Sustainable Aviation Fuel in Southeast Asia: Sustainable Supply Chain initiatives for Indonesia

Manvendra Madhukar Bhadange [1] and Irene Sondang Fitrinitia [2]

[1] School of Strategic and Global Studies, Universitas Indonesia

[2] School of Strategic and Global Studies, Universitas Indonesia
Manven.b@gmail.com; irene.sondangf@ui.ac.id

Abstract. The aviation Industry, with its environmental impact, needs urgent decarbonization and Sustainable Aviation Fuel (SAF) is a key near-term solution. This article examines SAF's current status, with a focus on establishing robust and sustainable supply chains for widespread adoption, particularly within ASEAN. It's a comprehensive review of literature to identify key challenges and opportunities across feedstock sourcing, production technologies, policies, and infrastructure in Southeast Asia, with focus on Indonesia.

Utilising systematic literature review (SLR) method for identifying, selecting, and critically appraising relevant research, the article analyzes global SAF production volumes, consumption forecasts to 2030, and the environmental and socio-economic impacts of SAF pathways with sustainable supply chain aspects, focusing on Southeast Asia, specifically Indonesia. The review emphasizes a multi-faceted approach of stakeholder collaboration, technological innovation, supportive policies, strategic partnerships & Lifecycle Assessment. It addresses research gaps, including long-term feedstock sustainability in Southeast Asia, lifecycle emissions of various SAF pathways, scalability of emerging technologies, and socio-economic implications across ASEAN.

Indonesia, with its abundant biomass, is positioned as a key SAF producer. This review explores opportunities and challenges for Indonesia and other ASEAN countries in developing sustainable SAF supply chains. The ultimate goal is a comprehensive overview and roadmap for policymakers, industry, and researchers to accelerate SAF adoption in ASEAN, reduce aviation's carbon footprint, and foster a sustainable aviation sector, ensuring regional economic growth.

Keywords: Sustainable Aviation Fuel, Supply Chain, Indonesia.

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1 Introduction

The aviation sector plays a vital role in global economy, by facilitating international commerce, tourism, and cultural interactions. However, aviation's environmental footprint now represents 2-3% of worldwide greenhouse gas (GHG) emissions (Raghu R. et. al. (2024), SKYNRG (2024) Sustainable Aviation Fuel Market Outlook). Aligning SAF research with sustainable development goals, presents a significant challenge in the fight against climate change, particularly in developing regions like Southeast Asia. In 2013, the industry generated 702 million tons of greenhouse gas emissions, surging to 920 million tons by 2019. The COVID-19 pandemic brought a temporary reprieve, with emissions plummeting to 495 million tons in 2020. However, post covid, with the resurgence of air travel, emissions rebounded to 800 million tons in 2022, 820 million tons in 2023 & expected to cross the pre covid values in 2025 (Inemesit Ukpanah 2024). Addressing this requires a focus on SAF strategies, especially in Indonesia, with its unique opportunities and challenges related to feedstock availability and supply chain development.

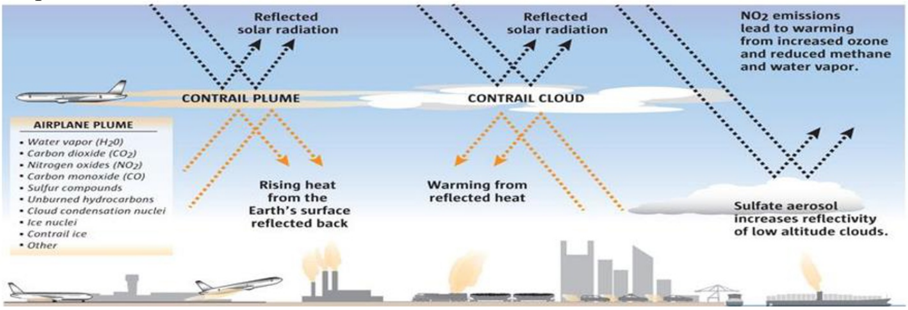

Figure 1: Climate effects from global aviation emissions and cloudiness (Lee, Fahey, et.al. (2021) Atmospheric Environment)

With air travel projected to increase, aviation emissions are expected to rise, making it more difficult to achieve net-zero targets. However, Public awareness and demand for sustainable practices are on the rise.

Strategies to decarbonize aviation include improving aircraft fuel efficiency, optimizing flight operations, developing alternative propulsion systems (electric and hydrogen), and utilizing carbon offsetting schemes. Aircraft efficiency improvement & flight operations optimization has a positive impact, but is offset due to increasing volume of Air travel. The electric and hydrogen aircraft propulsion face technological & economic challenges, and carbon offsetting schemes have been criticized for their reliability. Sustainable Aviation Fuel (SAF) emerges as a promising near-term solution, reducing lifecycle carbon emissions while utilizing existing infrastructure.

SAF refers to aviation fuel produced from sustainable and renewable feedstocks, as opposed to conventional jet fuel derived from finite fossil fuels like crude oil. SAF can be broadly divided in to three main categories (N. Bullerdiek et. All, Journal of Air Transport Management):

Biomass-based SAF: Produced from lipids (oils/fats), starch (corn, wheat), sugar (sugar cane, sugar beet), ligno-celluloses material (agricultural residues, forestry residues) and municipal / industrial organic waste.

Electricity-based SAF: Produced from renewable electricity and water to create hydrogen, which combines with a carbon source (CO2) in a Power-to-Liquid (PtL) process.

Hybrid SAF: represents combined biomass and electricity-based concepts, also referred to as "power and Biomass-to-Liquid" or Power and Biogas-to-Liquid (PBtL) processes. In contrast to pure biomass or electricity-based pathways, the energy content of the final fuel is provided by feedstocks and processes of both pathways, to increase fuel yields.

While the benefits of SAF are clear, widespread adoption faces complexities: technological hurdles, robust, sustainable, and scalable supply chains, and high cost. This article addresses a central challenge: translating global SAF demand into effective regional action within ASEAN. It delves into the global SAF landscape, understanding challenges, opportunities, and effective supply chain initiatives for successful adoption, particularly in Indonesia. Furthermore, the article investigates SAF capacity projections and governmental policies stimulating growth, especially within ASEAN member states. The article also assesses diverse technological pathways for SAF manufacturing and feedstock sustainability. Ultimately, the research explores and adapts sustainable supply chain initiatives, focusing on applicability and implementation within Southeast Asia, specifically Indonesia, contributing to sustainable air travel.

Sustainable supply chains must address issues like:

* Ensuring sustainable sourcing without impacting food security or causing deforestation.
* Minimizing production costs to compete with conventional jet fuel.
* Mitigating environmental impacts of SAF production.
* Establishing clear regulatory frameworks and certification standards.

* Expanding production capacity and developing efficient infrastructure.

These challenges needs solution through a comprehensive approach that considers the entire SAF value chain across the ASEAN region.

2 Theoretical Framework

To understand the complex factors influencing sustainable supply chains for SAF, this article draws on few established theories. These theories provide different insights on the economic, social, and environmental aspects that affect the growth, scalability, and success of SAF supply chains. Combining these perspectives helps to create a comprehensive view of the challenges and potential areas for improvement.

2.1 Resource-Based View (RBV):

This theory (Barney, 1991) suggests that a company's competitive edge comes from its unique VRIN (valuable, rare, hard to imitate, and non-substitutable) resources to ensure sustained advantage. For SAF, this includes access to sustainable feedstocks, advanced production technologies, strong partnerships across the supply chain (such as suppliers, technology providers, airlines, and governments), and supportive policies incentivizing SAF Production & promoting market access.

2.2 Stakeholder Theory:

Developed by Edward Freeman (1984), this theory emphasizes considering the interests of all stakeholders affected by a firm's activities. In SAF, stakeholders include airlines, fuel producers, feedstock suppliers, technology providers, policymakers, local communities, environmental groups, and travellers. Effective SAF supply chain initiatives must proactively cater to and manage the diverse concerns and expectations of all these stakeholders.

2.3 Supply Chain Management (SCM) Theories:

SCM theories provide framework for optimizing the flow of materials, information, and finances in the SAF supply chain. Lean SCM drives for reducing waste and inefficiencies. Agile SCM aims for flexibility and responsiveness to market demands. Resilient SCM focuses on building robustness to mitigate disruptions. These theories can be used to identify bottlenecks, optimize logistics, improve communication, and enhance the overall efficiency and sustainability of SAF value chain.

3 Review of Related Literature

A comprehensive and critical review of the existing literature on SAF supply chains, sustainability issues, and related technologies, provides an overview of key findings, identifies prominent research gaps, highlights ongoing debates, and analyses emerging trends in the field. The review encompasses a wide variety of sources, including peer-reviewed academic articles published in major scientific journals (Journal of Cleaner Production, Renewable and Sustainable Energy Reviews, Applied Energy), authoritative industry reports released by reputable organizations (IATA, IRENA, ASEAN Centre for Energy, SKYNRG, World Economic Forum), policy documents issued by government agencies (IEA), and insightful studies conducted by non-governmental organizations (NGOs) and think tanks.

Figure 2: Systematic Literature Review

In the second part of the study, the global SAF landscape is explored, with a systematic approach of gathering secondary data from industry reports, government publications, international aviation regulatory bodies, and academic journals. The data compiled spans a five-year period, allowing for an analysis of new trends, growth patterns, and different technologies.

The review is organized around the key themes of Sustainability, Feedstock, Technology, Economics, Policy & Regional factors for SAF adoption.

4 Global Production Capacity of SAF & Forecast:

SAF production volume, still a small share of global aviation fuel consumption, is growing significantly. In 2022, SAF production reached 300 million liters, more than doubled to over 600 million liters in 2023 and then doubled again to 1.3 billion liters in 2024, but still 0.3% of global jet fuel production (or 11% of global renewable fuel) (IATA Press Release 2024). Outlook for 2025 anticipate a volume of 2.70 billion liters, representing roughly 0.7% of overall jet fuel production and 13% of world's renewable fuel capacity (IATA Press Release 2024). These shows a rapid upward trend in SAF production, although it still is a small percentage of overall jet fuel used globally.

Global consumption of Sustainable Aviation Fuel (SAF) is steadily increasing, largely driven by regulation, airlines' sustainability commitments, and *growing* demand for more sustainable travel. Europe and the Americas *are leading in using SAF*, *supported by robust* policy frameworks, like the European Union's RED II and the U.S. Renewable Fuel Standard (RFS) *that promote* SAF *adoption*.

Among the airlines, major adopters are KLM, Lufthansa, Air France, United Airlines and Delta. In Dec 2021, United Airlines became the first to fly a commercial flight using 100% SAF (United Airlines website). Freight Airlines like UPS and DHL are also adopting SAF to reduce the carbon footprint of their fleets.

Looking ahead, projections for 2030 estimate 22 billion litres (17.3 Million Ton), and a more ambitious 312 billion litres by 2050 (SKYNRG 2024).

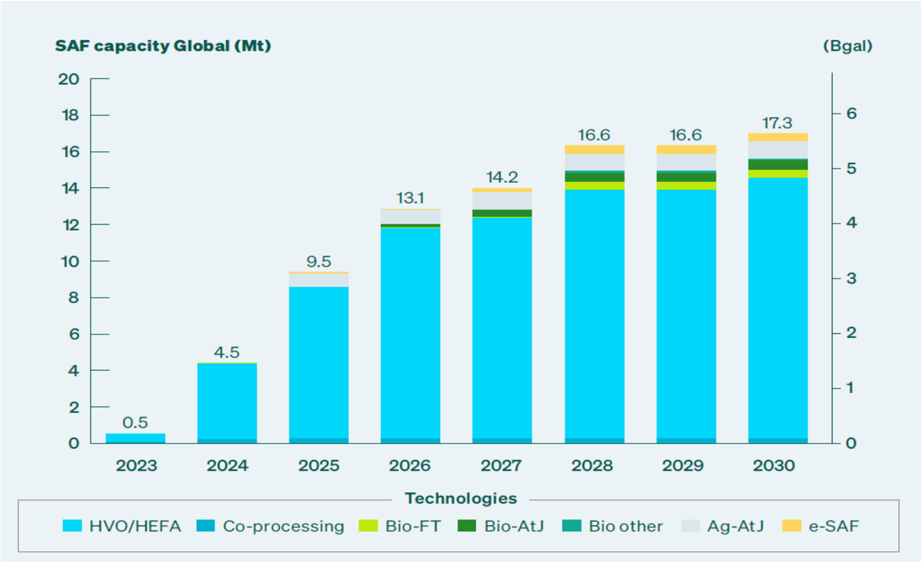

Figure 3: Global SAF capacity announcements until 2030 (Reference: Sustainable Aviation Fuel Market Outlook; SKYNRG (June 2024))

However, achieving these goals hinges on the rapid deployment of new production pathways utilizing biomass feedstocks and green hydrogen. Regional capacity projections for 2030 (SKYNRG (2024) SAF Market Outlook highlight North America as a leader with an estimated 7.0 million tonnes (Mt), followed by the European Union & UK at 3.8 Mt, China & Southeast Asia at 3.6 Mt, and Latin America at 2.3 Mt. Other regions including Africa and the Middle East are projected to have smaller volumes. These projections suggest a geographically diverse expansion of SAF production, with large investments and infrastructure development to realize the stated goals. The industry also faces challenges in feedstock availability, technology scaling, and policy support to achieve the ambitious targets set for the coming decades.

5 Versatility of SAF:

The flexibility of SAF in feedstock options and production pathways, makes it an exceptionally attractive solution for various regions and economies, as it allows for the utilization of locally available resources and the adaptation to specific environmental and socio-economic conditions, reducing lifecycle carbon emissions by up to 80% due to the closed-loop carbon cycle (Bofan Wang et. al. 2024)

5.1 Feedstock Sustainability and Availability:

The long-term sustainability and consistent availability of diverse and geographically dispersed feedstocks are paramount for ensuring the scalability and economic viability of SAF production. The existing literature extensively examines the environmental and socio-economic impacts of various potential SAF feedstocks, including algae, oilseeds (e.g., soybeans, canola, palm oil, camelina), forestry residues (e.g., wood chips, sawdust, logging slash, bark), municipal solid waste (MSW), agricultural residues (e.g., corn stover, wheat straw, rice husks, sugarcane bagasse), used cooking oil (UCO), dedicated energy crops (e.g., switchgrass, miscanthus, energy cane), and captured carbon dioxide (CO2). Feedstocks such as algae and MSW offer significant potential for reducing lifecycle GHG emissions compared to conventional jet fuel due to their ability to avoid competition with food production and to utilize waste streams that would otherwise contribute to environmental pollution (Stephenson et al., 2010). However, the sustainability of biomass-derived feedstocks remains a complex and contested issue, as their lifecycle GHG emissions depend heavily on factors such as land use change, water consumption, fertilizer use, and harvesting practices (Searchinger et al., 2008). Several studies emphasize the importance of avoiding deforestation and minimizing land conversion when cultivating biomass feedstocks to prevent the release of stored carbon and the loss of biodiversity.

5.2 Production Technologies and Efficiencies:

Selecting effective and efficient production technologies is crucial for converting various feedstocks into SAF. The aim is to reduce energy consumption, lower greenhouse gas emissions, and improve economic feasibility. ASTM standards guide the quality and blending of SAF with conventional jet fuel. ASTM D7566 (Standard specification for Aviation Turbine Fuel containing synthesized Hydrocarbons) specifies the standards for non-petroleum jet fuels made from synthesized hydrocarbons and details the maximum percentage that can be blended with Jet A. ASTM D1655 (Standard Specification for Aviation Turbine Fuels) allows for co-processing of biomass feedstocks at petroleum refineries, with up to 5% of the blend consisting of biomass-derived fuels.

The available literature discusses several methods for producing SAF which includes Fischer-Tropsch (FT) synthesis, hydro processed esters and fatty acids (HEFA), alcohol-to-jet (ATJ) conversion, gasification combined with catalytic upgrading, and power-to-liquid (PtL) methods.

FT synthesis is a proven technology that converts various feedstocks such as biomass, waste, and captured CO2 into synthetic fuels. Although flexible, it is energy-intensive and requires high capital investment, which can hinder its economic viability.

HEFA is a widely adopted technology in refining, transforming triglycerides from vegetable oils, animal fats, or used cooking oil into SAF with high yields and lower costs. But, its sustainability heavily relies on sourcing economical feedstocks that do not compete with food supplies or cause deforestation.

ATJ routes convert alcohols like ethanol or iso-butanol, produced from biomass or waste, into jet fuel. This process can achieve high yields with low greenhouse gas emissions throughout its lifecycle.

Gasification and pyrolysis process solid biomass or waste materials into syngas or bio-oil. These intermediates can then be upgraded catalytically into SAF.

Power-to-liquid (PtL) technologies aim to produce SAF by combining captured CO2 with hydrogen generated from renewable electricity, yielding carbon-neutral fuel cycle. However, these are still in nascent stage and face challenges related to energy efficiency, costs, and the availability of renewable electricity.

Table 1: Approved Production Pathways

Pathway	Approved Name	Blending Limitation	Feedstocks	FRL[b]	TRL[a]	Chemical Process
Fischer-Tropsch (FT) Synthetic Paraffinic Kerosene (SPK)	FT-SPK, ASTM D7566 Annex A1, 2009	50%	Municipal Solid waste, Agricultural and forest wastes, energy crops	6-7	6-8	Woody Biomass is converted to syngas using gasification, then a Fischer-Tropsch synthesis reaction converts the syngas to jet fuel. Feedstocks include various sources of renewable biomass, primarily woody biomass such as municipal solid waste, agricultural wastes, forest wastes, wood, and energy crops. ASTM approved in June 2009 with a 50% blend limit
Hydroprocessed Esters & Fatty acids	HEFA-SPK, ASTM D7566 Annex A2, 2011	50%	Oil-based feedstocks (e.g. jatropha, algae, camelina, and yellow grease)	9	9	Triglyceride feedstocks such as Plant Oil; animal oil; yellow or brown greases; or waste fail, oil, and greases are hydroprocessed to break apart the ling chain of fatty acids, followed by hydroisomerization and hydrocracking. This parhway produces a drop-in fuel and was ASTM approved in July 2011 with a 50% blend limit
Hydroprocessed Fermented Sugars to Synthetic isoparaffins	HFS-SIP, ASTM D7566 Annex A3, 2014	10%	Sugars	5-8	7-9	Microbial conversion of sugars to hydrocarbons. Feedstocks include cellulosic biomass feedstocks (e.g., herbaceous biomass and corn stover). Pretreated waste fat, oil, and greases also can be eligible feedstocks. ASTM approved in June 2014 with a 10% blend limit
FT-SPK with Aromatics	FT-SPK/A, ASTM D7566 Annex A4, 2015	50%	Same as A1	6-7	6-8	Biomass is converted to Syngas, which is then converted to Systhetic paraffinic Kerosene and aromatics by FT synthesis. This process is similar to FT-SPK ASTM D7566 Annex A1, but with the addition of aromatic components. ASTM approved in November 2015 with a 50% blend
Alcohol-to-Jet Synthetic Paraffinic Kerosene	ATJ-SPK, ASTM D7566 Annex A5, 2016	50%	Cellulosic biomass	7-8	6-8	Conversion of Cellulosic or starchy alcohol (isobutanol and ethanol) into a drop-in fuel through a series of chemical reactions - dehydration, hydrogenation, oligomerization, and hydrotreatment. The alcohols are derived from cellulosic feedstock or starchy feedstock via fermentation or gasification reactions. Ehanol and isobutanol produced from lignocellulosic biomass (e.g., corn stover) are considered favourable feedstocks, but other potential feedstocks (not yet ASTM approved) include methanol, iso-propanol, and long-chain fatty alcohols. ASTM approved in April 2016 for isobutanol and in June 2018 for ethanol with a 30% blend limit
Catalytic Hydrothermolysis Synthesized Kerosene	CH-SK or CHJ, ASTM D7566 Annex A6, 2020	50%	Fatty acids or fatty acid esters or lipids from fat oil greases	6-7	4-6	(also called hydrothermal liquefaction), clean free fatty acid oil from processing waste oils or energy oils is combined with preheated feed water and then passed to a catlytic hydrothermolysis reactor. Feedstocks for the CH-SPK process can be a variety of triglyceride based feedstocks such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil. ASTM approved in Feb 2020 with a 50% blend limit
Hydrocarbon-Hydroprocessed Esters and Fatty Acids	HC-HEFA-SPK, ASTM D7566 Annex A7, 2020	10%	Algal Oil	6	-	Conversion of the triglyceride oil, derived from Botryoncoccus braunii, into jet fuel and other fractionations. Botryococcus braunii is a high-growth alga that produces triglyceried oil. ASTM approved in May 2020 with a 10% blend limit
Fats, Oils and Greases (FOG) Co-Processing	FOG Co-Processing ASTM D1655 Annex A1	5%	Fats, oils, and greases			ASTM approved 5% fats, oils, and greases coprocessing with petroleum intermediates as a potential SAF Pathway. Used Cooking oil and waste animal fats are two other popular sources for coprocessing
FT Co-Processing	FT Co-processing ASTM D1655 Annex A1	5%	FT biocrude			In association with the University of Dayton Research Institute, ASTM approved 5% Fischer-Tropsch syncrude coprocessing with Petroleum crude oil to produce SAF

a TRL (Technology Readiness Level) are reported on a scale of 1-9, 1 representing "basic principles observed" (basic technology research) up to 9 representing "Full Plant Audited" (fully commercialized)

b FRL (Fuel Readiness Level) ranges from 1 "basic level" to 9 "production capability level"

Reference: M.J. Watson et. All. Journal of Cleaner Production 2024

6 Policy Support:

Government policies are essential for SAF development by creating a level playing field and attracting investment. Key policy instruments include:

6.1 Mandates:

Government mandates for SAF compel airlines to use a certain percentage of SAF blended in their fuel mix, creating a captive market. The ReFuelEU Aviation initiative by the European Union requires a minimum proportion of SAF at EU airports, beginning at 2% in 2025 (SKYNRG 2024) and rising to 70% in 2050 (European Commission, 2021).

6.2 Tax Credits:

Tax credits offer financial incentives for SAF producers and users. The Inflation Reduction Act in the U.S. offers a tax credit for the production of SAF, lowering its price to make it competitive with traditional jet fuel (IRS, 2022).

6.3 Carbon Pricing:

Measures, such as carbon tax and cap-and-trade systems, account for the environmental and societal costs associated with aviation emissions that are typically not reflected in fuel prices. By imposing a financial penalty on carbon outputs, these mechanisms incentivize airlines and stakeholders to seek lower-emission alternatives, notably SAF. This economic strategy not only encourages the adoption of SAF as a more sustainable option but also stimulates investment in innovative technologies and fuels that can reduce the aviation industry's overall carbon emissions. Ultimately, these mechanisms are crucial to balance economic incentives with environmental goals through encouraging more sustainable aviation practices.

6.4 Research Funding:

Government funding for SAF technology research and development advances innovation and brings new SAF technologies to market.

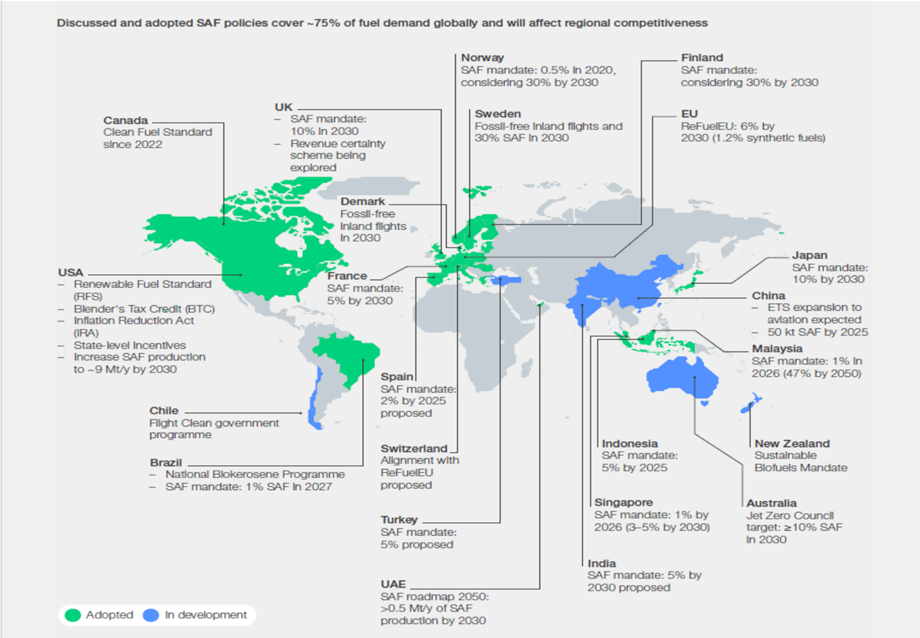

Figure 4: Global SAF Policies status (ICAO, ACI, IEA, Eurocontrol, Biomass Magazine, S&P Global, World Economic Forum (2024))

European Union: EU with its robust SAF ReFuelEU policy programme mandates a 2% share of SAF in EU airports from January 2025, increasing to 6% by 2030 (SKYNRG 2024). EU also promotes complementary policies such as the EU Emissions Trading System (EU ETS).

United States: The Clean Fuels Production Credit (section 45Z) is aimed to provide tax credits for low-emission fuels from 2025 (SKYNRG (2024) Sustainable Aviation Fuel Market Outlook). Nevertheless, 45Z programme long term impact cannot be ascertained as President Trump signed an executive order to halt and re-examine all new federal rules (World Economic Forum 2025)

Middle East: In 2023, the UAE implemented a SAF policy setting a voluntary goal to supply 1% locally produced SAF to National Airlines operating at UAE Airports by 2031(SKYNRG 2024). Saudi Arabia is formulating strategies to achieve net-zero emissions by 2060.

India: There are plans to establish a SAF mandate requiring a 1% blend by 2027, with the target rising to 2% by 2028 & 5% by 2030 (SKYNRG 2024)

Singapore: Singapore launched the Sustainable Air Hub Blueprint in February 2024, targeting net-zero aviation emissions by 2050. The policy mandates 1% SAF uptake by 2026, scaling to 3-5% by 2030 (SKYNRG 2024).

China: A Mandate for SAF blending is anticipated to be implemented as part of the 15th five-year plan (2026-2030), with the goal potentially reaching up to 15% by 2030 (SKYNRG & ICF 2025)

Malaysia: Under the 2023 National Energy Transition Roadmap, Malaysia has set a long-term target of a 47% SAF blend by 2050 (SKYNRG 2024)

Indonesia: The 2025-2029 SAF Action Plan focuses on supply (domestic feedstocks), demand (international flights using 1% SAF by 2027, increasing to 50% by 2060), and enablers (national SAF certification). Initiatives are also planned for implementing mandates for corporate and government travellers to use SAF (Giam, S. 2024).

Thailand: Thailand's SAF initiatives focus on UCO (IRENA 2024), with policy reactive to market signals. Incentives are provided for upstream activities within special economic zones.

The Philippines: The government is steadily developing policies to promote SAF adoption, involving agencies like the Civil Aviation Authority of Philippines and the Department of Energy (IRENA 2024)

South Korea: South Korea has implemented a SAF mandate stipulating that all international departing flights must include a minimum of 1% SAF in their fuel blend by 2027. Also the country offers tax benefits and other incentives to local refiners who invest in SAF production (SKYNRG & ICF 2025).

7 Supply Chains in SAF

The SAF supply chain defines a comprehensive sequence of interconnected operations, processes, and activities that facilitate the transformation of feedstock into SAF, incorporating stages such as feedstock sourcing, transportation, preliminary processing, conversion, blending, quality assurance, distribution logistics, and ultimately delivering the final product to end-users in the aviation sector. This intricate chain emphasizes the logistical, technical, and quality-control measures necessary to ensure the efficient, sustainable, and safe production and distribution of SAF throughout each critical step from initial source to final utilization.

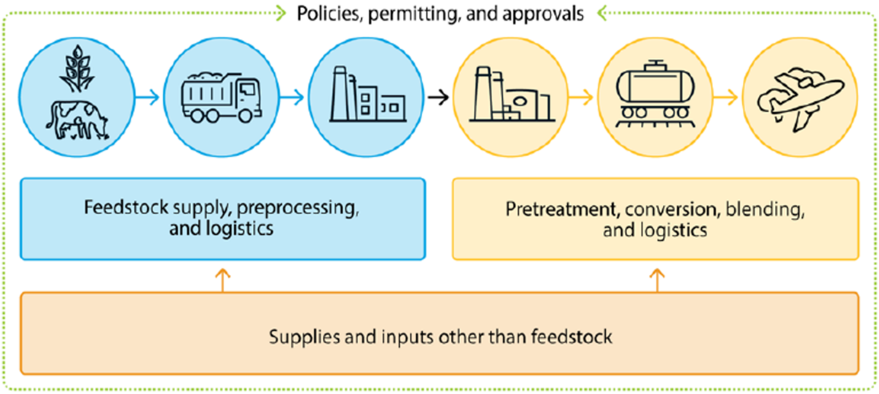

Figure 5: Overview of the SAF supply chain; (Oscar R. C. et. al. Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process; NREL (July 2024))

Supply Chain analysis is crucial because it helps to minimize uncertainties, risks and greenhouse gas emissions; enhance yields, reliability, and profitability across all operations; and pinpoint bottlenecks for improvement.

SAF Supply Chain structure can be considered as 3 main sections (Lina Martnez-Valencia et. al. 2021): (1) Upstream, covering Feedstock production, transportation, storage and preprocessing, (2) midstream, where the feedstock is processed into fuel, and (3) downstream, involving storage, distribution, and final use of the fuel.

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Table 2: Necessary supply chain decisions for a strategic level

Supply Chain Level	Decisions	
Upstream	Feedstock	Type, sourcing and allocation, material flow
	Storage	Location and capcity, site arrangements
	Pre-processing	Technology, location, capacity
	Transportation	Mode, Capacity, links, routing decisions / network design
	Feedstock contracts	Supplier selection for finished products, supply and demand contracts
	Sustainability	Ensuring GHG reductions
Midstream	Conversion	Technology (conversion rate), location, capacity, final product, product price, product demand - market
	Transportation	Mode, Capacity, links, routing decisions / network design
Downstream	Blending facility	Location and capcity, site arrangements
	Transportation	Mode, capacity, and links

8 Sustainable supply Chain Initiatives:

Sustainability in supply chain management (SSCM) has gained prominence for businesses worldwide given its substantial effects on financial stability, environmental health, and social responsibility. SSCM entails incorporating environmental, social, and economic factors into supply chain decision-making process, recognizing their impact on the ecosystems, communities, and economic systems (D. Fadly 2020). The increasing significance of SSCM is driven by awareness of the limited availability of natural resources and critical necessity to reduce environmental damage and climate change. With sustainable practices, Organizations can help conserve the environment, minimize resource exploitation, and enhance operational efficiency. Additionally, SSCM aligns with Sustainable Development Goals (SDGs), tackling global challenges such as poverty, inequality, and climate change (Hak et al., 2016).

Sustainable supply chain initiatives are crucial for ensuring that SAF reduces carbon emissions as well as provide broader environmental and social benefits. For SAF, these initiatives include integrated management of the whole SAF supply chain, from sourcing feedstock to blended Fuel production, distribution, and utilization. Collaboration among diverse stakeholders, including airlines, fuel producers, feedstock suppliers, policymakers, and researchers, is essential for the successful implementation of sustainable solutions along the SAF supply chain.

Table3: Summary of the challenges association with Supply chain operations (reference: Fereshteh M. et.al. (2014))

Challenges	Description of issues
Technical & Technological	Unavailability of Feedstock
	Seasonality of Feedstock
	Inefficiences of conversion facilities
	Infeasibility of large-scale production
	Conflicting decisions (technologies, locations, and routes)
	Complex Location analysis (source points, inventory facilities, and production plants
Financial	High capital costs (a thirst for operational savings)
	The limits for the economy of scale
	Unavailability and complexity of life cycle costing data
	Lack of infrastructural requirements
	Inflexibility to energy demand
	Risks associated with new technologies (insurability, performance, rate of return)
	Extended market volatilities (energy and food markets)
Social	Lack of participatory decision making
	Lack of public / community awareness
	Local supply chain impacts vs. global benefits
	Health and safety risks
	Conflicts with food supply chain
	Extra pressure on transport sector
	Decreasing the esthetics of rural area
Environmental	Loss of Biodiversity and natural habitats
	Soil overexploitation and degradation
	GHG emissions through the supply chain activities
	Excessive use of water
	Unavailability of data on environmental impacts
Policy and regulatory	Impact of fossil fuel tax on Transport
	lac of incentives to create competition among producers
	Focus on technology options and less attention to types of materials
	Lac of supprt for sustainable Supply Chain solutions
Institiutional and Organisational	Varied Ownership arrangements and priorities among supply chain parties
	Lack of supply chain standards
	Impact of Organizational norms and rules on decision making and supply chain coordination'
	Immaturity of change management practices in SAF supply chain

To implement Sustainable Supply Chain in SAF, following initiatives needs to be addressed:

8.1 Feedstock Sourcing: Sustainable Feedstock Sourcing is Paramount

Sustainable sourcing of feedstocks is paramount for SAF production due to factors like seasonality, climate, market demand, regulations, and opportunity costs, which are often beyond the control of SAF producers. As dependence on SAF increases, there will be higher scrutiny of feedstock sustainability, with focus on land conversion, deforestation, farming practices, food security, and biodiversity loss. Transparency and traceability in Supply chains are challenging but can be improved through technology investment and collaboration with stakeholder. SAF producers may need to process diverse feedstocks by contracting with various suppliers to mitigate these risks and ensure a steady supply by considering following sustainability criteria:

Prioritizing Non-Food, Non-Deforestation, and Biodiversity-friendly Feedstocks: Selecting feedstocks that don't compromise food security or aggravate environmental degradation is foundational.

In Southeast Asia, Indonesia with its reliance on palm oil, faces challenges due to deforestation. To mitigate the said challenge, Indonesia is exploring use of palm oil industry by-products like Palm Fatty Acid Distillate (PFAD) or Palm Oil Mill Effluent (POME) for SAF production, as well as algae cultivation (IRENA 2024). Malaysia is exploring microalgae as a SAF feedstock, potentially offering sustainability benefits (IRENA 2024). Thailand, considering sugarcane as feedstock, may face food security concerns, but could develop collection streams for Used Cooking Oil (UCO) or sugarcane bagasse utilization for additional revenue and reduced pollution. The Philippines is promoting coconut waste and non-standard coconuts as cheaper alternatives for biofuel production.

Utilizing Waste Streams:

Using a circular economy approach is important for SAF production. Waste materials like used cooking oil (UCO), agricultural residues, and municipal solid waste can be key feedstock. This minimizes environmental impact and supports recycling and sustainability in SAF manufacturing.

Indonesia has significant potential due to its large agricultural sector and Palm oil industry waste. Municipal Solid waste (MSW) can be added to the revenue stream and can increase waste potentials as fuel source. Malaysia is utilizing Palm Oil Mill Effluent (POME) in a large scale format that can create a closed-loop system where all wastes are energy. The Philippines explores non-standard coconuts for SAF production. Singapore, despite limited local feedstocks, focuses on waste-based SAF production, as seen by Neste's refinery utilizing waste and residue raw materials.

Robust Certification schemes:

Implementing certification schemes like RSB and ISCC is imperative for ensuring sustainable feedstock sourcing. Indonesia faces challenges gaining international acceptance for palm oil-based SAF due to prevailing non-recognition under major aviation biofuel certification schemes. Malaysia has an advantage in meeting international acceptance as it proactively adopts international sustainability certifications for its palm oil industry. Thailand's sugarcane industry's experience with sustainability certifications could be adapted for SAF production.

8.2 Production Technologies: Sustainable Production Practices are essential

SAF production requires a commitment to minimizing environmental impact through resource efficiency, technological innovation, and circular economy principles. Adopting circularity involves actively seeking opportunities to recycle carbon dioxide emissions and utilizing waste streams like municipal solid waste, agricultural residues, and waste fats, oils, and greases as feedstocks. This waste-to-fuel approach reduces reliance on natural resources and diversifies the feedstock supply chain.

To reduce resource consumption, a multi-pronged approach is needed. This includes reducing energy usage through advanced process integration and heat recovery systems, water conservation with closed-loop systems, and preventing pollution through advanced filtration and emission capture technologies. Furthermore, combining renewable energy sources like solar, wind, geothermal, or sustainably sourced biomass to power production stages is essential for decarbonization. Implementing advanced process control (APC) technologies, which use real-time data analysis and automated process parameters optimization, can further increase yields, reduce energy consumption, and improve product quality.

However, a challenge in SAF production is the current requirement for blending with conventional jet fuel, as SAF is not yet approved as a 100% replacement. This blending requirement adds complexity to the supply chain, necessitating additional infrastructure for blending and storage. Overcoming these challenges & prioritizing sustainable manufacturing processes, is crucial for the SAF industry to minimize its environmental footprint and provide a truly circular and climate-friendly alternative to conventional jet fuel.

8.3 Policy / Regulations:

Governments need to aid & coordinate efforts by revising & aligning international standards, ensuring synthetic jet fuels are safe and meet performance requirements, which can help drive wider adoptions of SAF. To promote rapid technological advancements in SAF, it is vital for governments to provide fiscal incentives such as subsidies, tax holidays, and grants to support Research & Development, and commercialization efforts. Support should also facilitate the retrofitting of existing refineries and the development of new SAF production plants construction by low-interest loans, technical assistance, and public-private partnership programs. Additionally, establishing strict environmental standards is essential to ensure that SAF produced sustainably, in an environment-friendly, and without harming the ecosystems. Renewable feedstocks should be promoted and incentivized to reduce waste and improve sustainability. Collaborative frameworks that bring together industry stakeholders can facilitate the transition to SAFs. Financial incentives for airlines and airports, such as tax breaks and grants for infrastructure upgrades, are necessary for widespread SAF adoption.

8.4 Transportation & Distribution: Minimizing transportation distances and optimizing logistics:

Proper Management of transportation and distribution logistics is required for SAF industry, to ensure its environmental benefits are not diminished. Minimizing transportation distances, optimizing logistics, and leveraging existing infrastructure are critical for a truly green pathway.

The most effective method is to utilize existing infrastructure like pipelines and associated rail networks, as pipelines are the primary means of transporting conventional jet fuel. These can significantly reduce the need for new construction and minimize disruptions. SAF made at existing refineries can be stored and blended in existing tanks and then transported through current pipelines as part of normal operations. However, transporting 100% SAF blended fuel via existing pipelines is not yet approved under ASTM D1655, and also, the existing pipeline excess capacity may be limited. Thus, Securing approval for 100% SAF blended fuel transportation through existing pipelines could improve transportation efficiency and reduce costs. Rail transport presents another viable option, particularly for connecting SAF manufacturing plants to pipeline networks or airports without direct pipeline access.

Developing regional SAF hubs is another crucial step. By establishing strategic locations for blending, storage, and distribution, SAF can be efficiently supplied to multiple airports, minimizing long-distance trucking and reducing transportation emissions. The location of these hubs must be well planned, ensuring proximity to both feedstock sources and end-use markets, as well as access to existing transportation infrastructure.

Switching to biodiesel or electric vehicles for trucking SAF from blending terminals to airports, along with electric or hybrid trains for rail transport of SAF, can boost sustainability and offer more opportunities to lower carbon emissions.

8.5 Collaboration and Partnerships:

Collaboration and partnerships are critical for developing sustainable SAF supply chains. These partnerships can bring together diverse expertise and resources, enabling the development and deployment of SAF at scale. Some key types of collaborations include:

Airline-Fuel Producer Partnerships: Airlines can partner with fuel producers to secure a reliable supply of SAF and make long term offtake agreements that de-risk SAF investments. For example, United Airlines has partnered with Alder Fuels to develop and deploy SAF produced from forestry residues (United Airlines, 2021). These partnerships can help to accelerate the adoption of SAF by providing a guaranteed market for the fuel.

Feedstock Supplier-Fuel Producer Partnerships: Fuel producers can partner with feedstock suppliers to ensure a sustainable and reliable supply of feedstocks. For example, Neste has partnered with REG to secure a supply of renewable diesel and renewable jet fuel (Neste, 2020). These partnerships can limit the risk of feedstock shortages as well as ensure that the feedstocks are produced sustainably.

Technology Provider-Fuel Producer Partnerships: Fuel producers can partner with technology providers to access the latest SAF production technologies. For example, LanzaTech has partnered with Suncor Energy to build a commercial-scale SAF facility in Canada (LanzaTech, 2021). These partnerships can fast-track the development and deployment of new SAF technologies.

Public-Private Partnerships: Governments can partner with private companies to support the development and commercialization of SAF. For example, the U.S. Department of Energy has partnered with several companies to fund research and development of SAF technologies (DOE, 2023). By working together, stakeholders can share costs, reduce risks, and make SAF projects more financially feasible. This can accelerate the transition to a more sustainable aviation industry.

9 Lifecycle Assessment:

Lifecycle assessment (LCA) is an important method for measuring the environmental effects of SAF throughout its entire supply chain lifecycle, from extracting raw materials and manufacturing to recycling or disposal. LCA can identify the most environmentally harmful stages or processes in the supply chain. This will assist researchers and industry stakeholders to develop specific strategies to reduce the overall environmental footprint of SAF and make its supply chain more sustainable.

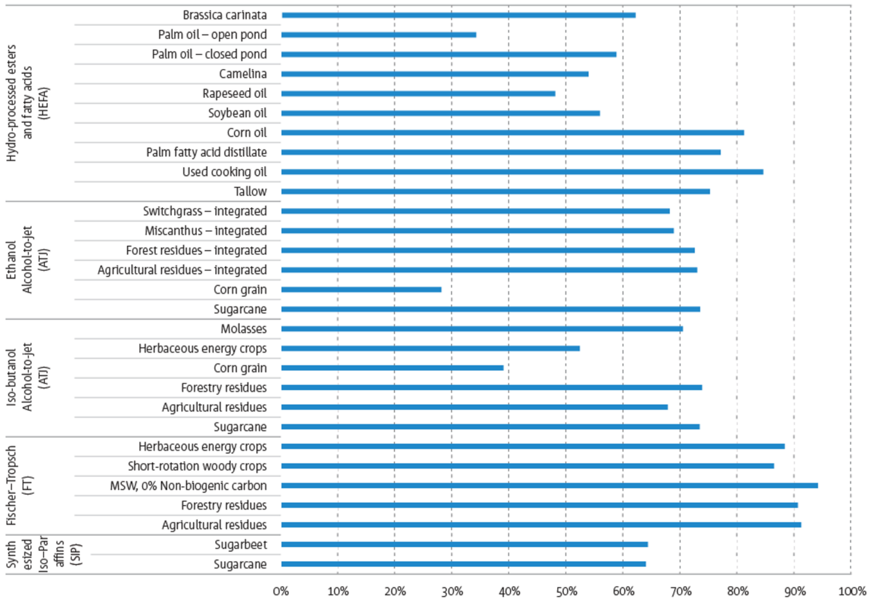

Figure 6: Comparison of Life Cycle Analysis (LCA) emissions reductions for various CORSIA eligible SAF Pathways and feedstock to fossil fuel reference value (89 g CO_2e/MJ), (European Union Aviation Safety Agency)

9.1 Key considerations in LCA for SAF are:

Greenhouse Gas Emissions: LCA should assess the greenhouse gas emissions at each stage of the SAF supply chain, which includes feedstock production, conversion to fuel, transportation, and utilization.

Land Use Change: LCA should assess the impacts of land use change for feedstock production, including deforestation, habitat loss, and soil degradation.

Water Consumption: LCA should assess the water consumption at each stage of the SAF supply chain, including feedstock production, fuel conversion, and transportation.

Air and Water Pollution: LCA should assess the air and water pollution at each stage of the SAF supply chain, including feedstock production, fuel conversion, and transportation

10 Localized Implementation of sustainable supply chain initiatives in SAF:

Association of Southeast Asian Nations (ASEAN) is promoting Southeast Asia as a global hub for SAF production, leveraging abundant biomass and waste feedstock, and aligning policies for regional decarbonization and economic growth. The ASEAN Economic Community (AEC) promotes SAF by advancing economic goals through regional integration and competitiveness in a new, green industry, and benefits the ASEAN Transport Strategic Plan and regional decarbonization targets by providing a pathway for aviation decarbonization.

Among Southeast Asian nations, Indonesia emerges as the leader in potential for SAF production, primarily when considering only residues and waste materials. Being the largest producer of palm oil in the world, Indonesia generates substantial quantities of residues from its extensive plantation industry, totaling approximately 7.5 million tonnes annually (IRENA 2024). These residues represents a significant share of the country's estimated SAF potential from agricultural residues, which is estimated at 9.3 million tonnes per year (IRENA 2024). Malaysia, ranking second globally in palm oil production, has a considerably lower SAF potential from its residues and waste, estimated at about 1.6 million tonnes annually (IRENA (2024), reflecting its lesser residue yield or utilization capacity. This disparity highlights Indonesia's dominant position in utilizing agricultural residues for SAF production. Thailand presents a different scenario; despite its comparatively smaller SAF potential from residues, its high international air travel volume, results in a consistently high demand for jet fuel. Nevertheless, Thailand faces challenges in achieving its ambitious SAF goals by relying exclusively on residues like rice straw and husks. Similarly, the Philippines and Vietnam also depend predominantly on rice straw and husks as their primary feedstock, contributing 57% and 78%, respectively (IRENA (2024)), of their SAF potential from residues. On the other hand, countries such as Laos, Myanmar, and Cambodia have the lowest demand for jet fuel; nevertheless, Myanmar and Cambodia possess considerable potential to produce SAF from residues and wastes. Brunei Darussalam also falls into this category, with relatively low jet fuel demand. The remaining countries show promising feedstock resources for expanding SAF production in the region.

The development of Sustainable Aviation Fuel (SAF) in Southeast Asia, requires a nuanced approach that considers local contexts, balances regional dynamics, and establishes stable policy frameworks.

10.1 Tailoring Strategies to Specific Regional Contexts:

Strategies for SAF development must be tailored to local circumstances to ensure sustainability and effectiveness. In Southeast Asia, this is especially crucial due to the diverse agricultural, economic, and environmental landscapes across countries. While global frameworks provide guidance, strategies must be tailored to address the specific regional and local circumstances, to ensure sustainability and foster community engagement. Understanding existing agricultural practices, availability of waste resources, and infrastructural constraints is crucial. The existing land usage, deforestation concerns, and community rights must be considered. Indonesia's vast archipelagic geography and abundant palm oil resources present both opportunities and challenges. The country has the benefit of expansive agricultural land and a mature palm oil industry, which could be leveraged for production of SAF. Malaysia is exploring more diverse feedstock options, such as microalgae, which gives it an advantage in terms of sustainability (IRENA 2024). Thailand is focusing on sugarcane as a feedstock for SAF through the alcohol-to-jet (ATJ) pathway, which is aligned with its agricultural strengths (IRENA 2024).

10.2 Balancing Production, Use, and Trade within the Region

Balancing local production, usage, and regional trade requires collaborative approaches that involve local communities at every stage. Supporting smallholder farmers through fair trade practices and ensuring local communities are benefitting from SAF production can enhance support and sustainability.

Collaborative efforts among Southeast Asian countries are essential for a sustainable SAF industry in the region. Indonesia has a significant advantage in terms of high production volume and relatively low capital expenditure (CAPEX) for SAF manufacturing. However, Indonesia's domestic aviation fuel demand is relatively low compared to its production potential, necessitating a focus on export strategies. Singapore, while lacking significant feedstock resources, has positioned itself as a major SAF consumer and potential trading hub. This creates an opportunity for feedstock-rich countries like Indonesia to supply Singapore's SAF production & consumption. The Philippines is exploring innovative approaches, such as using non-standard coconuts for SAF production, which could provide a unique niche in the regional SAF market (IRENA 2024). Creating effective SAF supply chains in Southeast Asia necessitates a localized, community-focused strategy supported by comprehensive policy frameworks. Prioritizing sustainable practices, fostering inclusivity, and promoting policy certainty will unlock the full potential of SAF and contribute to the region's economic and environmental well-being.

ASEAN role involves developing supportive policy frameworks, enhancing technical capacity, mobilizing investment, fostering collaboration, sharing best practices through initiatives like the ASEAN Sustainable Aviation Action Plan (ASAAP), with the goal to accelerate SAF deployment and complement the global sustainability goals.

10.3 Stable and Long-term Policy Frameworks

Attracting investment and fostering growth in the SAF sector in Southeast Asia requires stable and supportive policy environments. The ASEAN Secretariat, in collaboration with partners, works to enable supportive policy development for SAF production and deployment. Governments can create an enabling environment by establishing long-term policy goals that provide certainty for investors, offering fiscal incentives such as tax breaks and subsidies to reduce initial capital outlay, and streamlining regulatory approvals to help push the project development. Promoting research and development to enhance technological innovation and investing in infrastructure development to strengthen supply chains are also crucial.

Indonesia, in September 2024, introduced a policy plan for sustainable aviation fuel (SAF), making it easier for potential investors and stakeholders to understand the country's approach and future path in promoting SAF (Giam S. 2024). Malaysia has integrated SAF development within broader national plans, including the Twelfth Malaysia Plan (2021-2025) and the National Energy Transition Roadmap, which could give Malaysia an advantage over countries with less integrated policies. Thailand is still developing its national plan for SAF, which may put it at a temporary disadvantage compared to countries with established policies.

11 Discussion and Implications

The comprehensive review of existing literature and examples presented in the preceding sections have significant implications for future research, policy development, and industry practices related to SAF. This section provides a discussion of these implications, reflecting on how the reviewed literature and preliminary findings shape the ongoing research efforts, identifying potential contributions to the field of sustainable aviation, and exploring the relevance of these findings for future research directions, policy interventions, and industry innovation.

11.1 Contribution to the Field:

This research contributes to sustainable aviation by providing a synthesized analysis of the challenges and opportunities associated with SAF supply chains. By integrating diverse perspectives, the review offers a holistic understanding of factors influencing SAF's sustainability, scalability, and economic viability. Theoretical frameworks like the Resource-Based View & Stakeholder Theory provide an in-depth manner of analyzing the interplay of economic, social, and environmental considerations. The systematic literature review ensures the findings are grounded in robust understanding, minimizing bias and maximizing reliability. It further highlights the importance of regional approaches, especially in Southeast Asia, where collaboration and localized strategies can drive SAF adoption towards decarbonization targets and economic growth in the ASEAN region.

11.2 Informing Future Research:

The findings and research gaps point to opportunities for further development and implementation of SAF. Further research is needed to assess the long-term sustainability of SAF feedstocks and technologies via comprehensive lifecycle assessments, with focus on the diverse feedstocks available in Southeast Asia. Research is essential to develop and optimize innovative production technologies that efficiently convert diverse feedstocks into SAF while minimizing energy consumption, reducing GHG emissions, and achieving economic competitiveness. Addressing the social and economic implications of SAF projects on local communities in Southeast Asia is also necessary, ensuring equitable access to resources, supporting local development, and avoiding negative social impacts.

11.3 Relevance for Practice:

The research findings are of immediate significance to policymakers, industry stakeholders, and researchers, providing actionable insights for accelerating the transition to sustainable aviation. Policymakers can leverage these findings to create targeted policies and incentives—such as mandates, tax benefits, and research funding—that bolster SAF supply chains, considering the specific regulatory context of Southeast Asian countries. In parallel, industry players can make strategic decisions regarding SAF investments, feedstock procurement, and supply chain operations, ensuring compliance with regional sustainability criteria.

Airlines can develop sustainability targets and engage with SAF suppliers, contributing to the ASEAN Action Plan.

12 Conclusion

Sustainable Aviation Fuel (SAF) is crucial for aviation to reduce its carbon footprint amid mounting pressure for decarbonization. Establishing sustainable, resilient, and scalable supply chains in SAF is essential for widespread adoption. This review synthesizes literature and examples to deliver perspective for policymakers, industry stakeholders, and researchers, covering feedstock, production, projections, and policy.

The review highlights diverse feedstocks and technologies for SAF production, emphasizing a lifecycle guidance to ensure GHG emission reduction and minimal environmental impact. Collaboration among airlines, producers, technology providers, and policymakers is vital for scaling SAF production and fostering a sustainable ecosystem.

Supportive policies like SAF mandates, tax credits, and carbon pricing are crucial for levelling the playing field, incentivizing investments in facilities and innovation, and accelerating the transition to sustainable aviation.

More work is required along the entire value chain to turn the cautious stakeholder optimism into stronger confidence that the aviation industry can successfully achieve its carbon emissions reduction goals.

Despite SAF's promise, concerns remain, including cost competitiveness with conventional jet fuel, necessitating innovation and supply chain optimization. Sustainable feedstock availability without competing with food or causing deforestation is a concern, requiring responsible land use management. Reducing environmental impacts like water consumption and biodiversity loss requires best practices and lifecycle assessments. Addressing social and economic impacts on communities, ensuring fair labour and respecting local rights, is necessary for community support and equitable benefit sharing.

For Indonesia to fully realise the advantage of vast potential feedstock from agriculture residues and waste streams, it must address several challenges:

1. Sustainability concerns: Addressing international concerns about the sustainability of palm oil-based products, including SAF
2. Certification Alignment: Aligning its feedstock production practices with internationally recognized sustainability certification standards for SAF
3. Diversification: Exploring and developing a wider range of sustainable feedstock options beyond Palm oil and its by-products
4. Waste Stream Utilization: Improving infrastructure and mechanisms for efficient collection and processing of waste streams across its vast archipelago.

In Conclusion, Indonesia can establish a competitive edge over other Southeast Asian countries by committing to above. Indonesia's success in SAF not only positions them as a regional and global leader, it creates economic opportunities, and sets an example for others to follow, to ensure a truly sustainable future for both their Industry and the region as a whole.

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