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Selecting Sustainable Aviation Fuel Pathways for Indonesia

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Abstract
Sustainable Aviation Fuel is widely regarded as the indispensable near- to medium-term decarbonization option for commercial aviation because it can be used as a drop-in fuel in existing aircraft and fuel infrastructure. Yet the question facing Indonesia is not whether SAF matters, but which conversion pathway is most feasible for large-scale national development under Indonesian conditions. This article provides a **qualitative literature review**, rather than a systematic literature review, to compare SAF conversion technologies with emphasis on Indonesia's institutional, feedstock, environmental, and market context. Using the ASTM-oriented pathway summary as the primary input for pathway recognition and blending limits, the review synthesises recent literature since 2020 and selected official policy and industry sources to compare HEFA, Fischer-Tropsch, Alcohol-to-Jet, catalytic hydrothermolysis, hydroprocessed fermented sugars, algae-related hydroprocessing, and co-processing routes.

The analysis applies a thematic comparison across feedstock price and elasticity, market potential, feedstock availability, return on investment, maximum blending rate, technology partners, government policy, lifecycle emissions performance, and the international aviation ecosystem. The core finding is that **HEFA is the most feasible pathway for broad near-term SAF development in Indonesia**, particularly when integrated with existing refinery capability and waste/residue lipid streams, but only under strict sustainability safeguards that avoid overdependence on virgin crop-based oils. ATJ emerges as the most promising medium-term diversification route, while FT remains strategically important for long-term scale based on wider feedstock flexibility. The article concludes with a phased policy roadmap that combines near-term deployment, medium-term diversification, and long-term transition planning.

Keywords: Sustainable Aviation Fuel, Indonesia, HEFA, Alcohol-to-Jet, Fischer-Tropsch, Aviation Decarbonization, Biojet, Refinery Integration, Lifecycle Emissions, Feedstock Governance.

Introduction

Aviation is one of the hardest sectors to decarbonise because modern aircraft still depend on energy-dense liquid hydrocarbons, especially for medium- and long-haul operations. A growing body of research, therefore, treats Sustainable Aviation Fuel as the principal near-term decarbonization lever for commercial aviation, even while acknowledging that demand management, aircraft efficiency, hydrogen, and electrification will also matter over time. Bergero and colleagues estimate that aviation emitted about 1.03 GtCO2 in 2019, and that without strong action, the sector's emissions can remain structurally difficult to eliminate. It has been shown that aviation's climate impact is not limited to carbon dioxide, because non-CO2 effects make up a substantial share of aviation's warming effect [1-5].

The urgency of SAF development has intensified rather than diminished. Industry plans still rely overwhelmingly on SAF for reaching net zero by mid-century, but actual production remains far below ambition. Recent reporting based on IATA statements indicates that SAF may still cover less than 1% of aviation fuel demand in 2026, despite being expected to deliver the majority of aviation decarbonization by 2050. That mismatch matters for all countries with significant aviation sectors, but it is especially important for Indonesia because Indonesia is both a large archipelagic aviation market and a resource-rich country that could either become a regional SAF producer or remain dependent on imported compliance solutions [1,6,7].

Indonesia's case is particularly compelling for five reasons. First, Indonesia already has a large biofuel policy tradition in road transport, which means the country has institutional experience with mandates, feedstock politics, subsidy design, and refinery adaptation. Second, Indonesia possesses several classes of potential SAF feedstocks: waste lipids, residues from the palm value chain, agricultural residues, urban waste streams, and a possible ethanol base. Third, Indonesia has a large national oil and refining champion, Pertamina, which could act as the industrial fulcrum for SAF commercialization. Fourth, Indonesian aviation is deeply connected to tourism, domestic connectivity, and international route networks. Fifth, Indonesia faces unusually acute sustainability scrutiny because palm-driven land-use change remains internationally controversial. Those opportunities and constraints make the technology choice a strategic policy question rather than a purely engineering one [8-12].

This article, therefore, asks a focused question: **Which SAF conversion technology is most feasible for wide-scale development in Indonesia, when feasibility is defined holistically rather than narrowly?** The article does not assume that the technically certified pathway with the highest theoretical yield is automatically the right choice. Instead, it evaluates pathway suitability through the nine criteria specified in the literature: feedstock price and elasticity, SAF market potential, feedstock availability, return on investment, maximum blending rate, technology partners, government policy, environmental sustainability, including lifecycle emissions performance, and the international aviation business ecosystem. Additional criteria emerging from the literature, especially project delivery risk, financing readiness, infrastructure compatibility, and export legitimacy, are also included [3].

The central argument advanced in this manuscript is that **Indonesia should treat HEFA-SPK as the most feasible lead pathway for the current decade, while simultaneously preparing ATJ and FT as the next layers of a diversified national SAF strategy.**

This is a stronger and more nuanced conclusion than simply saying HEFA is "best." HEFA is best only when feasibility is interpreted as **short- to medium-term deployability under real-world Indonesian conditions**, not as a timeless or universal optimum. In a long-term decarbonization strategy, FT and potentially ATJ become more important, especially if Indonesia wants to avoid a dead-end dependence on limited lipid feedstocks or internationally contested virgin oils [3].

Literature Review and Analytical Framing

The concept of SAF is often discussed loosely, but in the aviation sector, it has a specific operational meaning. SAF refers to non-conventional jet fuels that can meet stringent safety and performance standards and can be blended into or, in some future cases, substitute for fossil jet fuel in existing aviation systems. Because aviation tolerances are exceptionally strict, pathway recognition depends on certification architecture rather than mere chemical plausibility. The ASTM-recognised routes and their maximum blending limits provide the starting point for any technology comparison in this paper [13-15]. The literature indicates that the SAF landscape is not a single technology family but a portfolio of conversion routes with very different properties. Aggregating the detailed list into the routes most relevant for the Indonesian strategy yields the following technological field [13-15].

To clarify the technological scope of the review, **Table 1** summarises the ASTM-recognised SAF conversion pathways used as the baseline for this article. The figure shows that SAF is not a single fuel pathway but a certified family of conversion routes, including Fischer-Tropsch, Hydroprocessed Esters and Fatty Acids, Alcohol-to-Jet, Catalytic Hydrothermolysis, Synthesised Iso-Paraffins, algae-related hydroprocessing, and refinery co-processing. The maximum blending limits are analytically important because they determine how far each pathway can contribute to near-term aviation decarbonization without requiring fundamental changes to aircraft engines, airport fueling infrastructure, or fuel safety certification systems. The figure also shows that several mature or strategically relevant routes, particularly HEFA-SPK, FT-SPK, ATJ-SPK, CHJ, FT-SKA, and ATJ-SKA, can reach a 50% blending limit, while SIP/HFS-SIP, HC-HEFA-SPK, and some co-processing routes have lower blend ceilings. This distinction is central to the article's argument that Indonesia should prioritise pathways that combine certification readiness, feedstock realism, and scalable blending potential [16-24].

Table 1: ASTM-Recognized Sustainable Aviation Fuel (SAF) Conversion Pathways and Maximum Blending Limits.

	ASTM reference	Technology pathway	Common feedstocks	Maximum blending rate
1	D7566 Annex A1	Fischer–Tropsch hydroprocessed synthesized paraffinic kerosene (FT-SPK)	biomass, municipal solid waste (MSW), natural gas, coal	50%
2	D7566 Annex A2	Hydroprocessed esters and fatty acids (HEFA-SPK)	vegetable oils, used cooking oil (UCO), animal fats	50%
3	D7566 Annex A3	Synthesized iso-paraffins from hydroprocessed fermented sugars (SIP / HFS-SIP)	sugars, sugary biomass	10%
4	D7566 Annex A4	FT synthetic kerosene with aromatics (FT-SKA / FT-SPK/A)	biomass, gas, coal	50%
5	D7566 Annex A5	Alcohol-to-Jet synthetic paraffinic kerosene (ATJ-SPK)	ethanol, isobutanol, isobutene	50%
6	D7566 Annex A6	Catalytic hydrothermolysis jet fuel (CHJ)	vegetable oils, UCO, animal fats	50%
7	D7566 Annex A7	Hydrocarbon–HEFA synthetic paraffinic kerosene (HC-HEFA-SPK / HH-SPK)	certain algae, especially *Botryococcus braunii*	10%
8	D7566 Annex A8	Alcohol-to-Jet synthetic kerosene with aromatics (ATJ-SKA)	C_2–C_5 alcohols from biomass	50%
9	D1655 Annex A1	Co-hydroprocessing esters and fatty acids in petroleum refinery (Co-processed HEFA/FA)	vegetable oils, UCO, animal fats plus petroleum	5%
10	D1655 Annex A1	Co-hydroprocessing Fischer–Tropsch hydrocarbons (Co-processed FT)	FT hydrocarbons plus petroleum	5%
11	D1655 Annex A1	Co-processing HEFA (Co-processed HEFA)	HEFA from biomass plus petroleum	10%

Source: Synthesised for ASTM-Recognised Pathways.

Table 1. provides the technical foundation for the subsequent feasibility comparison. For Indonesia, the most policy-relevant implication is that technological eligibility alone is insufficient. A pathway may be ASTM-recognised but still unsuitable for broad deployment if it has limited blending capacity, weak feedstock availability, high capital intensity, limited partner ecosystems, or sustainability risks. Conversely, a pathway with a lower theoretical novelty but higher industrial readiness may be more feasible for early national deployment. This is why the analysis does not compare SAF technologies only as chemical processes, but as socio-technical pathways embedded in feedstock markets, refinery systems, aviation demand, sustainability regulation, and international certification requirements [16-23].

Recent literature converges on several high-level findings. First, HEFA currently dominates practical SAF deployment because it is the most commercially mature route and integrates well with refinery know-how and existing hydroprocessing competencies. Second, FT is highly attractive because it can use a much broader feedstock base, particularly residues and wastes, but its gasification and synthesis chain is capital-intensive and execution-sensitive.

Third, ATJ is strategically important because it links aviation decarbonization with expanding alcohol industries, especially ethanol, but its economics depend heavily on alcohol price, carbon intensity, and policy support. Fourth, e-fuels and hydrogen-derived SAF remain important for long-run decarbonization, but most studies still regard them as too costly for decisive deployment at scale in the current decade [1,25-27].

Another major strand of literature emphasises that "sustainable" cannot be reduced to combustion emissions. Lifecycle accounting matters, and non-CO2 climate effects also matter. It has been noted that ICAO sustainability criteria require lifecycle reductions relative to fossil fuel, but that many studies still show wide variation in lifecycle performance depending on feedstock origin, land-use change, coproduct treatment, and time horizons [1]. It has been shown that non-CO2 effects are substantial in aviation's overall warming, while it has been shown that contrail cirrus alone is a major climate forcing component. This matters for the Indonesian pathway choice because a route that looks attractive on industrial policy grounds may perform poorly once land conversion and export-market acceptability are included. [1,2,28].

The Indonesian sustainability question is especially delicate because palm-linked land-use expansion remains globally contentious. Recent reporting on Indonesia's bioethanol-oriented food and energy estates highlights that large-scale fuel crops can trigger deforestation, biodiversity loss, and carbon debt concerns if governance is weak. In parallel, recent evidence on oil palm mapping in Indonesia underscores the continuing centrality of oil palm expansion to environmental governance. On the demand side, the European Union's SAF policy excludes palm- and soy-derived fuels from the favoured sustainability logic of ReFuelEU Aviation, while Singapore's SAF levy and emerging Asian market architecture indicate that regional buyers are increasingly attentive to demonstrable sustainability credentials. Indonesia, therefore, cannot assume that any domestically available bio-based feedstock will automatically translate into internationally credible SAF [29].

For technology selection, this article adopts a nine-factor comparison framework and expands it into twelve analytical dimensions. The first nine come directly from the literature review. Three additional dimensions emerge from the advanced literature: **project-delivery risk, infrastructure compatibility, and market-legitimacy risk.** Project-delivery risk matters because many promising SAF announcements fail before the final investment decision. Infrastructure compatibility matters because aviation fuel systems reward drop-in simplicity. Market-legitimacy risk matters because airlines, financiers, and regulators increasingly distinguish between nominally renewable fuels and widely accepted SAF. These additions are consistent with broader recent work showing that aviation's net-zero pathways depend not only on chemistry but also on policy design, financing, social acceptance, and system-level trade-offs [1,3,30,31].

Method

Qualitative Literature Review

This paper uses a **qualitative literature review** rather than a systematic literature review. The reason is epistemic as much as practical. The research question is not "What is the effect size of technology X on outcome Y?" but "How should different SAF technologies be comparatively interpreted, under Indonesian conditions, when technical, environmental, market, and institutional criteria interact?" That kind of question requires interpretive synthesis, thematic comparison, and policy-relevant judgment rather than protocol-driven aggregation of homogeneous studies. Accordingly, the method used here is purposive, analytical, and comparative rather than exhaustive in the systematic-review sense [3].

The ASTM-recognised pathways were used as the base document for determining which ASTM-recognised pathways and blending limits should enter the comparison. The ASTM-recognised pathways appear to function as a concise briefing note on SAF conversion technologies rather than as a full techno-economic dataset. Therefore, where the pathways did not provide local economic, policy, or lifecycle evidence, the review supplemented it with recent peer-reviewed literature, open scientific articles, official intergovernmental documents, and selected reputable news reporting for up-to-date policy and market developments [22,32-34].

A second methodological point concerns assumptions. This article interprets LCEF pragmatically as **lifecycle emissions factor or lifecycle emissions performance,** which is consistent with how SAF is commonly evaluated in academic and regulatory debates. The article deliberately avoids false precision on national feedstock quantities unless directly supported by accessible literature or official reporting. Instead, the assessment is conducted qualitatively using direction-of-travel judgments such as "broad," "limited," "volatile," or "bankable," always tied to cited literature or clearly marked synthesis [3].

Thematic Synthesis

The thematic synthesis proceeded in four steps. First, pathways were classified by certification and blend ceiling. Second, the literature was read comparatively around feedstock economics, feedstock breadth, maturity, and lifecycle performance. Third, external market and policy signals were examined, with particular attention to CORSIA, EU mandates, and Asian hub developments. Fourth, the evidence was synthesised into a policy-oriented feasibility judgment for Indonesia. The outcome is thus not a meta-analysis or score built mechanically from databases, but an analytically reasoned ranking based on converging evidence from multiple source types [35].

This methodology has limitations. Because it is not systematic, it does not claim exhaustive coverage of all SAF pathway publications. Because it is policy-oriented, it gives greater weight to decision-relevant literature than to narrow process-engineering optimisation studies. Because some current commercial developments are reported first in industry or major news sources instead of journals, a limited number of non-journal sources are used alongside peer-reviewed work. These choices are justified by the objective of preparing a manuscript that can answer a strategy question for Indonesia in real time while maintaining scholarly discipline [36].

Twelve-Dimension Evaluation Framework for ASTM-Recognised Pathways

This section explains how a twelve-dimension evaluation framework was applied to assess ASTM-recognised sustainable aviation fuel pathways for Indonesia in a way that is comprehensive, context-sensitive, and suitable for qualitative literature review. The framework was built because pathway choice cannot be reduced to one variable such as cost, carbon intensity, or technology readiness alone. Aviation decarbonization is constrained simultaneously by climate performance, feedstock sustainability, certification rules, infrastructure compatibility, logistics, finance, and public policy. Recent aviation-decarbonization studies also show that reaching net zero requires combinations of efficiency gains, low-carbon fuels, supportive policy, and careful treatment of non-CO2 effects and resource constraints, not merely adoption of any one "green fuel" option [17,37,38].

The pathway universe in this framework followed the ASTM-recognised SAF routes summarized in the uploaded reference note, including FT-SPK, HEFA-SPK, SIP/HFS-SIP, FT-SKA, ATJ-SPK, CHJ, HC-HEFA-SPK, ATJ-SKA, and co-processing pathways, with maximum blending limits ranging from 5% to 50%. The framework then evaluated pathways through twelve dimensions: feedstock price and price elasticity, SAF market potential, feedstock availability, return on investment, maximum blending rate, technology partners, government policy, environmental sustainability, international aviation-services ecosystem, technology maturity/readiness, supply-chain logistics, and social acceptance/policy risk. This multi-dimensional structure was necessary because ICAO itself does not treat SAF as a single homogeneous product: under CORSIA, fuels are assessed at the feedstock-pathway level, and their lifecycle emissions values differ substantially even within the same ASTM pathway [18,39-42].

Applied to Indonesia, the framework suggests that HEFA-SPK is the strongest near-term candidate for scaled introduction, ATJ-SPK is a plausible medium-term diversification route if low-carbon alcohol supply can be organized, and FT-SPK is a strategically important longer-term option whose carbon performance can be excellent but whose deployment depends heavily on solving residue and waste logistics, project complexity, and capital intensity. That conclusion is not a deterministic "winner-takes-all" ranking; it is a staged portfolio judgment derived from triangulating pathway certification, carbon performance, technology readiness, logistics, and policy fit [17,25,43-46].

Rationale for a Multi-Dimensional and Qualitatively Weighted Assessment

A multi-dimensional framework was used because SAF pathway choice is a socio-technical decision rather than a purely engineering choice. Recent review and scenario studies converge on the point that aviation decarbonization depends on trade-offs among costs, resource requirements, climate effects, demand trajectories, infrastructure, and policy design. It has been shown that even global net-zero aviation pathways depend on an interplay among demand management, aircraft efficiency, SAF volumes, and carbon removals [1]. Brazzola et al. and Dray et al. further show that non-CO2 effects, climate definitions, and system costs matter materially to pathway choice, while Sacchi et al. underline that climate-neutral aviation pathways can become excessively resource-intensive if evaluated narrowly or without attention to lifecycle boundaries [1,17,25, 43-46].

A purely quantitative weighted-sum model was not adopted for this article because the evidence base is heterogeneous. The literature mixes lifecycle emissions values, techno-economic analyses, certification documents, policy analyses, qualitative case studies, and pathway-specific engineering evidence that are not fully commensurable. In addition, ICAO's own treatment of CORSIA-eligible fuels is feedstock- and configuration-specific: one conversion process can show very different lifecycle performance depending on the feedstock used, whether the design is integrated or stand-alone, whether coal-based process heat is involved, and whether ILUC is relevant. That makes a simple "score once per technology" approach analytically weak [17,25, 43-47].

Instead, the framework used **qualitative weighting**. In practice, this means some dimensions were treated as **hard constraints**, some as **strategic differentiators**, and some as **contextual risks.** Hard constraints were: certified blending feasibility, feedstock availability, environmental sustainability/LCEF performance, technology readiness, and logistics. Strategic differentiators were: feedstock price exposure, ROI, market potential, technology partners, and ecosystem readiness. Contextual risks were: government policy stability and social acceptance/policy risk. This hierarchy reflects how SAF projects actually become bankable: a pathway with attractive theoretical carbon savings but weak feedstock logistics, unclear sustainability compliance, or low readiness is unlikely to scale in a country-level deployment programme [33,48-55].

The Twelve Dimensions and their Operational Indicators

The twelve dimensions were defined to translate broad comparative questions into specific reading criteria that could be applied consistently across the literature. Table 2 summarises the dimensions, what each means, and what indicators or proxies were used during coding and synthesis.

Table 2: Twelve Dimensions, Definitions, and Operational Indicators Used in the Qualitative Review.

Dimension	Definition	Operational indicators used in the literature review
1. Feedstock price and price elasticity	The expected cost of the primary input and its sensitivity to shocks, competing demand, or commodity cycles.	Share of feedstock in total production cost; recent price volatility; competing uses such as renewable diesel or food/feed; exposure to import dependency; sensitivity analysis in techno-economic studies.
2. SAF market potential	The ability of a pathway to serve domestic and/or export SAF demand at a commercial scale.	Jet-fuel demand outlook, airport demand concentration, airline offtake potential, export potential to mandate-driven markets, book-and-claim compatibility, and ability to meet certified product specifications.
3. Feedstock availability	The practical availability of sustainable, traceable, and bankable feedstock in Indonesia.	Collectable waste/residue volumes, seasonality, geographic dispersion, moisture/quality constraints, traceability, sustainability certification feasibility, competition from other sectors.
4. Return on investment	The likely financial attractiveness of projects under realistic market and policy conditions.	CAPEX, OPEX, minimum selling price, IRR, payback period, sensitivity to feedstock/fuel prices, value of co-products, exposure to incentives or carbon credits.
5. Maximum blending rate	The certified share at which a pathway can be blended into conventional jet fuel without requiring fleet-wide equipment change.	ASTM D7566/D1655 pathway limit; practical implications for near-term deployability and share of achievable SAF penetration.
6. Technology partners	The availability of licensors, EPC firms, catalyst suppliers, refiners, airlines, and other implementation partners.	Number and credibility of technology vendors; operational track record; bankability of licensors; presence of refinery, airline, or airport partners; evidence of commercial projects.
7. Government policy	The extent to which public policy can realistically support the pathway.	SAF mandates, tax credits, grants, carbon pricing, low-carbon fuel standards, sustainability rules, permitting environment, state-owned-enterprise compatibility, aviation and energy planning alignment.
8. Environmental sustainability	The lifecycle climate and sustainability performance of the fuel, including carbon and broader ecological screens.	ICAO default or actual LCEF, ILUC risk, carbon-stock effects, water, soil, biodiversity, waste hierarchy, fossil process heat dependence, likely CORSIA eligibility.
9. International aviation-services ecosystem	The fit between a pathway and the operating system of global aviation.	Airport fueling integration, certification readiness, chain-of-custody systems, book-and-claim readiness, airline procurement norms, compatibility with international reporting and claims.
10. Technology maturity and readiness	The engineering and commercial maturity of the pathway.	TRL/commercial status, number of operating plants, demonstration history, certification age, time to scale-up, performance reliability, bankability evidence.
11. Supply-chain logistics	The feasibility of collecting, preprocessing, transporting, storing, and converting feedstock at consistent quality and cost.	Collection radius, bulk density and transport cost, contamination risk, aggregation needs, storage stability, preprocessing demand, co-location opportunities with refineries or alcohol plants.
12. Social acceptance and policy risk	The risk of public contestation, sustainability controversy, or policy instability that could delay or delegitimize deployment.	Food-versus-fuel debate, land-use change controversy, palm-related scrutiny, local community opposition, waste governance concerns, reversals in subsidy/certification rules, reputational risk for airlines.

Source: Author's Synthesis for the Qualitative Literature Review.

These dimensions were derived by combining the original decision criteria with the additional three dimensions that are analytically indispensable in current SAF assessment: technology maturity/readiness, supply-chain logistics, and social acceptance/policy risk. The operational logic also reflects ICAO's CORSIA framework, which evaluates fuels not only for lifecycle GHG savings but also for carbon stock, water, soil, air, conservation, and related sustainability conditions. Since 2025, the ICAO sustainability framework for CORSIA-eligible fuels explicitly requires at least a **10% net lifecycle GHG reduction** relative to the aviation-fuel baseline and adds sustainability themes covering carbon stock, greenhouse-gas permanence, water, soil, air, and conservation [33,48-55].

For this article, the environmental-sustainability dimension was therefore operationalised around **LCEF** and certification logic rather than around generic "green" claims. ICAO defines LCEF as **core LCA value + ILUC - emission credits**, which means that the same ASTM pathway can move from attractive to unattractive depending on feedstock and process configuration. This is especially important for Indonesia, where public debate can easily overstate theoretical resource abundance while understating the importance of traceability, land-use sensitivity, and conversion configuration [17,25,43-47].

Application and Synthesis Procedure

The framework was applied in five stages. First, the pathway universe was fixed using the ASTM-recognised routes listed in the uploaded SAF pathway summary. filecite turn0 file0 Second, the evidence base was assembled from four source families: ASTM-related pathway definitions; ICAO CORSIA fuel-eligibility, sustainability, and lifecycle documents; IEA aviation and policy tracking; and recent peer-reviewed journal articles on lifecycle performance, climate impacts, transition costs, and SAF deployment pathways [18,39-42].

Third, each source was coded against the twelve dimensions. The coding rule was deliberately **pathway-sensitive** rather than pathway-generic. If a paper reported ATJ economics from corn ethanol, that evidence was not treated as identical to ATJ from sugarcane or lignocellulosic ethanol. If ICAO reported multiple default values within the same pathway, these were treated as evidence of **within-pathway heterogeneity**, not noise. Fourth, the coded evidence was synthesized into qualitative judgments using three broad labels: **high, medium**, and **low** suitability for Indonesia, interpreted as relative rather than absolute. Fifth, the pathway judgments were checked against Indonesia-specific plausibility: whether the pathway could realistically be matched with domestic feedstocks, industrial capabilities, airport demand, and policy capacity within a staged development strategy [17,25,43-46].

Trade-offs were handled through **triangulation rather than averaging**. Where one dimension strongly favored a pathway and another penalized it, the framework asked whether the weakness was temporary and manageable, or structural and likely to persist. For example, low readiness can be overcome over time, but weak sustainable feedstock availability cannot be solved by policy alone. Conversely, a pathway can show excellent lifecycle carbon performance in a paper while still ranking poorly for immediate deployment if the supporting supply chain and partners are absent. Following this rule, the framework gave more decision weight to dimensions that determine near-term feasibility and regulatory eligibility than to dimensions whose disadvantages may be reduced through learning or incentives [1].

Uncertainty was treated explicitly in three ways. First, the review privileged more recent pathway-specific evidence over older generic claims. Second, official/primary sources were given priority when a journal article and a secondary source appeared to conflict. Third, uncertainties were recorded when results depended heavily on feedstock class, regional ILUC assumptions, or process integration. This mattered especially for HEFA and ATJ, where the literature shows strong variation across feedstock types and process energy sources [33,48-56].

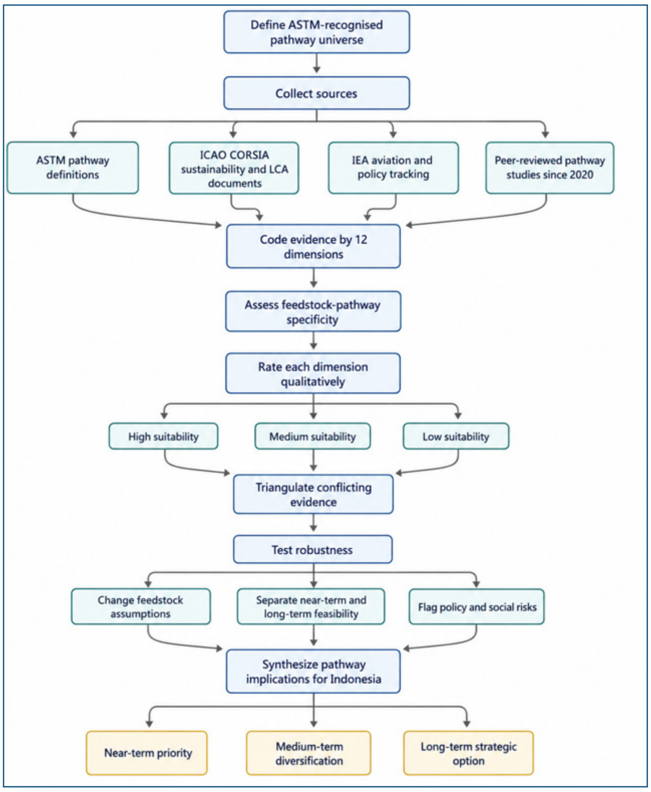


Figure 1: Mermaid Flowchart of the Evaluation Process.

Illustrative comparison of HEFA-SPK, ATJ-SPK and FT-SPK

The Table 3 below does not claim universal superiority of one pathway over another. It is an illustrative synthesis showing how the twelve-dimensional framework differentiates among the three ASTM pathways that matter most for Indonesia's near- to medium-term policy debate: HEFA-SPK, ATJ-SPK, and FT-SPK.

Table 3: Three-Pathway by Twelve-Dimention Qualitative Comparison for Indonesia.

Dimension	HEFA-SPK	ATJ-SPK	FT-SPK	Interpretation for Indonesia
1) Feedstock price and price elasticity	Medium	Medium	Medium	HEFA is exposed to lipid competition; ATJ to alcohol/sugar markets; FT to logistics more than commodity pricing.
2) SAF market potential	High	High	High	All three are relevant to decarbonizing aviation if bankable supply can be created.
3) Feedstock availability	Medium	Medium	Medium	Indonesia has plausible resource bases for all three, but bankable supply is narrower than theoretical supply.
4) Return on investment	Medium–High	Medium	Low–Medium	HEFA benefits from maturity; ATJ depends on alcohol economics; FT is typically more capital intensive.
5) Maximum blending rate	High	High	High	All three exemplar pathways have 50% ASTM blending limits.
6) Technology partners	High	Medium	Medium–High	HEFA has broad refining and licensing ecosystems; ATJ and FT have partners but smaller deployment bases.
7) Government policy fit	High	Medium	Medium	HEFA is easiest to align with early mandates and refinery-adjacent policy instruments.
8) Environmental sustainability	Medium–High	Medium	High	HEFA can be strong on waste lipids but controversial on palm-linked inputs; ATJ varies by ethanol source; FT is strongest on residues/MSW.
9) International aviation-services ecosystem	High	Medium	Medium	HEFA aligns best with current airline, refinery, and airport procurement routines.
10) Technology maturity/readiness	High	Medium	Medium	HEFA is the most deployment-ready; ATJ and FT are certified but less widely commercialized.
11) Supply-chain logistics	Medium	Medium	Low–Medium	FT is most penalized by bulky feedstocks and aggregation complexity.
12) Social acceptance/policy risk	Medium	Medium	Medium–High	HEFA faces traceability and land-use scrutiny; ATJ risks food-versus-fuel concerns; FT can gain legitimacy if based on waste/residues.

Note: Qualitative Ratings Reflect Synthesis from the Review and are Intended as Comparative Judgments Rather than Numerical Scores.

Source: Author's Synthesis for the Qualitative Literature Review.

Note on evidence behind Table 3. The qualitative comparison is anchored in ASTM-recognised pathway limits from the uploaded pathway summary, which records HEFA-SPK, ATJ-SPK, and FT-SPK as 50% blend pathways. fileciteturn0file0 It is also anchored in ICAO's feedstock-specific default lifecycle values. Under ICAO's November 2025 default tables, **gasification FT** shows very low default core LCA values for agricultural residues (**7.7 gCO2e/MJ**), forestry residues (**8.3**), and municipal solid waste with zero non-biogenic carbon (**5.2**). **HEFA** shows stronger values for waste lipids such as used cooking oil (**13.9**) and tallow (**22.5**) but weaker values for some animal fats, such as poultry fat (**33.7**). **ATJ-SPK from ethanol** varies widely, for example, from integrated sugarcane (**24.1**) or integrated agricultural residues (**24.6**) to corn grain (**65.7**) under certain configurations. The table, therefore, reflects a core methodological point of this article: pathway choice in Indonesia cannot be separated from feedstock choice and process design [17,25,43-46].

HEFA-SPK scores highest for **near-term deployment** because it combines certified 50% blending capability, comparatively high maturity, strong partner availability, and a close fit with existing refining and airport-fuel systems. Its main weakness is not certification or maturity, but feedstock politics and economics. If HEFA relies on genuinely waste-based lipids, its carbon performance can be strong under ICAO rules; if it drifts toward higher-risk or contested feedstocks, its sustainability legitimacy and public acceptability decline. In other words, the framework does not treat "HEFA" as automatically sustainable; it treats **waste-based, traceable HEFA** as materially different from HEFA linked to more problematic land-use pathways [17,25,43-46].

ATJ-SPK emerges as a **medium-term diversification** pathway. Its attractiveness lies in Indonesia's potential to connect SAF to alcohol production chains rather than to scarce lipid streams alone. But the framework penalises ATJ when its alcohol feedstock is high-carbon or exposed to food-market volatility, and it rewards ATJ when alcohol production is low-carbon, integrated, and traceable. ICAO's default values make that contrast very clear: residue- and sugarcane-based ethanol routes can be materially stronger than crop- and coal-heat-intensive routes. This makes ATJ strategically promising, but conditional on upstream alcohol decarbonization and robust chain-of-custody systems [17,25,43-46].

FT-SPK is the most interesting **longer-term strategic pathway** in the framework. It can perform very well environmentally when linked to agricultural residues, forestry residues, or well-characterized municipal solid waste streams, and it offers diversification away from lipid bottlenecks. However, the pathway is penalized on capital burden, project complexity, and logistics. Residues and wastes are often abundant in theory but difficult to aggregate at stable quality and cost. For a country like Indonesia, that means FT-SPK may be strategically superior on carbon and feedstock diversity, but inferior on immediate deliverability unless waste governance, aggregation, preprocessing, and long-term offtake structures mature. The framework, therefore, interprets FT not as an early leader, but as a route worth preparing now so that it becomes scalable later [17,25,43-46].

Limitations, Robustness and Implications for Indonesia

This framework has three main limitations. First, it is **qualitative rather than econometric**. It is designed for rigorous synthesis and pathway discrimination, not for predicting a unique numerical optimum. Second, it is only as strong as the underlying evidence, and the evidence is uneven across pathways: HEFA has a deeper commercial literature than ATJ, and FT often has stronger engineering literature than deployment literature. Third, Indonesia-specific data on sustainably collectable feedstock, logistics cost, and project finance are less standardised than ASTM and ICAO certification data, so national judgments still require cautious interpretation [17,25,43-46].

To improve robustness, the framework used three checks. The first was a **feedstock-switch check**: if changing the feedstock within the same pathway altered the carbon or economic picture substantially, the pathway was flagged as feedstock-sensitive rather than being assigned a simple generic score. The second was a **time-horizon check**: pathways were assessed separately for near-term, medium-term, and longer-term feasibility. The third was a **policy-sensitivity check**: pathways that require strong subsidies, certification architecture, or public tolerance were treated as more policy-dependent than pathways that can more easily use existing industrial systems. These checks reduce the risk of overrating technically elegant but institutionally fragile options [17,25,43-46].

The policy implication for Indonesia is therefore a **sequenced portfolio strategy** rather than a single-pathway doctrine. On the evidence reviewed here, the most prudent reading is: **HEFA-SPK first**, provided the feedstock base is genuinely traceable and low-risk; **ATJ-SPK second,** as a medium-term complement if low-carbon alcohol production scales; and **FT-SPK third,** as a strategically important route to be de-risked through residue and waste system-building rather than expected to carry the first deployment wave. That conclusion is consistent with the uploaded ASTM pathway landscape, with ICAO's increasingly detailed sustainability and lifecycle governance, and with the broader literature showing that SAF scaling depends on market creation, readiness, and resource integrity as much as on laboratory conversion success [18,39-42].

A final implication is methodological. For Indonesia, the decisive question is not simply **which pathway is globally most celebrated, but which feedstock-pathway combinations can pass sustainability scrutiny, mobilise partners, fit existing aviation-service systems, and remain financeable under Indonesian conditions.** That is why the twelve-dimension framework is valuable: it forces pathway choice to be evaluated holistically, and it makes explicit that "most suitable for Indonesia" is a context-specific judgment shaped by certification, carbon performance, feedstocks, institutions, and time [33,48-55].

Results

The first thematic finding is that **technological maturity and certified blending potential strongly favour HEFA as Indonesia's initial anchor technology.** The ASTM-recognised pathways show that HEFA, FT, ATJ, and CHJ-related routes can reach high blending limits, while HFS-SIP and several niche routes remain constrained by much lower ceilings. The literature then narrows the field further. It has been characterised that HEFA and FT as among the few advanced biofuel pathways with near-commercial readiness, while the ASTM-recognised pathways underscore that HEFA and ATJ already occupy the core certification space relevant to Indonesia [1]. In practical policy terms, this means Indonesia does not need to choose among all imaginable SAF technologies; it needs to choose among a smaller subset of routes that are already technically recognised and commercially viable [1,3].

The second thematic finding is that **feedstock economics divide the pathways sharply.** HEFA offers high conversion efficiency and near-term refinery compatibility, but it depends on relatively scarce lipid feedstocks. It has been reported that HEFA feedstocks can range from roughly \$0.70/kg to \$2.60/kg and emphasises that feedstock availability is limited and prices are unlikely to fall much because these lipids already serve competing renewable fuel markets [1]. They also note that used cooking oil availability is constrained and that such feedstocks are already heavily used in biodiesel systems. This is highly relevant for Indonesia, because the existence of a large palm economy does not automatically solve the HEFA problem: what matters is the availability of acceptable low-cost lipids, not simply any oil-rich biomass [3].

By contrast, **FT is economically harder at the plant level but more expensive at the feedstock level.** It has been estimated that FT production costs in a broad range of roughly \$1.00/L to \$2.29/L depending on biomass cost and conversion efficiency, while also noting that FT can draw on a much broader feedstock base than HEFA [1]. This broader base is strategically attractive for Indonesia because it aligns better with agricultural residues, municipal solid waste, and other non-lipid streams. Yet the same literature also shows that FT routes are capital-intensive and more sensitive to plant execution risks than HEFA. In a country that may still be building its SAF finance architecture, that distinction matters: feedstock flexibility improves long-run scalability, but high capital complexity can delay first deployment [3].

ATJ occupies an intermediate position. The ASTM-recognised pathways show that ATJ belongs to the recognised route family with a deployment-relevant blend ceiling. The broader industry ecosystem also demonstrates that ATJ has moved beyond laboratory status: LanzaJet's commercial plant in the United States, Gevo's retrofit logic for alcohol platforms, and additional planned projects show that ATJ is institutionally real, not merely experimental. At the same time, ATJ's bankability depends on whether low-carbon ethanol or isobutanol can be supplied competitively and sustainably. For Indonesia, this creates both opportunity and caution. If the country can mobilise low-carbon ethanol from molasses, sugarcane, or eventually cellulosic pathways without triggering adverse land-use change, ATJ could become a major second-wave pathway. If not, ATJ inherits the same sustainability disputes that trouble first-generation biofuels [22,32-34].

A third thematic finding concerns **return on investment and financing logic.** In a purely engineering comparison, the "best" technology might be the route with the widest feedstock base or most future-proof carbon logic. In investment reality, however, the best technology is often the one that investors can most plausibly underwrite. HEFA benefits here because it can piggyback on hydroprocessing knowledge, refinery integration, and relatively familiar project structures. FT offers strategic upside but requires larger and more complex integrated facilities. ATJ can become attractive where ethanol assets and offtake structures already exist. It has also been emphasised that airline economics are tight and that fuel costs already form a large share of airline operating costs, meaning that SAF pathways requiring very high price premiums face slower market uptake unless policy support closes the gap. This makes early HEFA and co-processing projects more plausible in Indonesia's financing environment than a large national FT rollout in the first instance [3,57].

A fourth thematic finding is that **policy and market pull now matter as much as process chemistry**. The European Union has enacted an SAF mandate that starts at 2% and rises steeply over time, while Singapore is implementing a dedicated SAF levy and positioning itself as the region's policy and logistics pioneer. Meanwhile, IATA-linked estimates still assume that SAF must carry most of the decarbonization burden. The implication for Indonesia is simple: there is now a durable external market signal for compliant SAF. Indonesian producers are not only serving domestic airlines; they are entering a regional and global compliance economy. Any pathway that performs poorly on export legitimacy or sustainability documentation will therefore be structurally disadvantaged even if it looks attractive in domestic feedstock terms [35].

A fifth thematic result concerns **environmental sustainability and lifecycle credibility**. It has been explicitly warned that lifecycle emissions for biofuels vary widely and that ICAO's minimum threshold should not be mistaken for actual climate optimality [1]. AP reporting on Indonesia's bioethanol expansion and recent palm-related evidence reinforces the risk that land-use change can erode or even reverse the climatic value of nominally renewable fuels. For Indonesia, therefore, a pathway is not environmentally feasible unless it can be tied to feedstocks with strong chain-of-custody credibility, low indirect land-use risk, and defensible lifecycle accounting. This is precisely why a waste-and-residue-centred HEFA strategy is stronger than a virgin-oil-centred one, and why FT and future cellulosic ATJ deserve policy support as hedge technologies against sustainability backlash [3,57].

The Resulting Cross-Pathway Comparison can be Summarised in table 4 as Follows

Table 4 translates the qualitative comparison into a visual assessment matrix. The figure is not intended to serve as a quantitative scoring model; rather, it provides a synthetic interpretation of the thematic findings from the qualitative literature review. The matrix compares six major SAF pathway groups against eight decision criteria that are especially relevant for Indonesia: feedstock availability, feedstock cost stability, technology maturity, capital burden, environmental performance, blending flexibility, ecosystem readiness, and investment attractiveness. This visual format helps reveal why HEFA-SPK emerges as the most feasible near-term option, why co-processing is best understood as a transitional bridge, and why ATJ-SPK and FT-SPK should be treated as medium- to long-term diversification pathways rather than immediate substitutes for HEFA.

Table 4. expands the pathway comparison from a shorter visual matrix into a twelve-dimensional evaluative framework that is fully consistent with the methodological logic of this article. Rather than comparing SAF technologies only in narrow techno-economic terms, the table assesses them across feedstock availability, feedstock price resilience, domestic market fit, technology maturity, capex feasibility, ROI attractiveness, ASTM blending limits, technology-partner availability, policy alignment, lifecycle emissions performance, international aviation ecosystem fit, and supply-chain readiness. This broader structure is necessary because the suitability of a SAF pathway for Indonesia depends not only on chemical conversion efficiency, but also on whether the pathway can be supplied with credible feedstocks, financed at acceptable risk, integrated into international aviation governance, and scaled through realistic domestic logistics and institutional capacity [25].

Table 4: 12-Dimension Comparative Assessment of Major ASTM-Recognised SAF Pathways for Indonesia.

SAF PATHWAY	TWELVE-DIMENSION EVALUATION FRAMEWORK: 1 Feedstock Availability & Security	2 Feedstock Sustainability & GHG Intensity	3 Technology Maturity	4 Process Economics (Cost Competitiveness)	5 Capital Intensity & Financing Feasibility	6 Infrastructure & Integration Readiness	7 Environmental Performance (LCA)	8 Scalability Potential	9 Policy & Regulatory Alignment	10 Market Demand & Offtake Potential	11 Risk & Supply Chain Resilience	12 Social Acceptance & Stakeholder Support	OVERALL READINESS (Indonesia Context)
HEFA-SPK	High	High	Very High	Medium	Medium	High	High	High	High	High	High	High	High
ATJ-SPK	Medium	Medium	Medium	Low	Low	Medium	High	Medium	Medium	Medium	Medium	Medium	Medium
FT-SPK	High	Medium	High	Medium	Medium	Medium	High	High	Medium	Medium	Medium	Medium	Medium
CHJ	Medium	Medium	Medium	Medium	Medium	Medium	High	Medium	Medium	Medium	Medium	Medium	Medium
SIP / HFS-SIP	Low	Low	Low	Low	Low	Low	Medium	Low	Low	Low	Low	Low	Low
Co-processing (HEFA/FA & FT)	Medium	Medium	High	Medium	Medium	Medium	Medium	High	Medium	Low	Very High	High	Medium–High

RATING LEGEND: Very High – Excellent / Very favorable; High – Favorable; Medium – Moderate / Partially favorable; Low – Unfavorable / Limited; Very Low – Not favorable / Major barriers

Notes: Ratings reflect qualitative expert judgment synthesized from recent literature (2020–2024) and context-specific conditions in Indonesia.

Synthesis

HEFA-SPK demonstrates the strongest overall readiness for Indonesia due to abundant feedstocks (UCO, animal fats), proven technology. Strong policy alignment, and infrastructure compatibility. Co-processing offers a practical transitional bridge leveraging existing refinery assets. ATJ-SPK and FT-SPK present Promising medium-term options contingent on technology cost reduction, feedstock diversification, and market development.

Key Takeaway

A diversified SAF portfolio-led by HEFA-SPK in the near term, supported by co-processing, and complemented by ATJ-SPK and FT-SPK in the medium term-provides the most resilient pathway for indonesia.

Using this twelve-dimension framework, HEFA-SPK emerges as the strongest near-term pathway for broad deployment in Indonesia, while co-processing performs best as a transitional refinery bridge. ATJ-SPK and FT-SPK should be interpreted as medium-term diversification routes that become more attractive as low-carbon alcohol supply, waste logistics, and larger-scale project finance mature. CHJ remains a secondary but potentially useful complementary route, whereas SIP/HFS-SIP appears least favourable under present Indonesian conditions because of its lower maturity, narrower ecosystem support, and lower blending ceiling [25].

The matrix reinforces three substantive conclusions. First, HEFA-SPK performs strongly because it combines high technology maturity, high blending flexibility, strong partner availability, and relatively high investment attractiveness. However, its medium rating for feedstock cost stability reflects the risk that waste oils, used cooking oil, animal fats, and other lipid inputs may become increasingly expensive as global SAF and renewable diesel demand grow. Second, co-processing receives strong ratings for ecosystem readiness and investment attractiveness because it can use existing refinery infrastructure, but its lower blending flexibility and limited renewable share make it a bridge rather than a final strategic solution. Third, ATJ-SPK and FT-SPK show meaningful promise but require deeper preparation: ATJ depends on a reliable low-carbon alcohol supply, while FT requires more complex biomass, residue, municipal solid waste, gasification, and synthesis infrastructure. Thus, Table 2 supports a phased portfolio strategy rather than a single-pathway national SAF policy.

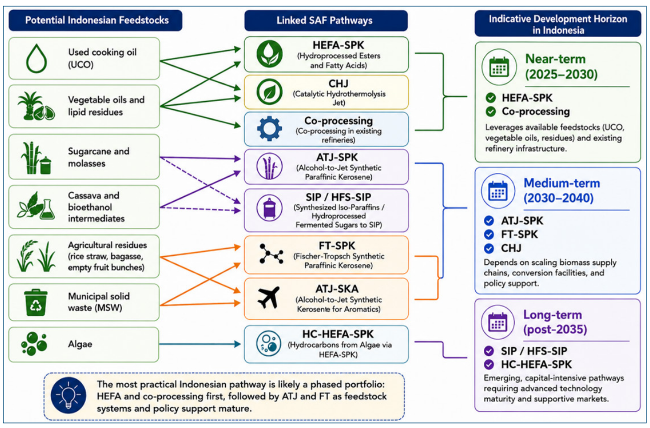
The sixth thematic result concerns **technology partners and ecosystem readiness.** HEFA enjoys the deepest partner field, spanning refiners, established process licensors, and firms with real SAF production track records. ATJ has a growing but more specialised partner ecosystem, with LanzaJet, Gevo, and related alcohol conversion actors demonstrating commercial momentum. FT also has major industrial associations but a more mixed history of project delivery and financial execution. In the Indonesian context, this matters because a pathway that can be partnered quickly with credible licensors, offtakers, and refinery operators is more likely to make it from feasibility study to commissioning. Indonesia's state-owned energy structure gives HEFA and co-processing an additional advantage because they map better onto existing institutional assets [58].

Finally, the results suggest that **international aviation business conditions reward early movers with credible SAF.** Singapore's SAF levy shows that Southeast Asia is no longer a policy laggard; it is becoming an active arena of SAF competition. The EU's mandate creates external demand pull. Global airline decarbonization targets, even if increasingly difficult to meet, still make SAF a strategic procurement priority. For Indonesia, this means that SAF is not merely an input substitution problem. It is a competitive positioning problem in the regional aviation economy. That broader business ecosystem strengthens the case for starting with the pathway that can produce certifiable volumes soonest, even if broader technology diversification is needed later [59].

Discussion and Policy Analysis

The evidence assembled above points to a layered answer. If the question is **Which pathway should Indonesia prioritise for immediate, wide-scale development?**, the answer is **HEFA-SPK**, specifically through a **waste- and residue-centred model** rather than an open-ended virgin-oil model. If the question is **Which pathway should Indonesia build in parallel as a strategic second wave?,** the answer is **ATJ,** especially where carbon-credible ethanol can be mobilised. If the question is **Which pathway best positions Indonesia for deep decarbonization at a larger scale over the longer term?,** the answer is **FT,** because no other pathway offers comparable flexibility to move beyond the lipid bottleneck. This is not a contradiction. It is a staged strategy shaped by temporal feasibility [3].

The Indonesian SAF decision is fundamentally a feedstock-to-technology matching problem. Figure 2 maps potential Indonesian feedstock groups to the SAF pathways for which they are most relevant and then links those pathways to an indicative development horizon. This figure is important because it prevents the policy discussion from treating SAF technologies as abstract global options detached from Indonesia's material base. Used cooking oil, vegetable oils, and lipid residues are most directly aligned with HEFA-SPK, CHJ, and co-processing. Sugarcane, molasses, cassava, and bioethanol intermediates are more relevant to ATJ-SPK and, to a more limited extent, SIP/HFS-SIP. Agricultural residues and municipal solid waste are better aligned with FT-SPK and ATJ-SKA, while algae remains a longer-term option through HC-HEFA-SPK or related pathways.



Source: Synthesised for ASTM-Recognised Pathways

Figure 2: Indonesia Feedstock-to-Technology Oppertunity Map for SAF Development.

Figure 2. shows why Indonesia's most practical SAF strategy should be sequenced rather than uniform. In the near term, HEFA-SPK and co-processing are more feasible because they can draw on lipid-based feedstocks and existing refinery capabilities. In the medium term, ATJ-SPK, FT-SPK, and CHJ become more relevant as Indonesia develops more reliable alcohol, residue, waste, and biomass supply chains. In the long term, SIP/HFS-SIP and HC-HEFA-SPK may become part of a more diversified SAF ecosystem, but they are unlikely to serve as the backbone of national deployment in the current decade because of blending limitations, technology maturity constraints, and uncertain feedstock scalability. The figure therefore supports the article's main conclusion: Indonesia should not merely ask which SAF technology is globally attractive, but which pathway can be credibly matched with domestic feedstock systems, sustainability governance, and aviation market demand over time.

Why does HEFA come first? The reason lies in the interaction of **maturity, financing, and infrastructure.** HEFA is not the most abundant feedstock route, and it is not the least controversial route environmentally. Yet it is the pathway most likely to move from paper to plant under Indonesian institutional conditions within the present decade. It offers high certified blending relevance, strong technology partner availability, compatibility with refinery assets, and a straightforward narrative for investors and airlines. In that sense, HEFA is the pathway of **industrial plausibility.** The literature consistently treats it as the market benchmark even while highlighting its feedstock constraints [3].

However, a naïve HEFA strategy would be a mistake. If Indonesia interprets HEFA feasibility as permission to lean heavily on virgin palm-based oils, it could achieve physical fuel production while losing environmental credibility and possibly even market access in key jurisdictions. That is why the phrase **"strict sustainability guardrails"** is essential. Those guardrails should include a feedstock hierarchy that puts used cooking oil, tallow, genuinely residual palm-chain feedstocks with robust traceability, and other wastes ahead of virgin edible oils; mandatory lifecycle accounting; land-use safeguards; and export-market compatibility screens. Without these, Indonesia might build a SAF industry that is technically valid but commercially discounted. ATJ deserves stronger emphasis than it usually receives in short-term policy debates [29].

Indonesia's biofuel history and current policy attention to ethanol mean that ATJ could become the critical bridge between today's hydroprocessing-heavy SAF market and tomorrow's more diversified low-carbon fuel economy. ATJ's strategic appeal is that it can tap a broader industrial platform than HEFA if low-carbon alcohol becomes available at scale. It also fits a world in which aviation seeks pathways beyond scarce lipids but before e-fuels become cost-competitive. For Indonesia, ATJ should not displace HEFA in the immediate term, but it should absolutely be built into pilot policy, licensing discussions, and ethanol decarbonization planning now [42,57,60-62].

FT is the pathway most likely to matter once Indonesia's SAF ambition moves from "initial deployment" to "national scaling and long-run competitiveness." The reason is structural. HEFA suffers from lipid scarcity. ATJ depends on the alcohol market evolution. FT, by contrast, can eventually use a very broad family of waste and residue resources. This makes FT the most powerful hedge against feedstock bottlenecks and the most future-aligned route if Indonesia wants to integrate agricultural residues, forestry residues, municipal waste, or later syngas-based electrofuel hybrids. Yet this strategic strength is precisely why FT should be treated as a **second-phase infrastructure and risk-reduction agenda,** not as the first commercial move. Indonesia should use the 2020s to build feedstock logistics, waste aggregation systems, gasification capability, and financing structures rather than forcing premature large-scale FT deployment [3].

The lesser-priority pathways are easier to classify. HFS-SIP and related niche routes have low strategic value for mass deployment because limited blending ceilings reduce their system-wide decarbonization contribution. CHJ and related hydrothermal routes are technically interesting and may become useful, but they currently lack the combination of partner depth, visible commercialisation, and policy momentum needed to justify first-priority status in Indonesia. Co-processing deserves more nuance: it is not a full strategic answer, but it can be an excellent **bridge technology** because it allows early learning, distribution adjustment, and initial SAF volumes using existing refinery systems. In other words, co-processing should be used tactically, not mistaken for the final architecture of a national SAF industry [3,62].

The policy roadmap implied by this interpretation is phased and cumulative rather than binary. The comparative review indicates that Indonesia should not approach SAF development as a one-step technology selection problem, but rather as a staged industrial transformation. Different pathways become feasible at different moments depending on feedstock readiness, technology maturity, infrastructure capacity, policy support, and market formation. For that reason, the strategic implication of this review is best expressed through a phased roadmap rather than through a single static ranking of technologies. Figure 3 presents this phased strategic roadmap, showing how Indonesia can sequence actions across the short, medium, and long term to build a credible SAF ecosystem while reducing technological, financial, and logistical risks.

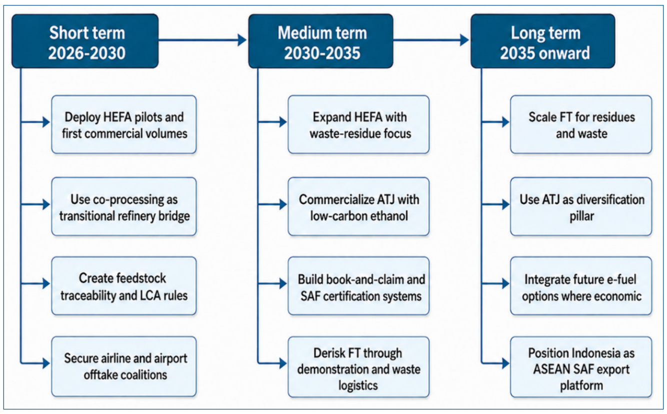


Figure 3: Phased Strategic Roadmap for SAF Development in Indonesia.

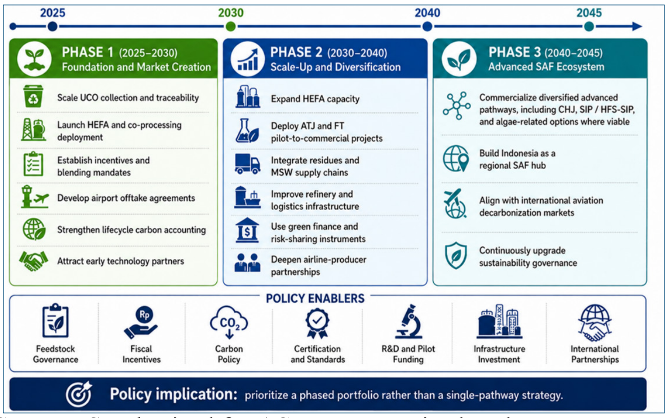
Figure 3. illustrates that the recommended SAF strategy for Indonesia is inherently sequential and cumulative. In the s**hort term (2026-2030)**, the priority is to establish the foundations of a domestic SAF market by deploying HEFA pilot projects and first commercial volumes, using co-processing as a transitional refinery bridge, developing feedstock traceability and life-cycle

assessment (LCA) rules, and securing airline and airport offtake coalitions. These measures are essential because they reduce early market uncertainty and help create the institutional and commercial conditions necessary for broader SAF adoption. The short-term phase, therefore, emphasises practicality, regulatory preparation, and low-risk entry pathways rather than technological diversification for its own sake. In the **medium term (2030-2035),** the roadmap shifts from market initiation to scaling and system building. At this stage, Indonesia is expected to expand HEFA deployment with a stronger waste- and residue-based orientation, commercialise ATJ using low-carbon ethanol, build book-and-claim and SAF certification systems, and de-risk FT development through demonstration projects and improvements in waste logistics. This phase is particularly important because it links technological expansion with market credibility. HEFA remains important, but the strategy begins to diversify toward ATJ and FT as domestic capabilities improve and as feedstock supply systems become more organised and reliable.

In the **long term (2035 onward),** the roadmap envisions Indonesia moving from early deployment and scale-up toward regional leadership and technological diversification. The figure shows that FT can be scaled for residue- and waste-based production, ATJ can serve as an important diversification pillar, and future e-fuel options may be integrated where they become economically viable. The roadmap also highlights an outward-looking strategic ambition: positioning Indonesia as an ASEAN SAF export platform. In substantive terms, this means that the country should not only meet domestic aviation decarbonization needs but also develop the institutional, industrial, and logistical capacity to participate competitively in regional and international SAF markets [62].

This phased roadmap reflects the literature's distinction between what is commercially near-ready now and what is strategically scalable later, as well as the external demand signals created by CORSIA, ReFuelEU, and Singapore's SAF policy [3]. From this analysis, six integrated policy recommendations follow. First, Indonesia should formally adopt a **pathway hierarchy** in policy: HEFA first, ATJ second, FT third. Second, it should create a **feedstock hierarchy** centred on wastes and residues, not just renewability rhetoric. Third, it should tie SAF incentives to **verified lifecycle carbon performance** rather than to generic biomass categories. Fourth, it should use Pertamina and related state structures to build **industrial coordination platforms** with airlines, airports, certification bodies, and technology licensors. Fifth, it should design financing instruments that match pathway maturity: grants and refinery upgrades for early HEFA, blended finance for ATJ, and risk-sharing mechanisms for FT demonstrations. Sixth, it should align domestic SAF policy with the realities of export legitimacy, especially in relation to EU and regional market standards [8-12].

The policy implications of the review can be organised into a phased roadmap. Figure 4 presents a practical sequence for broad SAF development in Indonesia from 2025 to 2045. The roadmap is designed to avoid two policy errors: moving too slowly and losing regional market opportunities, or moving too quickly into capital-intensive pathways before feedstock governance, certification systems, and bankable offtake structures are mature. The roadmap, therefore, begins with HEFA-SPK and co-processing as deployment-oriented pathways, then expands toward ATJ-SPK, FT-SPK, and CHJ as supply chains and project capabilities mature, and finally moves toward an advanced SAF ecosystem capable of supporting diversified pathways and regional export positioning.



Source: Synthesised for ASTM-Recognised Pathways.

Figure 4: Phased Roadmap for Broad SAF Development in Indonesia.

Figure 4. emphasises that Indonesia's SAF policy should be built as a staged industrial transition. Phase 1, covering 2025-2030, should focus on market creation, feedstock traceability, early HEFA deployment, refinery co-processing, lifecycle carbon accounting, and airport or airline offtake agreements. Phase 2, covering 2030-2040, should expand HEFA capacity while developing ATJ and FT pilot-to-commercial projects, improving logistics infrastructure, and mobilising green finance. Phase 3, covering 2040-2045, should position Indonesia as a more advanced regional SAF hub by commercialising diversified pathways and aligning with international aviation decarbonization markets. The policy enablers shown at the bottom of the figure are not secondary details; they are the conditions that determine whether SAF production becomes merely a technical experiment or a credible national industry. Feedstock governance, fiscal incentives, carbon policy, certification, R&D support, infrastructure investment, and international partnerships should therefore be treated as the institutional foundation of Indonesia's SAF transition [62].

A final point of analysis concerns the broader question of national strategy. Indonesia should avoid the false choice between **industrial sovereignty and environmental credibility.** In SAF, those two goals increasingly depend on each other. A pathway that cannot pass sustainability scrutiny will struggle to attract capital, partners, or premium offtake. Conversely, a pathway that is environmentally elegant but commercially impossible will not decarbonise real aircraft. The most feasible Indonesian solution is therefore the one that lies at the intersection of both. In the current decade, that intersection is occupied most clearly by a well-governed HEFA strategy, backed by ATJ incubation and FT preparation [3].

Conclusion

This qualitative literature review set out to compare SAF conversion technologies and determine which is most feasible for large-scale development in Indonesia. The answer, based on thematic synthesis of the ASTM-recognised pathways summary, recent literature, and current policy-market signals, is that **HEFA-SPK is the most feasible lead technology for Indonesia in the near term,** but only when feasibility is understood comprehensively and only when the pathway is governed through strong sustainability rules. HEFA wins not because it is abundant, cheap, or environmentally unproblematic, but because it is the pathway that best combines commercial maturity, investability, partner availability, refinery compatibility, and immediate deployment potential.

At the same time, the review rejects the idea that Indonesia should equate “most feasible now” with “best forever.” Long-run resilience requires diversification beyond lipid dependence. Therefore, **ATJ should be the principal medium-term diversification route,** especially if Indonesia can produce low-carbon ethanol without repeating the land-use mistakes associated with first-generation biofuels. **FT should be the principal long-term scale route,** particularly for residues and waste-based production, once logistics, financing, and project development capabilities improve. In other words, Indonesia’s optimal SAF strategy is not mono-technological but sequenced: **HEFA for deployment, ATJ for diversification, FT for transformation.**

The substantive policy implication is that Indonesia needs a SAF strategy that is **simultaneously industrial, environmental, and geopolitical.** Industrially, it must mobilise refinery assets, licensor partnerships, and project finance. Environmentally, it must tie incentives to credible lifecycle performance and guard against deforestation-linked feedstocks. Geopolitically and commercially, it must position Indonesian SAF within the tightening standards and demand pull created by CORSIA, ReFuelEU, and the emerging ASEAN SAF ecosystem led by Singapore. A nationally serious SAF strategy will therefore be judged not only by litres produced, but by whether those litres are financeable, certifiable, tradable, and climate-credible.

If Indonesia pursues that integrated strategy, it can become more than a marginal SAF user. It can become a serious regional producer with an export-capable compliance product and a credible decarbonization narrative. If it does not, it risks remaining trapped between externally imposed sustainability standards and domestically fragmented biofuel politics. The choice of technology, therefore, matters profoundly. On the evidence reviewed here, the most coherent path is clear: **start with HEFA under strict safeguards, build ATJ as the next lane, and prepare FT as the long-run backbone of a diversified Indonesian SAF economy.**

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