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From Palm Oil to Sustainable Aviation Fuel: Prospects, Challenges, and Policy Pathways for Accelerating SAF Development in Indonesia

Loso Judijanto

IPOSS Jakarta, Indonesia

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Abstract

The aviation industry faces mounting pressure to decarbonise as global climate commitments intensify. Sustainable Aviation Fuel (SAF) has emerged as one of the most technologically feasible medium-term solutions, capable of reducing lifecycle greenhouse gas emissions by 60–90 per cent while maintaining compatibility with existing aircraft fleets and airport infrastructure. As one of the world's largest producers of palm oil, biomass, and agricultural residues, Indonesia possesses significant comparative advantages for SAF production. Yet translating these resource endowments into a commercially viable and internationally accepted industry requires overcoming complex technological, economic, institutional, environmental, and governance challenges. This qualitative literature review synthesises recent scholarly evidence regarding Indonesia's SAF development progress, evaluates feasible production pathways for developing countries, and examines multidimensional factors influencing implementation. The review adopts an interpretative approach integrating evidence from energy policy, aviation economics, biomass utilisation, life-cycle assessment, industrial strategy, and sustainability governance. Findings indicate that Indonesia has made encouraging progress through successful bioavtur demonstration flights and abundant renewable feedstock availability, yet significant constraints persist regarding production costs, technological readiness, certification requirements, investment risks, and regulatory certainty. The paper argues that Indonesia's long-term competitiveness requires integrating industrial policy, sustainability governance, technological innovation, carbon pricing, infrastructure investment, and international collaboration within a holistic national SAF strategy.

***Corresponding author**: Loso Judijanto, IPOSS Jakarta, Indonesia

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Introduction

Climate change has fundamentally transformed the strategic direction of the global aviation industry. Although aviation contributes approximately two to three per cent of total global anthropogenic CO_2 emissions, its relative share is projected to grow as other sectors decarbonise more rapidly through electrification and renewable energy [1]. Commercial aircraft require energy-dense liquid fuels for long-distance operations, making battery-electric substitution impractical for the foreseeable future. Consequently, SAF has emerged as one of the few technologically feasible solutions that can substantially reduce lifecycle greenhouse gas (GHG) emissions while maintaining full compatibility with existing aircraft, airport infrastructure, and fuel distribution systems [2,3]. Depending on feedstock and production pathway, SAF can reduce lifecycle GHG emissions by between 60 and over 90 per cent compared with conventional aviation fuel, explaining its centrality to the International Air Transport Association (IATA) net-zero-by-2050 commitment and the ICAO Long-Term Aspirational Goal [4-7].

Within this context, Indonesia occupies a uniquely strategic position. As one of the world's largest producers of palm oil, used cooking oil, agricultural residues, and lignocellulosic biomass, the country possesses substantial comparative advantages for developing multiple SAF production pathways [8]. These advantages are further reinforced by long-standing biodiesel experience, established refinery infrastructure, and growing governmental commitment to energy transition [9,10]. Nevertheless, resource abundance does not guarantee industrial success; commercialisation requires sophisticated technological capabilities, internationally recognised sustainability certification, reliable regulatory frameworks, and strong multi-stakeholder collaboration. Understanding Indonesia's current progress therefore demands comprehensive multidisciplinary evaluation [11,12].

Despite growing scholarly attention toward SAF, existing literature exhibits several gaps. Many studies focus on developed economies whose institutional and resource conditions differ substantially from Indonesia's. Numerous publications examine isolated dimensions — lifecycle assessment, techno-economic analysis, or aviation policy — without integrating them into a comprehensive framework. Discussions about Indonesia frequently emphasise either technical feasibility or environmental controversy without synthesising broader industrial development opportunities, energy transition strategies, or international market dynamics [13,14]. This paper addresses these gaps through four objectives: reviewing theoretical and production-pathway foundations relevant to developing economies; evaluating Indonesia's current SAF progress; identifying principal opportunities and constraints; and proposing an integrated policy framework for long-term implementation. The study adopts a qualitative interpretative literature review methodology — appropriate for emerging policy issues characterised by rapidly evolving technologies and complex institutional interactions [15].

Literature Review

SAF within the Global Energy Transition

SAF refers to aviation fuels produced from renewable or low-carbon feedstocks that satisfy ASTM D7566 fuel quality specifications before blending with conventional Jet A or Jet A-1 fuels [16]. Its lifecycle perspective encompasses feedstock cultivation, transportation, processing, refining, distribution, and combustion, thereby providing a comprehensive environmental assessment [17]. Recent studies confirm that appropriately produced SAF can reduce lifecycle GHG emissions by approximately 60–90 percent relative to fossil jet fuel [18]. Beyond climate mitigation, SAF contributes to energy diversification, rural industrialisation, technological innovation, and enhanced national energy security [7,19]. For developing economies with abundant renewable biomass, SAF represents an opportunity to integrate agricultural production with advanced manufacturing, fostering structural economic transformation [20]. Figure 1 illustrates the comparative lifecycle GHG reduction performance of the five principal ASTM-certified SAF production pathways relative to conventional fossil jet fuel.

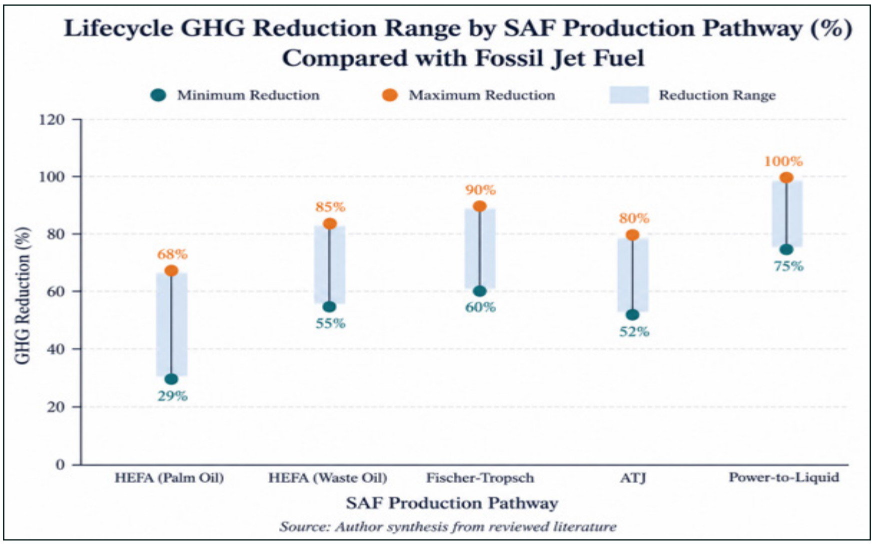

Figure 1: Lifecycle GHG Reduction Range by SAF Production Pathway (%) Compared with Fossil Jet Fuel.

As shown in Figure 1, Power-to-Liquid (PtL) fuels demonstrate the highest potential GHG reduction range of 75–100 per cent, followed by Fischer-Tropsch (60–90 percent) and Alcohol-to-Jet (52–80 percent) pathways. HEFA derived from waste cooking oil achieves 55–85 per cent reduction, while HEFA produced from palm oil delivers 29–68 per cent reduction, with the lower end of this range reflecting scenarios in which inadequate land-use governance generates significant indirect land-use change emissions. These findings highlight that while all ASTM-certified SAF pathways substantially outperform fossil jet fuel, environmental performance varies considerably depending on feedstock origin and production management. The results underscore the critical importance of sustainability governance in determining the net climate benefit achievable through Indonesia's near-term HEFA pathway, and reinforce why regulatory frameworks that incentivise waste-based and residue feedstocks can significantly enhance the overall GHG performance of domestic SAF production [3,4,18].

Theoretical Frameworks

Three complementary theoretical perspectives inform this analysis. Energy Transition Theory describes the long-term transformation from carbon-intensive to cleaner energy systems, driven by climate policies, technological innovation, and international commitments rather than market competition alone [21]. Within aviation, SAF functions as a transitional technology capable of reducing emissions without requiring immediate replacement of aircraft or infrastructure. Sustainability Transition Theory — particularly the Multi-Level Perspective (MLP) — conceptualises transitions as interactions among landscape pressures (climate change and international agreements), socio-technical regimes (existing fuel markets and certification systems), and innovation niches (pilot projects and demonstration plants), suggesting that policy interventions enabling niche scaling are essential during early commercialisation stages [10,22]. Innovation Systems Theory further argues that technological development depends upon coordinated interactions among governments, universities, research institutions, industries, and financial organisations [23]. Indonesia possesses relevant strengths in biodiesel industries, agricultural expertise, state-owned energy companies, and expanding research capacity through BRIN, though effective inter-institutional coordination remains a key challenge [24].

Major SAF Production Pathways

The ASTM certification framework recognises several technological pathways, each differing in technological maturity, feedstock requirements, capital intensity, lifecycle emissions, and commercial readiness [25]. Hydroprocessed Esters and Fatty Acids (HEFA) is the most commercially mature pathway, currently accounting for the overwhelming majority of global SAF production by converting vegetable oils, used cooking oil, and animal fats into hydrocarbons through hydrotreating and hydroisomerisation [4,18]. Indonesia is particularly well positioned for HEFA commercialisation because of its extensive biodiesel experience, abundant palm oil resources, and existing refinery infrastructure. The Fischer–Tropsch (FT) pathway converts biomass into synthesis gas followed by catalytic conversion into liquid hydrocarbons and can utilise forestry residues, agricultural waste, and municipal solid waste, though FT plants require large-scale investment and stable feedstock supply chains [26,27]. The Alcohol-to-Jet (ATJ) pathway converts ethanol or butanol into aviation fuel and offers long-term potential through Indonesia's sugar industry and emerging second-generation bioethanol capabilities, while Power-to-Liquid (PtL) technologies synthesise fuels using renewable hydrogen and captured CO_2, representing a longer-term opportunity contingent upon declining renewable electricity costs and expanded hydrogen infrastructure [28,29].

Feedstock Availability and the Palm Oil Debate

Feedstock availability is the most decisive determinant of SAF competitiveness. Indonesia is uniquely positioned because it possesses nearly all major feedstock categories simultaneously — crude palm oil, used cooking oil, empty fruit bunches, palm kernel shells, palm oil mill effluent, rice straw, coconut oil, sugarcane, cassava, forestry biomass, and municipal organic waste — enabling diversified production strategies that reduce dependence upon any single resource and improve resilience against international market fluctuations [13,18]. Among these, palm oil occupies a distinctive and contested position: oil palm exhibits the highest oil yield per hectare among commercial oil crops, making it one of the most land-efficient vegetable oil sources, while Indonesia's mature palm oil industry provides logistics networks, experienced producers, refining infrastructure, and decades of industrial learning [30,31]. However, international debate concerning deforestation, peatland conversion, indirect land-use change, and traceability remains significant, particularly within the European Union [32-34]. Recent literature increasingly argues that sustainability performance depends less on the crop itself than on production practices, governance quality, certification systems, methane capture, and land-use planning, implying that Indonesia's competitiveness must be built upon measurable improvements in sustainability governance rather than resource abundance alone [35]. Figure 2 presents a multi-dimensional comparative assessment of Indonesia's major SAF feedstock categories across three evaluative dimensions: resource availability, current technological maturity, and sustainability performance.

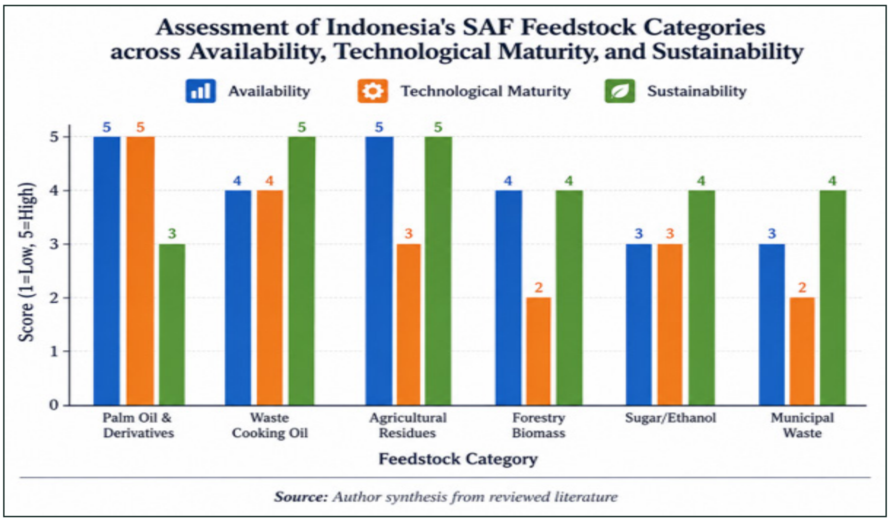

Figure 2: Assessment of Indonesia's SAF Feedstock Categories across Availability, Technological Maturity, and Sustainability (Score 1–5)

As illustrated in Figure 2, palm oil and its derivatives score highest on both availability and technological maturity (both scoring 5 out of 5), reflecting Indonesia's decades of experience in vegetable oil processing and biodiesel production, and the extensive plantation and refinery infrastructure already in place. However, the sustainability score for palm oil (3 out of 5) is comparatively lower, reflecting persistent international concerns regarding land-use change, deforestation, and certification credibility. Waste cooking oil scores highly on sustainability (5) but has lower current availability (4), reflecting the underdeveloped state of domestic waste oil collection infrastructure. Agricultural residues achieve balanced scores across all three dimensions, making them an attractive medium-term diversification target that combines reasonable availability with strong sustainability credentials and improving technological maturity. Municipal waste and gas fermentation feedstocks score at moderate levels across all dimensions, reflecting early-stage infrastructure and technological development. This assessment strongly reinforces the strategic argument for a diversified feedstock portfolio that progressively shifts emphasis toward higher-sustainability feedstocks as collection systems, certification infrastructure, and advanced conversion technologies mature over time [13,18,30,31].

Methodology

This study adopts a qualitative literature review (QLR) grounded within an interpretivist research philosophy, which assumes that understanding complex policy phenomena requires interpretation of multiple perspectives rather than identification of universal causal relationships [36]. Unlike a Systematic Literature Review, which employs standardised search protocols and statistical synthesis, a QLR develops integrated conceptual understanding through critical interpretation and thematic synthesis of multidisciplinary knowledge [15,37]. This approach is particularly appropriate for SAF development in Indonesia — a multidimensional issue spanning energy economics, chemical engineering, environmental science, aviation management, agricultural economics, industrial policy, climate governance, life-cycle assessment, and sustainable development — because the interdisciplinary nature of the topic renders purely quantitative synthesis insufficient for addressing the study's broader research questions.

The literature synthesised primarily consists of peer-reviewed journal articles published mainly since 2020, reflecting the rapid expansion of scholarly interest following the acceleration of global aviation decarbonization initiatives. Literature was retrieved from Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, MDPI, and IEEE Xplore, supplemented by reports from ICAO, IATA, IEA, IRENA, and Indonesian governmental agencies [21,38]. Publications were selected using a purposive relevance-based strategy, prioritising studies addressing SAF technologies, aviation decarbonization, biomass conversion, lifecycle GHG emissions, renewable energy transitions, and Indonesia or comparable developing-country contexts. Scientific quality was ensured by favouring journals such as Renewable and Sustainable Energy Reviews, Journal of Cleaner Production, Energy Policy, Applied Energy, Fuel, and Biomass and Bioenergy.

Qualitative thematic analysis was conducted through five iterative stages: familiarisation with key concepts and policy debates; initial coding of findings into preliminary themes such as feedstock availability, technological readiness, economic competitiveness, regulatory development, and stakeholder collaboration; theme development integrating related concepts into broader analytical categories; cross-theme interpretation examining interactions, reinforcing mechanisms, and policy trade-offs; and conceptual synthesis producing an integrated narrative of Indonesia's current progress, implementation barriers, strategic opportunities, and policy recommendations [39]. The analytical framework conceptualises SAF implementation as an interaction among six mutually reinforcing dimensions — Feedstock Resources, Technology, Economics, Governance, Market Development, and Sustainability — consistent with the Multi-Level Perspective of sustainability transitions theory [22]. Limitations include inherent scholarly judgment in publication selection, rapid technological evolution since review completion, comparatively limited Indonesia-specific empirical literature requiring analogous international evidence, and the absence of original quantitative modelling or lifecycle simulation. These limitations are acknowledged in interpreting findings but do not substantially undermine the study's analytical contributions [40]. The conceptual framework guiding this study is presented in Figure 3, which illustrates how six interconnected input dimensions together shape the SAF production and blending system and ultimately determine Indonesia's broader developmental outcomes.

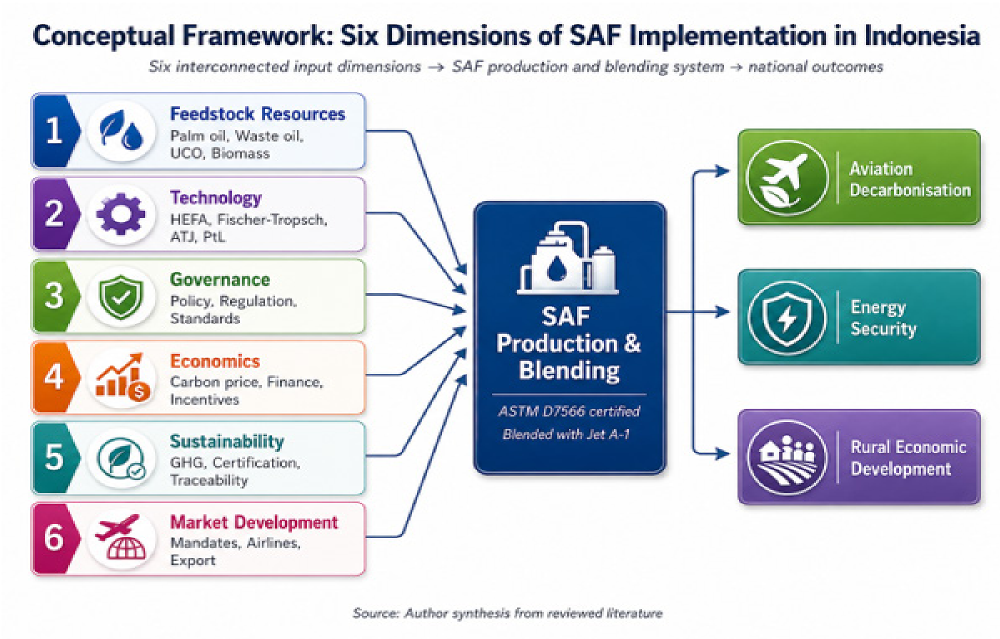

Figure 3: Conceptual Framework — Six Dimensions of SAF Implementation in Indonesia.

Figure 3 demonstrates that Indonesia's SAF development cannot be reduced to a single-sector technological challenge but must instead be understood as a systemic interaction among feedstock resource management, technological capability, governance structures, economic incentives, sustainability assurance mechanisms, and market development initiatives. Each of these six input dimensions directly feeds into the SAF production and blending system, which in turn generates three interconnected national-level outcomes: aviation sector decarbonisation aligned with Indonesia's international climate commitments, enhanced national energy security through reduced dependence on imported fossil fuels, and rural economic development through expanded demand for domestically sourced renewable biomass. The mutually reinforcing nature of these dimensions implies that weakness in any one area — such as insufficient regulatory certainty or inadequate sustainability certification — can constrain progress across the entire system, regardless of how well other dimensions are developed. This integrated systems framing is consistent with both Innovation Systems Theory and the Multi-Level Perspective of sustainability transitions, both of which emphasise the systemic and institutional nature of successful technological commercialization [22-24].

Results

Current Progress of SAF Development in Indonesia

Indonesia has progressed beyond the exploratory stage of SAF development, demonstrating technological validation through successful bioavtur demonstration flights and the Green Refinery initiative led by PT Pertamina. National energy companies, BRIN, ministries, and universities have established collaborative research ecosystems extending beyond individual technological development toward coordinated industrial preparation [8]. At the policy level, SAF development is increasingly aligned with Indonesia's energy transition commitments and greenhouse gas reduction targets, recognising aviation as a hard-to-abate sector requiring technological solutions beyond electrification [41]. Indonesia also benefits from over two decades of biodiesel policy implementation, which has generated valuable institutional knowledge concerning feedstock logistics, blending mandates, sustainability certification, and stakeholder coordination — providing institutional capital that can substantially reduce future SAF commercialisation barriers [42]. However, commercial production capacity remains limited, domestic SAF markets are nascent, and dedicated regulatory frameworks continue to evolve, indicating that the critical transition from pilot-scale validation to economically viable industrial-scale production remains Indonesia's next major challenge [43-45].

Economic Opportunities and Competitiveness Challenges

The emergence of global SAF markets presents Indonesia with substantial economic opportunities encompassing industrial upgrading, export revenue, rural economic development, and energy security [14]. SAF production could transform Indonesia's role from exporting raw agricultural commodities toward capturing value through advanced downstream processing, green chemical industries, and aviation fuel certification. Expanding international SAF demand — driven by blending mandates in the European Union, United States, and other jurisdictions — creates opportunities for Indonesia to supply certified SAF throughout the Asia-Pacific region [20]. Nevertheless, production costs remain substantially higher than conventional Jet A-1 fuel, with techno-economic assessments indicating SAF costs are typically two to four times greater due to feedstock expenses, hydrogen consumption, capital investment, and limited economies of scale [26,27,46]. The literature consistently demonstrates that early commercialisation requires supportive policy instruments including carbon pricing, production incentives, tax credits, investment guarantees, and long-term purchase agreements, as private investment alone is insufficient given current cost differentials [11,19]. Figure 4 provides a comparative illustration of the substantial production cost differential between conventional fossil jet fuel and the principal SAF production pathways currently available to Indonesia. Figure 4 provides a comparative illustration of the substantial production cost differential between conventional fossil jet fuel and the principal SAF production pathways currently available to Indonesia.

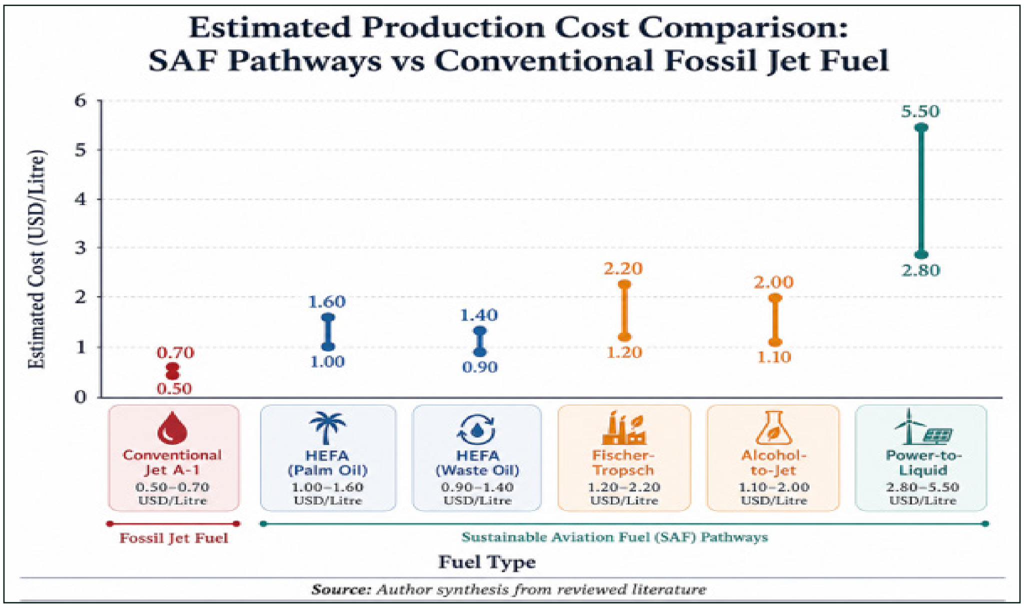

Figure 4: Estimated Production Cost Comparison — SAF Pathways vs Conventional Fossil Jet Fuel (USD/Litre)

Figure 4 clearly demonstrates that conventional Jet A-1 fossil fuel remains the lowest-cost option at an estimated USD 0.50–0.70 per litre under prevailing market conditions. In contrast, all SAF pathways carry significant cost premiums: HEFA from waste cooking oil (USD 0.90–1.40 per litre) and HEFA from palm oil (USD 1.00–1.60 per litre) represent the most cost-competitive SAF options, reflecting the relatively mature state of hydroprocessing technology and Indonesia's existing refinery infrastructure advantages. Fischer-Tropsch and Alcohol-to-Jet pathways entail higher costs of approximately USD 1.20–2.20 per litre, while Power-to-Liquid fuels remain the most expensive at USD 2.80–5.50 per litre due to high renewable hydrogen and carbon capture costs. These cost differentials visually underscore why the literature consistently identifies economic competitiveness as the primary barrier to SAF commercialisation and calls for supportive policy instruments — including carbon pricing, production tax credits, blending mandates, and green financing mechanisms — as the fundamental enabling conditions for closing the cost gap between SAF and conventional fossil aviation fuel [11,19,26,27,47].

Environmental Sustainability and Lifecycle Performance

Environmental sustainability represents both the principal motivation for SAF development and one of its most complex implementation challenges. Lifecycle GHG performance varies considerably depending on feedstock selection, agricultural productivity, fertiliser use, methane emissions, land-use change, refinery energy sources, and co-product allocation methodologies [3,18]. For Indonesia, international concerns about palm oil land-use governance remain a significant market access challenge, particularly within the European Union. However, recent literature increasingly demonstrates that sustainability outcomes depend primarily on governance quality, productivity improvements, methane capture, digital traceability, certification compliance, and zero-deforestation commitments rather than on the biological characteristics of the crop itself [32,38]. Greater utilisation of waste cooking oil, agricultural residues, and palm biomass residues — particularly POME-based HEFA pathways — can achieve significantly lower lifecycle emissions compared with conventional vegetable oil feedstocks [44]. The literature therefore recommends diversified feedstock strategies integrated within circular bioeconomy frameworks capable of simultaneously reducing emissions, improving resource efficiency, and enhancing economic value creation [43,47,48].

Institutional Development and Regulatory Progress

Successful commercialisation requires robust institutional capacity alongside technological readiness. Indonesia has established foundational policy frameworks for renewable energy and industrial downstream processing, but dedicated SAF regulations remain under development [41,49]. International experience consistently demonstrates that successful SAF markets depend on policy certainty encompassing blending mandates, sustainability certification, carbon pricing, long-term procurement commitments, standardised lifecycle accounting, and ASTM-aligned certification [14,16]. Indonesia therefore faces an important opportunity to develop a coherent national SAF roadmap integrating the Ministries of Energy, Transportation, Industry, Agriculture, Finance, and Environment, with BRIN, Pertamina, airlines, and financial institutions, in order to ensure regulatory consistency and minimise investment uncertainty. Alignment with ICAO CORSIA sustainability criteria and emerging international certification frameworks will significantly influence Indonesia's export competitiveness, and regional cooperation within ASEAN and bilateral engagement with Japan, South Korea, and the European Union — among the world's most active SAF market developers — represents important channels for accelerating technology transfer, investment promotion, and sustainability certification capacity building [6,13,50]. Figure 5 presents an indicative timeline for the commercialisation of different SAF production pathways in Indonesia, categorised into near-term, medium-term, and long-term development horizons through to 2040. Figure 5 presents an indicative timeline for the commercialisation of different SAF production pathways in Indonesia, categorised into near-term, medium-term, and long-term development horizons through to 2040.

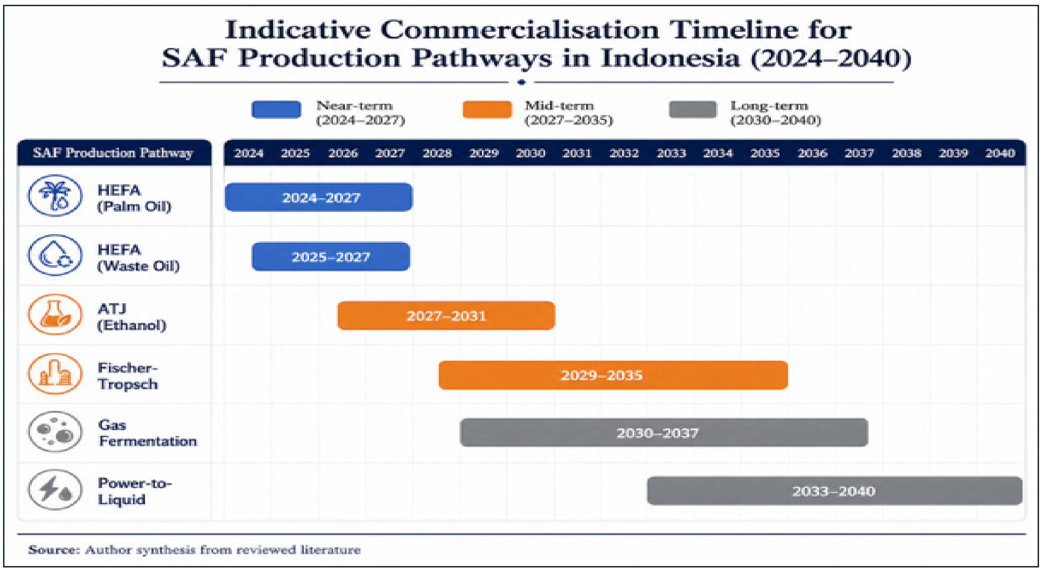

Figure 5: Indicative Commercialisation Timeline for SAF Production Pathways in Indonesia (2024–2040)

As shown in Figure 5, HEFA pathways utilising both palm oil and waste cooking oil are positioned for near-term commercialisation, with scale-up expected between 2024 and 2027, building directly upon Indonesia's existing biodiesel refinery infrastructure, established feedstock supply chains, and accumulated institutional experience in biofuel policy and certification. Alcohol-to-Jet technologies represent a medium-term opportunity, with commercial deployment anticipated in the 2027–2031 window, contingent upon the maturation of Indonesia's bioethanol industry and advances in lignocellulosic feedstock processing. Fischer-Tropsch technologies are projected to reach commercial readiness between 2029 and 2035, as they require larger capital investments, sophisticated gasification systems, and stable long-term biomass supply chains that are still in formative development. Gas fermentation and Power-to-Liquid pathways represent longer-term opportunities expected beyond 2030 and 2033, respectively, contingent upon substantial renewable electricity expansion, green hydrogen cost reductions, and the scaling of carbon capture technologies. This sequenced development approach is consistent with the portfolio diversification strategy recommended throughout the literature, enabling Indonesia to leverage existing capabilities in the near term while progressively building capacity for more advanced and ultimately more sustainable production pathways over the longer-term horizon [4,28,29,48,51,52].

Discussion

From Comparative Advantage to Competitive Advantage

The thematic synthesis confirms that Indonesia occupies a uniquely advantageous yet complex position within the emerging global SAF industry. Unlike most countries that possess either advanced technological capabilities or abundant renewable feedstocks, Indonesia benefits from both — yet resource endowments alone do not guarantee industrial success [8,41]. Indonesia faces a strategic transformation challenge: the fundamental question is no longer whether sufficient feedstocks exist but whether they can be converted into internationally certified, economically competitive, and environmentally credible aviation fuels. Long-term competitiveness requires transforming natural comparative advantages into dynamic industrial competitive advantages through coordinated progress in technological capability, industrial ecosystems, institutional quality, and sustainability governance [4,24]. Institutional learning from two decades of biodiesel implementation provides valuable organisational knowledge for accelerating SAF commercialisation, while incremental improvements in catalyst performance, hydrogen utilisation, refinery integration, digital monitoring, and logistics optimisation can progressively narrow the cost gap between SAF and conventional fossil jet fuel [23,42].

Sustainability Governance as a Competitive Asset

The academic literature reveals two contrasting narratives regarding palm oil in SAF: the first emphasises deforestation, peatland conversion, and biodiversity risks, while the second highlights palm oil's exceptional land-use efficiency and its potential contribution to renewable energy transitions under robust sustainability standards [30-33]. Recent scholarship increasingly demonstrates that sustainability performance depends primarily on management systems rather than the biological characteristics of feedstocks. For Indonesia, this finding carries important strategic implications: rather than abandoning one of its most productive renewable resources, the country can achieve greater competitiveness by strengthening sustainability governance throughout the entire value chain — improving plantation productivity, expanding digital traceability, enhancing independent certification, increasing methane capture, protecting high-conservation-value areas, and promoting circular economy utilisation of biomass residues [34,35,44]. Such improvements simultaneously enhance environmental performance and international market acceptance, enabling Indonesia to leverage its resource advantages while meeting the increasingly stringent sustainability expectations of global SAF markets. A diversified feedstock strategy combining certified vegetable oils, waste oils, agricultural residues, and eventually synthetic fuels would further enhance resilience against market fluctuations and regulatory changes [13,18].

Policy Coherence and Financing the Transition

One of the strongest themes emerging from the literature concerns the indispensability of policy coherence. Successful SAF commercialisation cannot be achieved through energy or industrial policy in isolation, as it requires coordinated action across energy, transportation, industrial, agricultural, environmental, trade, and financial policy domains [8,14]. Fragmented governance generates regulatory uncertainty, discourages private investment, and slows commercialisation timelines. Economically, early-stage development requires complementary policy instruments — carbon pricing, production tax credits, green bonds, public-private partnerships, long-term offtake agreements, and concessional financing — to bridge the gap between current production costs and fossil fuel prices, as private investment alone cannot resolve the fundamental economics of early SAF industrialization [11,19]. Investment in SAF should be understood as strategic industrial development rather than mere energy expenditure, given that its returns span agricultural development, advanced manufacturing, green chemistry, digital technology, and carbon market participation. International experience from the EU SAF mandates and the US Inflation Reduction Act demonstrates that well-designed financing frameworks catalyse private investment at multiples of public expenditure when policy certainty is established [20,25].

Contributions to the Literature

This review contributes to existing scholarship in three principal ways. First, it synthesises fragmented discussions on technology, economics, sustainability, governance, and industrial policy into a single, integrated analytical framework that specifically addresses Indonesia, filling a significant gap in country-specific SAF scholarship for major biomass-producing developing economies. Second, it demonstrates that Indonesia's future competitiveness depends not solely on feedstock abundance but on the interaction among technological innovation, institutional quality, sustainability governance, and market development, thereby extending beyond narrowly techno-economic perspectives to incorporate systemic and institutional dimensions [23,24,46]. Third, it proposes a holistic strategic framework grounded in multidisciplinary theoretical foundations and comprehensive empirical synthesis, providing actionable guidance for policymakers, investors, and researchers engaged with SAF development in emerging economies. Collectively, these contributions extend existing scholarship by emphasising the systemic, interdisciplinary nature of SAF commercialisation and contributing to broader debates on renewable energy industrialisation and energy transition governance in developing countries [21,22]. Figure 6 synthesises key findings from this review by visually mapping Indonesia's current (2026) SAF policy readiness against the aspirational target level of development required across seven strategic policy dimensions by 2040. Figure 6 synthesises key findings from this review by visually mapping Indonesia's current (2026) SAF policy readiness against the aspirational target level of development required across seven strategic policy dimensions by 2040.

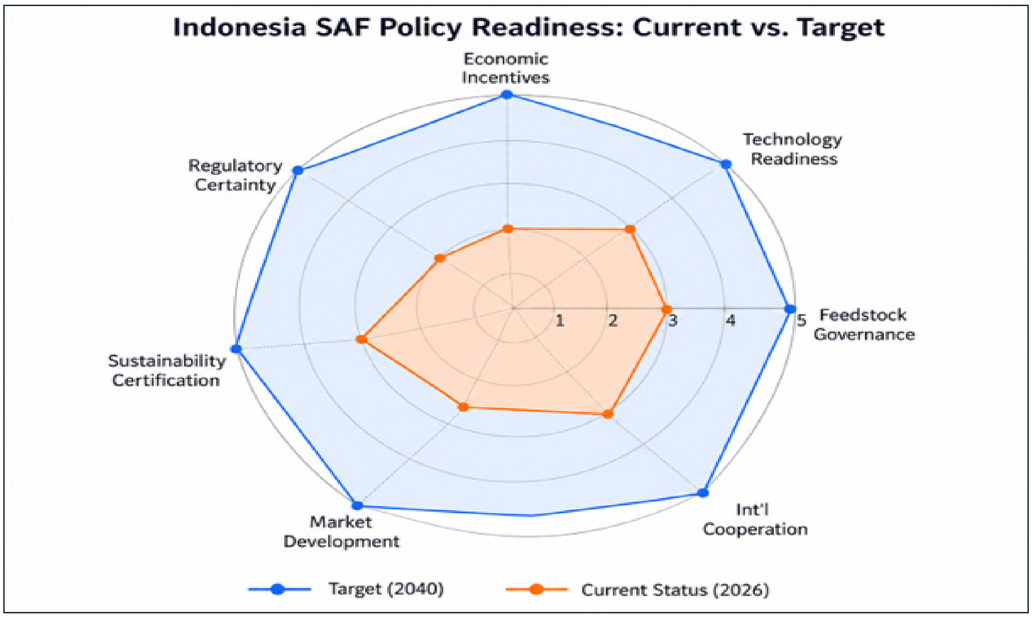

Figure 6: Indonesia SAF Policy Readiness Radar — Current Status (2026) vs Target (2040) across Seven Strategic Dimensions

The radar diagram in Figure 6 reveals that Indonesia's current SAF policy ecosystem presents uneven readiness across the seven assessed dimensions. Feedstock governance and international cooperation score relatively higher at 3 out of 5, reflecting Indonesia's existing palm oil sustainability governance experience and initial international SAF cooperation activities. However, economic incentives and regulatory certainty both currently score only 2 out of 5, reflecting the absence of dedicated SAF-specific fiscal instruments and the early stage of regulatory framework development. Sustainability certification and market development also score 2 out of 5, indicating that both domestic SAF blending demand mechanisms and internationally recognised certification infrastructure remain substantially underdeveloped relative to what successful commercialisation requires. Technology readiness scores 3 out of 5, reflecting Indonesia's demonstrated HEFA capability alongside limited progress toward more advanced production pathways. The visible gap between current scores and the target level of 5 across all dimensions powerfully illustrates the magnitude of the coordinated policy and institutional development challenge that Indonesia must address over the coming fifteen years. Achieving the 2040 target will require simultaneous progress across all seven dimensions through the integrated national SAF strategy, inter-ministerial coordination framework, and comprehensive financing mechanisms recommended in Section 6.2 of this paper [8,14,22,41].

Conclusion And Policy Recommendations

Conclusion

This qualitative literature review demonstrates that Indonesia possesses exceptional potential to become a major SAF producer, combining renewable biomass diversity, established biofuel industries, refining infrastructure, agricultural expertise, and growing governmental commitment to energy transition. Among currently available technologies, HEFA represents the most realistic near-term pathway due to its technological maturity and compatibility with existing refinery capabilities and institutional knowledge accumulated through biodiesel implementation. However, long-term competitiveness must not depend exclusively on HEFA; Indonesia should progressively diversify toward FT, ATJ, and eventually PtL technologies as renewable electricity deployment, hydrogen production, and biomass logistics systems expand. The review further indicates that sustainability governance is not merely a compliance cost but a strategic enabler of international market access: demonstrating credible lifecycle greenhouse gas performance, robust traceability, independent certification, and biodiversity protection are increasingly decisive determinants of competitive advantage in global SAF markets. Critically, SAF commercialisation is a systemic challenge requiring coordinated simultaneous progress across technology, policy, finance, institutional capacity, sustainability governance, and market development — it cannot be achieved through isolated interventions in any single dimension. Indonesia has progressed beyond the exploratory stage and stands at a critical transition point where strategic policy choices made in the coming decade will have lasting implications for its position within global low-carbon aviation supply chains.

Policy Recommendations

Based on findings from this review, the following integrated policy recommendations are proposed. Indonesia should formulate a long-term National SAF Roadmap extending to 2050, establishing clear production targets, technology investment priorities, sustainability standards, financing strategies, and institutional responsibilities across relevant ministries and agencies, with regulatory certainty being the most fundamental enabling condition for private investment. Feedstock diversification should be actively promoted through accelerated research and commercialisation of agricultural residues, waste oils, municipal solid waste, and lignocellulosic biomass alongside certified sustainable palm oil, reducing strategic vulnerability and improving lifecycle greenhouse gas performance. A stable domestic demand mechanism — through gradually increasing voluntary and eventually mandatory SAF blending targets accompanied by long-term airline procurement agreements — should be established to reduce investment uncertainty and accelerate economies of scale. Investment certainty must be strengthened through complementary fiscal instruments including tax incentives, green bonds, concessional loans, carbon pricing, and public-private risk-sharing mechanisms that make early-stage SAF production economically attractive. Sustainability governance should be elevated as a strategic priority, with investments in digital traceability platforms, independent certification infrastructure, lifecycle GHG accounting systems, methane capture at palm mills, and smallholder capacity building to meet ICAO CORSIA criteria and international market requirements. Research, development, and innovation capacity should be strengthened through cross-institutional collaboration among BRIN, Pertamina, universities, and international technology partners, targeting catalyst improvement, hydrogen integration, refinery modernisation, and emerging pathways such as POME-based HEFA [24,44]. Finally, Indonesia should actively pursue international partnerships for technology transfer, investment promotion, certification alignment, and regional SAF supply cooperation — positioning the country as a principal Asia-Pacific SAF supplier and contributor to global aviation decarbonisation.

Final Remarks

The transition toward sustainable aviation represents one of the most ambitious industrial transformations of the twenty-first century. Indonesia possesses many of the structural prerequisites to participate substantively in this transition. However, realising this opportunity requires sustained policy consistency, institutional coordination, technological innovation, financial investment, and internationally credible sustainability governance. The success of Indonesia's SAF industry will ultimately depend not on any single technological breakthrough but on the country's capacity to integrate diverse sectors into a coherent national strategy that simultaneously advances economic competitiveness, environmental stewardship, social inclusion, and energy security. In this broader context, Sustainable Aviation Fuel should be viewed not merely as an alternative aviation fuel but as a strategic catalyst for Indonesia's transition toward a resilient, competitive, and sustainable low-carbon economy.

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