hub airports to secondary and regional airports requires extensive investment in distribution infrastructure or acceptance of regionally differentiated fuel pricing/availability—potentially creating competitive disadvantages for airlines serving secondary routes [28].

Policy, Regulatory, and Institutional Gaps

Despite progressive policy development, significant gaps persist in Indonesia's SAF regulatory framework. The absence of a dedicated financial support mechanism, analogous to the Palm Oil Estate Fund, for biodiesel production represents a critical gap. SAF production costs substantially exceed conventional jet fuel costs—estimates suggest 2-5 times higher depending on feedstock prices, conversion efficiency, and crude oil pricing—yet no clear subsidy mechanism, production tax credit, or fuel price support has been defined to bridge this gap. Without assurance of economic viability, private-sector investment will remain constrained regardless of technical potential [48].

Export versus domestic allocation policies require clarification. Indonesia's SAF action plan mentions potential domestic market obligations (DMO) for PFAD and export quotas/tariffs for UCO to ensure domestic feedstock availability, but specifics remain undefined. The palm oil industry has experienced periods of export restrictions, quotas, and levies that created uncertainty and complicated business planning. Extending similar interventions to SAF feedstocks risks repeating these challenges unless designed with clear triggers, transparent implementation, and stakeholder consultation [46].

Feedstock classification and customs codes present regulatory ambiguities. Indonesia's Ministry of Industry Regulation No. 32/2024 addresses palm oil derivatives, including biofuels, but POME oil's classification requires clarification to distinguish it from EFB oil, palm acid oil (PAO), and other similar products under Indonesian customs nomenclature (HS codes). Ambiguous classification creates fraud risks, as higher-value feedstocks may be misrepresented as lower-value alternatives, undermining sustainability assurance and market confidence [49,50].

Sustainability certification requirements and enforcement mechanisms need to be strengthened. While Indonesia mandates ISPO certification for domestic palm oil operations, ISPO lacks international market recognition comparable to that of RSPO or ISCC. For SAF exports, ISCC or RSB certification will be necessary, requiring Indonesian palm oil mills and SAF producers to obtain and maintain these additional certifications. The institutional capacity to audit, verify, and enforce certification compliance across Indonesia's vast and heterogeneous palm oil sector remains limited, with reports of certification irregularities and inadequate monitoring [43].

Land use governance and deforestation monitoring intersect with SAF sustainability. Even though POME is classified as a waste residue and is therefore exempt from direct ILUC calculations, the underlying palm oil industry's environmental performance affects social license and market acceptance. Concerns about deforestation, peatland conversion, and biodiversity loss in Indonesian palm oil production have historically constrained international market access and motivated EU regulatory restrictions. SAF, derived from Indonesian palm industry by-products, inherits these sustainability concerns unless robust governance systems demonstrate credible environmental safeguards [51].

Institutional coordination challenges span multiple government ministries and agencies. SAF development involves the Ministry of Transportation (aviation policy and airports), Ministry of Energy and Mineral Resources (fuel standards and blending mandates), Ministry of Industry (downstream industrial policy), Ministry of Agriculture (palm oil sector governance), Ministry of Environment and Forestry (environmental compliance), Ministry of Finance (tax policy and fiscal incentives), and multiple implementing agencies. Effective policy implementation requires coordinated action across these entities, yet interagency coordination in Indonesia has historically proven challenging, leading to policy inconsistencies, implementation delays, and bureaucratic obstacles for investors [52].

Subnational policy variations add complexity. Provincial and local governments have authority over land-use planning, environmental permitting, and business licensing that affect SAF projects. Regional resistance to downstream industrial development, due to limited fiscal benefits captured by local governments, could impede facility siting or the development of feedstock aggregation infrastructure. Harmonizing national-level mandates with subnational implementation incentives requires a fiscal architecture ensuring local governments benefit from SAF investments in their jurisdictions [36].

Financial and Investment Challenges

Capital requirements for SAF production facilities are substantial. HEFA biorefinery construction costs typically range from $400-800 million for commercial-scale facilities (100,000-200,000 tonnes of annual SAF capacity), depending on site-specific factors such as infrastructure availability, labor costs, and equipment sourcing. Integrated facilities, including feedstock pretreatment, renewable hydrogen production, and by-product processing infrastructure, may cost more than $1 billion. These capital intensities require access to large-scale project finance, either through corporate balance sheets, syndicated bank loans, project bonds, or blended public-private financing structures [53].

Access to affordable financing poses challenges for Indonesian developers. While large integrated palm oil companies possess substantial balance sheets, smaller independent refiners or dedicated biofuel developers face financing constraints. International project finance for emerging economy biofuel projects typically requires comprehensive risk mitigation, including offtake agreements with creditworthy buyers, feedstock supply guarantees, completion guarantees from experienced contractors, political risk insurance, and sponsor equity contributions of 20-40% [53].

Revenue certainty and price risk management create additional financial hurdles. Without guaranteed offtake prices through fixed contracts or price-floor support mechanisms, SAF project revenues depend on volatile factors including crude oil prices (affecting conventional jet fuel pricing), feedstock costs (influenced by palm oil markets, biodiesel demand, and export policies), renewable fuel incentive values (such as US RIN credits or European RFNBO certificates), and airline willingness-to-pay premiums for low-carbon fuel. This revenue uncertainty increases financing costs, as lenders demand higher interest rates or equity investors require higher return hurdles to compensate for risk [54].

Offtake agreement challenges exacerbate revenue uncertainty. While major international airlines have announced SAF purchase commitments—including Singapore Airlines, Cathay Pacific, Qantas, Emirates, and others—translating these aspirational commitments into binding, long-term offtake contracts with Indonesian producers requires negotiating pricing mechanisms, volume guarantees, quality specifications, and force majeure provisions. Airlines may hesitate to commit to multi-year fixed-price contracts given their own exposure to fuel price volatility and competitive pressure to minimize operating costs [42].

Foreign exchange risk affects projects with mixed currency cash flows. Feedstock costs, labor, and domestic operations incur expenses in Indonesian Rupiah, while SAF sales—particularly exports—generate US dollar revenues. Currency fluctuations can materially impact project returns, requiring hedging strategies or contractual provisions that allocate exchange rate risk between the parties. Limited availability of long-term Rupiah hedging instruments complicates risk management for projects with 20-30 year economic lifespans [53].

Competition for investment capital from alternative renewable energy projects creates opportunity costs. Indonesia's renewable energy ambitions encompass solar, wind, geothermal, hydropower, battery storage, electric vehicle manufacturing, green hydrogen, and multiple bioenergy pathways. SAF competes for limited public funding, development bank financing, and private capital against these alternatives, many of which may offer shorter payback periods, lower technical risks, or greater proven commercial experience [55].

Technology licensing costs add to capital requirements. Licensing HEFA process technology from Honeywell, Topsoe, or other providers typically involves upfront licensing fees ($5-15 million), royalties based on production volumes (2-5% of revenues), and requirements to purchase catalysts and specialized equipment from the licensor or approved suppliers. While these arrangements provide access to proven technology and ongoing technical support, they increase project costs and create ongoing financial obligations [14].

Feedstock Supply Chain Complexity and Quality Assurance

Ensuring consistent feedstock quality and reliable supply represents a fundamental challenge for SAF producers. POME oil's physical and chemical properties vary based on FFB ripeness, processing conditions, sterilizer efficiency, clarification effectiveness, and recovery technology deployed. This variability creates challenges with feedstock specifications, as HEFA processes require consistent inputs to maintain conversion efficiency and product quality [56].

Quality assurance systems must monitor critical parameters including free fatty acid content (typically requiring <5% for direct HEFA processing or 15-20% if acid pretreatment is employed), moisture and sediment content (<1-2% typically required), metals concentration (especially iron, calcium, phosphorus, which poison catalysts), and contaminants, including chlorides, sulfur, and nitrogenous compounds. Establishing quality testing infrastructure, training technicians, and implementing quality control protocols across multiple palm oil mills supplying a single SAF refinery requires coordination, standardization, and continuous monitoring [16].

Supply reliability concerns arise from seasonal variation in FFB production and palm oil processing. Indonesia experiences production cycles influenced by monsoon patterns, with peak production typically in August-October and lower production in February-April. These seasonal fluctuations affect POME generation volumes and potentially oil recovery rates, requiring SAF facilities either to maintain substantial feedstock inventory (increasing working capital requirements) or accept variable capacity utilization (reducing economic efficiency) [57].

Competition for feedstock between end uses creates supply risk. PFAD, for example, serves established oleochemical markets producing soaps, detergents, and cosmetics. UCO supplies both biodiesel production for land transport and SAF production for aviation. EFB can be used for mulching, composting, bio-board manufacturing, or energy generation. As SAF demand increases, competition for these multi-purpose feedstocks will intensify, potentially driving price increases that erode SAF project economics [58].

International feedstock trade dynamics further complicate the supply picture. UCO and PFAD are globally traded commodities, with significant exports from Indonesia to Europe, China, and other markets. If international prices exceed domestic SAF producers' willingness-to-pay, feedstock may be exported rather than supplied domestically, undermining Indonesia's SAF development goals despite physical availability within the country. The proposed domestic market obligation (DMO) and export quotas aim to address this risk, but implementation effectiveness remains uncertain [58].

Fraudulent feedstock practices pose integrity risks. Incidents of "fake UCO"—virgin vegetable oil fraudulently labeled as used cooking oil to claim waste residue status and associated regulatory benefits—have been documented in European and Asian biofuel markets. Similar risks exist for POME oil, where virgin palm oil or lower-grade CPO might be fraudulently mixed with recovered POME oil to increase volumes while inappropriately claiming waste feedstock status. Detecting such fraud requires sophisticated analytical testing (stable isotope analysis, fatty acid profiling) and robust chain-of-custody documentation from collection through conversion [58]

Smallholder integration presents distinct challenges. While large plantation companies own and operate integrated mill facilities amenable to corporate POME recovery investments, independent mills purchasing FFB from thousands of smallholder farmers operate under different business models and constraints. Smallholder suppliers may lack the incentives or capabilities to implement best agricultural practices that optimize FFB quality and, consequently, POME composition. Integrating smallholders into sustainable SAF feedstock supply chains requires targeted extension services, financing mechanisms, and benefit-sharing arrangements [19].

Implementing a traceability system across fragmented supply chains requires substantial investment in digital infrastructure, training, and auditing. Blockchain-based tracking systems, GPS-tagged transport vehicles, sample custody protocols, and third-party verification all increase supply chain complexity and cost. While these systems enhance sustainability, credibility, and market access, the investment requirements may disadvantage smaller mills or traders, potentially consolidating feedstock supply among larger players and reducing diversity [23].

Technology Transfer and Capacity Building Deficits

Indonesia's current technical capacity for SAF production, while emerging, still has significant gaps that require targeted capacity-building investments. Process engineering expertise in HEFA technology remains limited, with only Pertamina's Cilacap facility demonstrating operational experience. Scaling beyond initial demonstration projects requires developing a cohort of trained chemical engineers, process operators, and technicians familiar with hydroprocessing unit operations, catalyst management, and safety protocols specific to hydrogen-intensive facilities [22].

Equipment manufacturing capabilities create dependencies. While Indonesia possesses basic refining equipment fabrication capacity, specialized high-pressure reactors, hydrogen compressors, and certain heat exchangers may require imports from established suppliers in Europe, North America, or Asia. Developing domestic manufacturing capabilities for SAF-specific equipment would reduce project costs and import dependencies, but it would require technology transfer, workforce training, and sustained market demand to justify investment [59].

Sustainability certification expertise and audit capacity need substantial development. While Indonesia has experience with RSPO and ISPO certification in the palm oil sector, ISCC CORSIA and RSB certification for SAF supply chains entail additional technical requirements, traceability protocols, and life-cycle assessment competencies. Training auditors, developing certification body capacity, and achieving international recognition for Indonesian certification entities requires a multi-year effort and international collaboration [60].

Analytical and quality control laboratory capabilities require enhancement. SAF specifications under ASTM D7566 include numerous parameters, such as density, viscosity, flash point, freezing point, distillation curve, aromatics content, sulfur content, thermal stability, and others. Ensuring SAF production consistently meets these specifications requires sophisticated analytical equipment (e.g., gas chromatography-mass spectrometry, nuclear magnetic resonance) and trained analytical chemists. While Pertamina and some research institutions possess these capabilities, scaling to support multiple SAF facilities requires broader development of laboratory infrastructure [13].

Research and development capacity affects Indonesia's ability to optimize technologies for local conditions. While licensing foreign HEFA technology provides proven process designs, adapting these for Indonesian-specific feedstock characteristics (POME oil properties differing from European UCO or American soybean oil) and operating conditions may require R&D capabilities. Indonesia's universities and research institutes (ITB, IPB, BPPT, and others) conduct relevant research, but strengthening linkages between academic research and industrial application through collaborative projects and technology transfer mechanisms would accelerate innovation [14].

Workforce training systems require alignment with the SAF industry's needs. Vocational education and university curricula currently emphasize traditional petroleum refining or first-generation biodiesel production, with limited content on advanced biofuels, HEFA technology, hydrogen safety, or sustainability certification. Developing specialized training programs, certification courses, and apprenticeship models to prepare technicians and engineers for employment in the SAF industry requires coordination among educational institutions, industry, and government [35].

International expertise access remains important. Technology licensors provide training and commissioning support, but sustained knowledge transfer requires longer-term partnerships, including staff secondments, joint troubleshooting, and continuous improvement collaborations. Indonesia's success in attracting such partnerships depends on perceived market opportunity, political stability, intellectual property protection, and collaborative approaches that benefit both technology providers and recipients [59].

Environmental and Social Sustainability Concerns

While POME-based SAF offers significant GHG emission reductions, broader environmental sustainability concerns surrounding Indonesia's palm oil industry create reputational and market access risks. Deforestation associated with oil palm expansion has been extensively documented, with studies estimating that oil palm plantations contributed to substantial forest loss in Indonesia between 1990 and 2015. Although more recent data indicate declining deforestation rates due to moratorium policies, historical associations between palm oil and deforestation persist in international perceptions, particularly in European markets [51].

Peatland conversion presents another environmental concern. Oil palm cultivation on peatlands—estimated to cover several hundred thousand hectares in Indonesia—generates substantial GHG emissions from peat oxidation and drainage, potentially offsetting emission benefits from biofuel production. While POME as a residue does not directly cause new peatland conversion, SAF's connection to the broader palm oil sector requires demonstrating that feedstocks originate from plantations that meet deforestation-free and peat-protection commitments [60].

Biodiversity impacts represent a third environmental challenge. Oil palm plantations, even when not causing direct deforestation, typically exhibit lower biodiversity than the natural forests they may have replaced. High conservation value (HCV) areas and high carbon stock (HCS) forests require protection under leading certification standards, necessitating rigorous land-use planning, spatial mapping, and compliance-monitoring systems. Ensuring that palm oil mills supplying POME for SAF source FFB from certified sustainable plantations respecting biodiversity conservation principles demands robust verification systems [45].

Water quality impacts from palm oil mill operations require attention. Despite POME treatment, effluent discharge may still affect river water quality if treatment is inadequate or discharge standards are insufficiently stringent. Heavy rainfall events can cause treatment system overflows, releasing untreated or partially treated effluent. Converting POME to SAF eliminates the POME waste stream, potentially improving water quality outcomes, but comprehensive water management addressing all mill wastewater streams remains necessary [61].

Social sustainability dimensions encompass multiple issues. Land rights conflicts between plantation companies and indigenous communities or smallholders have been documented in Indonesia, reflecting historical land acquisition processes that may not have respected customary rights. Ensuring free, prior, and informed consent (FPIC) for plantation operations, resolving legacy land conflicts, and providing benefit-sharing mechanisms for affected communities are increasingly expected under sustainability standards [45].

Labor conditions and workers' rights present additional social concerns. Reports of inadequate wages, unsafe working conditions, restrictions on union organization, and, in some cases, forced labor or child labor have emerged from palm oil plantations in Southeast Asia. Certification standards, including RSPO and RSB, mandate compliance with labor rights, minimum wages, occupational health and safety, and prohibition of forced and child labor, but monitoring and enforcement challenges persist, particularly at smallholder operations and contractor arrangements [45].

Smallholder livelihoods and inclusion raise equity considerations. Approximately 40% of Indonesian palm oil production comes from smallholder farmers managing plots typically 2-5 hectares. While palm oil provides meaningful livelihoods for millions of rural families, smallholders often face challenges, including limited access to quality planting material, fertilizers, and technical extension services; low productivity relative to plantation operations; price volatility and buyer market power imbalances; and difficulty accessing certification schemes due to cost and complexity. Ensuring SAF development benefits rather than marginalizes smallholders requires inclusive business models, targeted support programs, and equitable distribution of benefits [46].

Gender dimensions merit attention. Women play significant but often unrecognized roles in palm oil production, particularly in smallholder farming systems, yet may face unequal land rights, limited access to training and credit, and exclusion from decision-making. Gender-responsive SAF development strategies would assess differentiated impacts on women and men, ensure women's participation in benefit streams, and address structural barriers to gender equity [19].

Conclusion and Recommendations

Synthesis of Key Findings

Indonesia stands at a pivotal juncture in the global sustainable aviation fuel landscape, with extraordinary potential to emerge as a leading POME-based SAF producer, yet confronting substantial implementation challenges that could constrain or delay its realization. The confluence of the world's largest palm oil industry, which generates millions of tonnes of recoverable POME oil annually, ICAO's recent approval of favorable life-cycle emissions values for POME-based SAF, and accelerating global and regional SAF demand driven by decarbonization mandates creates a unique strategic opportunity.

The technical and commercial prospects are compelling. POME-based SAF achieves 79.6% reductions in greenhouse gas emissions compared to conventional jet fuel, positioning it among the most environmentally favorable SAF pathways globally. Indonesia's theoretical POME oil recovery potential of 2.5 million tonnes annually, supplemented by other palm-based waste oils, could substantially support a SAF industry that exceeds domestic aviation requirements while establishing Indonesia as a regional export hub. The HEFA production pathway's technological maturity, the circular-economy value proposition of waste-to-fuel conversion, and emerging policy-support frameworks provide a strong foundation for development.

However, formidable challenges temper this optimism. Technological barriers in POME oil recovery and pretreatment require site-specific solutions adapted to Indonesia's diverse and heterogeneous palm oil mill landscape. Infrastructure gaps spanning feedstock aggregation, biorefinery development, and airport handling systems demand multi-billion-dollar investments with uncertain returns absent precise financial support mechanisms. Policy and regulatory frameworks, while progressively improving, exhibit critical gaps, including a lack of explicit subsidy mechanisms, ambiguous feedstock governance, and insufficient international certification capacity. Financial and investment constraints reflect the capital intensity of SAF projects, revenue uncertainties in volatile commodity markets, and competition from alternative renewable energy investments. Feedstock supply chain complexities, including quality variability, seasonal fluctuations, competing end uses, and fraud risks, require sophisticated management systems. Environmental and social sustainability concerns surrounding Indonesia's palm oil industry pose reputational risks to SAF market access and social license.

The overarching finding is that Indonesia's POME-based SAF prospects will be realized not through feedstock abundance or technical potential alone, but through deliberate, coordinated, and sustained efforts by government, industry, financial institutions, civil society, and international partners to address the multidimensional challenge set systematically. Success requires integrating technological innovation, policy clarity, financial engineering, sustainability assurance, and inclusive development approaches into a coherent national strategy.

Strategic Recommendations

For Government and Policymakers:

1. **Establish a dedicated SAF Development Fund analogous to the successful BPDPKS model for biodiesel.** This fund should be capitalized through palm oil export levies, aviation passenger levies, or carbon pricing mechanisms, and deployed to bridge the price gap between SAF and conventional jet fuel, provide production incentives for SAF facilities, finance feedstock aggregation infrastructure, and support sustainability certification costs for mills and producers. Clear, transparent mechanisms for fund allocation, performance-based disbursements, and sunset provisions as SAF achieves commercial competitiveness would enhance credibility and investment confidence.

2. **Clarify feedstock governance through comprehensive regulations addressing POME oil classification under Indonesian customs nomenclature, domestic market obligation (DMO) mechanisms for priority SAF feedstocks with clearly defined triggers and implementation procedures, export licensing requirements, and allocation systems balancing domestic supply security with export opportunities, and quality standards and testing protocols ensuring consistency and preventing fraud.** These regulations should balance supply security for domestic SAF development with the legitimate commercial interests of feedstock producers and exporters, ideally through stakeholder consultation and iterative refinement informed by implementation experience.

3. **Develop coordinated infrastructure investment plans integrating feedstock collection networks, strategically located SAF biorefinery sites, hydrogen production or supply infrastructure, airport SAF handling facilities, and distribution logistics.** Public-Private Partnership (PPP) models can mobilize private capital while ensuring alignment with national development priorities. Special Economic Zones focused on bioenergy and biochemicals could accelerate industrial clustering and provide streamlined permitting, tax incentives, and infrastructure provision.

4. **Strengthen sustainability governance systems through enhanced monitoring and enforcement of ISPO certification, support for palm oil mills and plantations obtaining internationally recognized ISCC and RSB certification, development of national accreditation capacity for SAF certification bodies with international recognition, implementation of robust traceability systems employing digital technologies, including blockchain, and transparent public reporting on sustainability performance, deforestation, and social indicators.** These measures would enhance market confidence in the sustainability of Indonesian SAF while addressing legacy environmental and social concerns.

5. **Establish interagency coordination mechanisms ensuring policy coherence across ministries involved in SAF development.** A high-level SAF Implementation Committee or Task Force, with representation from the Transportation, Energy, Industry, Agriculture, Environment, and Finance ministries, empowered to resolve policy conflicts and accelerate implementation, would address coordination challenges that have historically impeded the effectiveness of Indonesian industrial policy.

6. **Engage actively in international forums, including ICAO CAEP processes, regional SAF collaborations such as APSAC, bilateral technology and investment partnerships, and climate finance mechanisms under the UNFCCC.** Indonesia's successful advocacy securing ICAO approval for POME's LCA default value

demonstrates the value of proactive engagement; sustaining this through proposing additional feedstocks (EFB oil, palm kernel expeller), participating in standard-setting, and attracting international climate finance for SAF development would strengthen Indonesia's global positioning.

For Industry Stakeholders:

1. **Palm oil mills should invest in POME oil recovery infrastructure.** Technologies such as POMEVap or alternative separation systems can achieve 4-year payback periods through recovered oil revenues and by-product sales. Mills should conduct feasibility assessments, access financing through government incentive schemes or commercial lenders, and pursue pilots demonstrating recovery efficiency and product quality. Collaborative approaches where multiple mills co-invest in shared aggregation infrastructure may improve economics for smaller operations.

2. **SAF project developers should pursue integrated biorefinery models leveraging multiple feedstock streams (POME oil, UCO, PFAD, EFB oil) to enhance supply security and capacity utilization.** Flexible feedstock processing capabilities reduce dependence on single sources vulnerable to seasonal variation or market shocks. Developers should secure long-term feedstock supply agreements with mills, establish rigorous quality specifications and testing protocols, and implement certified chain-of-custody systems from feedstock collection through SAF production.

3. **Engage airlines in offtake partnerships early in project development.** Binding long-term offtake agreements with creditworthy airlines provides revenue certainty that facilitates project financing. Offtake negotiations should address pricing mechanisms (fixed, indexed, or floor prices), volume guarantees and flexibility provisions, quality specifications aligned with ASTM D7566, and sustainability reporting requirements.

4. **Pursue ISCC CORSIA and/or RSB certification for SAF production facilities and supporting feedstock supply chains.** Certification demonstrates compliance with international sustainability standards, enables market access to European and North American buyers, and facilitates participation in carbon credit trading platforms. Early investment in certification infrastructure, training, and auditing pays dividends in the form of enhanced marketability and price premiums.

5. **Collaborate with technology providers through licensing partnerships that include not just technology transfer but capacity building, training, and ongoing technical support.** Negotiating license terms that enable knowledge absorption and eventual indigenous innovation rather than perpetual dependency strengthens long-term competitiveness.

For Financial Institutions and Investors:

1. **Develop financial products tailored to SAF project characteristics, including long capital recovery periods (15-25 years), revenue volatility requiring hedging or price stabilization mechanisms, technology risks in emerging pathways, and public policy dependencies.** Blended finance structures combining concessional public capital with commercial private investment can enhance returns while managing risks.

2. **Support supply chain finance mechanisms enabling palm oil mills to invest in POME recovery infrastructure through equipment leasing, working capital facilities for inventory, or receivables financing against feedstock supply contracts.** Improving mill-level economics strengthens upstream feedstock supply.

3. **Engage in policy dialogue with the government regarding financial support mechanisms, risk-sharing instruments, and regulatory clarity.** Private capital mobilization depends critically on clear policy frameworks; financial institutions' advocacy can contribute to policy improvement.

For Civil Society and International Development Partners:

1. **Monitor and advocate for robust environmental and social safeguards in Indonesia's SAF development.** While SAF offers climate benefits, ensuring these are not achieved through deforestation, peatland degradation, labor rights violations, or land conflicts requires vigilant civil society oversight, public reporting on sustainability

performance, and advocacy for strengthened standards and enforcement.

2. **Support smallholder inclusion programs enabling smallholder palm oil farmers to participate in and benefit from SAF value chains.** Inclusive business models, capacity building, access to finance, and fair benefit distribution prevent marginalization and enhance social sustainability.

3. **Provide technical assistance and capacity building support through international development agencies, multilateral organizations, and philanthropic foundations in areas including POME recovery technology adaptation, sustainability certification training, policy development, and investment facilitation.** Indonesia's capacity development needs exceed domestic resources; international partnership accelerates progress.

4. **Facilitate knowledge exchange and South-South cooperation between Indonesia and other palm oil-producing nations (Malaysia, Thailand, Colombia) to share experiences, avoid common pitfalls, and accelerate learning curves. Regional collaboration on harmonized sustainability standards, technology development, and market creation benefits all participants.**

Future Research Directions

This review identifies several areas warranting further investigation. First, site-specific POME oil recovery optimization studies across diverse Indonesian mill types would generate practical implementation guidance addressing technology selection, pretreatment configurations, and economic performance under varying local conditions. Second, comprehensive life cycle assessment studies that examine not only greenhouse gas emissions but also water consumption, air quality, biodiversity, and social dimensions would provide a holistic sustainability evaluation. Third, supply chain modeling and optimization research could identify efficient logistics networks, optimal biorefinery locations, and cost-effective aggregation strategies. Fourth, policy design experiments and economic modeling could evaluate alternative financial support mechanisms, comparing their effectiveness, efficiency, and equity implications. Fifth, comparative case studies examining SAF development in other palm oil-producing nations could extract lessons regarding policy effectiveness, technology deployment strategies, and sustainability governance.

Indonesia's journey toward becoming a leading POME-based SAF producer will be neither swift nor straightforward, but the confluence of feedstock abundance, technological readiness, policy momentum, and sustainability imperatives creates a compelling strategic opportunity. Realizing this opportunity requires sustained commitment, systematic problem-solving, and inclusive collaboration across government, industry, finance, civil society, and international partners. The stakes extend beyond aviation decarbonization to encompass economic development, technological advancement, environmental stewardship, and Indonesia's emergence as a leader in the global bioeconomy transition.

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