A Study on the Optimization of Aviation Manufacturing Supply Chain Management Models Based on Green Development Principles

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Abstract: In the context of decarbonization and circular economy imperatives, this study examines how aviation manufacturing supply chains can be optimized under green development principles by integrating sustainable aviation fuel (SAF) and end-of-life (EOL) aircraft treatment strategies. Key findings from industry data indicate that global SAF output remains minimal (approximately 1.3×10^9 L or ~0.3% of jet fuel demand in 2024). SAF production is constrained by high costs (often 2–8 times that of fossil kerosene) and requires substantial new infrastructure for blending and distribution. International policies like ICAO's CORSIA and the EU's SAF mandates impose strict sustainability criteria and blending targets, shaping SAF deployment and viability. In parallel, effective EOL management can recover nearly all aircraft components: rigorous dismantling processes allow >99% of engine parts and major airframe metals to be salvaged. For example, recycled carbon fiber from decommissioned planes can cut energy consumption by ~98% compared to new composites, exemplifying circular-economy benefits. These findings underscore that aligning SAF adoption and aircraft recycling with policy frameworks (e.g., CORSIA) enables a low-carbon, resource-efficient aviation supply chain. The study outlines how optimized supply chain models can incorporate these green strategies to meet future environmental targets.

1 INTRODUCTION

The aviation industry faces mounting pressure to reduce its environmental impact, aligning with global climate commitments (International Civil Aviation Organization [ICAO], 2022). Air traffic is projected to roughly double in the next two decades, driving a surge in both new aircraft deliveries and retired (end-of-life, EOL) airframes. In this context, the principles of green development and circular economy are increasingly emphasized. Two key strategies have emerged: the use of sustainable aviation fuel (SAF) and the circular management of decommissioned aircraft. SAF can lower the carbon intensity of flight operations, while EOL practices focus on salvaging materials from retired planes. SAF has drawn significant attention as an immediate carbon-reduction option. However, current SAF production is extremely limited. For instance, IATA (2024) reports that global SAF output in 2024 was only about 1.3×10^9 liters (around 0.3% of annual jet fuel demand), well below the volumes needed for meaningful decarbonization. At the same time, SAF is much more expensive than fossil jet fuel. Techno-economic analyses find that SAF pathways (e.g., HEFA, Fischer–Tropsch, Alcohol-to-Jet) often cost several times more per liter than conventional fuel. As a result, large investments or subsidies are needed to expand SAF production. Integrating SAF into the fuel supply chain also imposes technical requirements: for example, SAF must be blended (typically ≤50%) with conventional kerosene under ASTM standards, necessitating new storage, metering, and certification steps. International policies are driving SAF deployment but also imposing strict sustainability criteria. The ICAO CORSIA scheme (ICAO, 2022) allows airlines to meet carbon-offset obligations with SAF, provided it achieves a minimum life cycle GHG reduction and avoids feedstocks from deforested or high-carbon lands. Similarly, the European Union's ReFuelEU Aviation initiative (European Union Aviation Safety Agency [EASA], 2024) mandates rising SAF blending rates (for example, 2% by 2025, rising to 70% by 2050). These policies aim to ensure

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that SAF delivers genuine carbon benefits, but they also elevate costs and restrict eligible feedstock choices (e.g., excluding virgin palm oil from cleared lands). Such regulatory trends underscore that SAF supply chain models must not only scale up production but also comply with sustainability constraints. In parallel with fuel strategies, managing aircraft at EOL is emerging as a crucial component of sustainable aviation. Analysts note that effective EOL treatment can confer a competitive advantage and reduce life-cycle impacts. Practically, EOL processing involves careful disassembly and material recovery. Industry data indicate that more than 99% of an aircraft's engine components can be salvaged and reused. Similarly, the major airframe alloys (e.g. aluminum, steel, and titanium) and composite materials are recovered from retired planes (de Jong, 2027). These recovered materials are recycled into new products, exemplifying a circular economic approach. For example, recycled carbon fiber from decommissioned aircraft can cut manufacturing energy use by about 98% compared to virgin composites (Asmatulu et al., 2013). Thus, EOL recycling conserves resources and reduces emissions, and its importance is reflected in industry guidelines and standards for aircraft dismantling and recycling. Optimizing aviation supply chains to integrate SAF and EOL processes thus requires addressing both technological and logistical challenges. Technologically, SAF production pathways vary in maturity, yields, and cost (Ng et al., 2021) and blending SAF into fuel networks demands appropriate infrastructure and quality assurance. Logistically, existing fuel systems must adapt: many SAF plants lack direct pipeline connections and must transport fuel by truck or rail. Upgrading fuel terminals with dedicated blending tanks and testing labs adds capital expense. Moreover, collecting dispersed biomass feedstocks (such as used cooking oil or agricultural residues) can be complex; studies note that the current feedstock supply may be insufficient for projected SAF targets. In parallel, EOL supply chain integration involves coordination between airlines, recyclers, and regulatory bodies to safely recover parts and materials without disrupting operations. Overcoming these challenges through new coordination, equipment, and processes is essential if the aviation supply chain is to meet green development goals. Integrating SAF and EOL management into these supply chains is the focus of this study, which aims to propose optimized models that align with green development targets. The remainder of this paper is organized as follows. Section 2 reviews the literature on SAF and aircraft recycling. Section 3 examines SAF production, supply chain integration challenges, and key policy frameworks (including CORSIA and EU mandates), and discusses EOL aircraft treatment within the aviation supply chain. Finally, Section 4 concludes by summarizing insights and outlining recommendations for optimizing aviation manufacturing supply chain models under green development principles.

2 SUSTAINABLE AVIATION FUEL

Sustainable aviation fuel (SAF) has attracted growing attention as a carbon-reduction strategy in aviation. However, current SAF production and deployment remain extremely limited. For example, IATA (2024) reports that global SAF output was only ~1.3×10^9 liters in 2024 (roughly 1 million tonnes, about 0.3% of jet fuel demand) (International Air Transport Association [IATA], 2024). This is far below projected needs: one industry estimate suggests on the order of 40–50 Mt/year of SAF may be required by mid-century to meet aviation decarbonization targets (WEF, 2024). Investment in SAF is accelerating, but much more capacity is needed. In the Asia-Pacific region, for instance, the 1.4 Mt/yr Neste refinery in Singapore is currently the world's largest SAF plant (ING Think, 2024), and total APAC SAF capacity is only about 1.8 Mt/yr (600 million gallons) by 2024. Even if all planned projects proceed, APAC capacity might reach ~5.1 Mt/yr by 2030 (≈4% of regional jet fuel demand). In short, SAF supply is still nascent and outstripped by airline commitments and regulatory targets. Economically, SAF remains much more expensive than petroleum jet fuel. Reported production costs (and minimum fuel selling prices, MFSP) vary widely by technology and feedstock. Industry sources estimate HEFA (hydro processed esters and fatty acids) from waste oils can cost on the order of €0.88–1.0/L ($1.0–1.1/L)(Ng et al., 2021), whereas routes like "hydro processing of fermented sugars" (HFS, from starch/sugar) may cost >€3.4/L ($3.9/L). In practical terms, SAF often sells for ~2–8× the price of fossil kerosene. Recent analyses (Ng et al., 2021) summarize MFSPs across pathways: HEFA from oil/fat feedstock averages ≈ $1.20/L (range ~$1.07–1.32/L), whereas Fischer–Tropsch (FT) and Alcohol-to-Jet (ATJ) routes average $1.76/L. In contrast, sugar-to-fuel (HFS) is far higher ($4.27/L). By comparison, conventional jet fuel typically costs roughly $0.3–0.5/L, so SAF currently incurs a substantial premium. These high costs imply large capital investments and/or subsidies are needed to make SAF commercially viable. Airlines and investors note that, despite growing offtake agreements, producers face weak demand signals and policy uncertainty; as one IATA statement puts it, "governments are sending mixed signals" and investors are "waiting for guarantees" before committing, since SAF margins are low(International Air Transport Association [IATA], 2024). Different production technologies have distinct techno-economic profiles. HEFA is the most mature and widely deployed route: it converts triglyceride oils (vegetable or waste) into synthetic paraffinic kerosene (SPK). HEFA offers high product yields (>1000 L per tonne of oil, e.g., ~1060 L/t for soybean oil or ~1110 L/t for palm oil) and relatively low capital cost. Ng et al. report HEFA capex on the order of $0.34 per Liter (of annual output), far lower than for the other pathways. Consequently, HEFA's MFSP ($1.2/L) is the lowest of the certified routes. FT synthesis (gasification of biomass to syngas and Fischer-Tropsch conversion) is very capital-intensive: roughly 50–75% of the FT production cost is tied up in capital equipment. ATJ (fermentative alcohol followed by catalytic conversion) has lower capital intensity (capex 20–50% of cost) but higher operating costs – its feedstock (e.g., cellulosic ethanol) can contribute 15–60% of total cost. Both FT and ATJ often have similar MFSP ($1.76/L average) despite these differences. Sugar-to-jet (HFS) is still at demonstration scale; it has the highest MFSP ($4.3/L) due to low yields and high processing complexity. In summary, HEFA has the best current economics because of high oil yields and low capex, but it competes with existing biodiesel markets, whereas FT and ATJ have more expensive but potentially feedstock-flexible pathways. Tables of production cases show that feedstock choice strongly influences cost. For example, FT using dedicated energy crops or forest wood incurs a higher MFSP (e.g., $2.15/L) than FT on municipal solid waste or agricultural residues ($1.5–1.9/L). A similar trend holds for ATJ: using sugars from energy crops costs more than from crop residues. HEFA production from vegetable oils tends to be lower cost in capital terms but can have higher feedstock costs. Overall, SAF capital expenditure must fall substantially, and scale-up is required to reduce per-unit costs, as many studies note. Ng et al. stress that route choice should balance economic and environmental metrics, and that further cost reductions are needed, especially for FT, ATJ, and HFS to enable commercialization.

2.1 Supply Chain Integration Challenges

SAF is a drop-in fuel, meaning it must be mixed with conventional jet kerosene to meet fuel specifications. By regulation, ASTM D7566 (the aviation fuel spec) currently limits most SAF blends to 50% (by volume) of the final jet fuel. This implies that SAF is distributed through the existing petroleum jet infrastructure. In practice, there are two general integration models. If SAF is co-processed at an oil refinery (for example, by hydrotreating vegetable oils with petroleum fractions), the blended fuel meets the normal jet-fuel spec (ASTM D1655) and simply flows out through the refinery's pipeline networks to airports. If SAF is produced at a standalone bio-refinery, the raw SAF product must be transported (by truck, rail, or barge) to a fuel terminal for blending with conventional jet fuel. Fuel terminals are typically equipped with blending tanks, pumps, and quality-control systems. The common approach is to receive SAF and Jet A in separate tanks, meter them into a dedicated blending tank, mix the batch, and then certify the blend to the jet-fuel standard. The blended product can then be delivered to airports through the same pipelines or trucks used for ordinary jet fuel. U.S. DOE analysis notes that "SAF produced at a stand-alone facility… requires blending… at a terminal," and afterwards the SAF/Jet-A blend is transported in the same pipelines and trucks as before. Despite using common infrastructure, several logistical challenges arise. First, petroleum jet and SAF have different molecular composition (SAF is paraffinic and typically lacks aromatic compounds). To preserve fuel properties, the allowable blend is capped (ASTM limits FT/HEFA SPK to 50% blends with Jet A). In practice, most service pumps deliver blends far lower than 50% (often 30–38%), because higher ratios can compromise seal swell and other fuel characteristics. Meeting fuel-spec quality at scale requires careful quality assurance: each batch of SAF is accompanied by an ASTM-D7566 certificate, and each blended batch by a certificate of analysis (COA) under ASTM D1655. Second, most SAF producers (especially early plants) lack pipeline connections, so they rely on trucking or rail to move fuel to terminals. Pipeline transport of neat SAF is rare, so systems must adapt to bring SAF to a blending point. Third, fuel terminals may need upgrades (additional storage, mixers, and certification labs) to handle SAF. Although these can be done, they represent nontrivial capital costs and coordination among stakeholders. As one DOE review notes, SAF supply chains are still immature and will require significant investment:

"Because current fuel certifications… require SAF to be blended with conventional fuels, the SAF supply chain also requires coordination with conventional jet fuel industries". Feedstock supply is another integration hurdle. Collecting and aggregating biomass or waste oils (used cooking oil, agricultural residues, etc.) to feed plants is logistically complex, especially in Asia's dispersed geographies. For example, plans in APAC assume massive uptake of used cooking oil (UCO), but current UCO collection is limited. ING research estimates that Asia's current UCO supply (~5 million tonnes) would only produce ~1.2 billion gallons of SAF, far short of planned output; bridging the gap will necessitate "increasing SAF plants [that]… rely on palm oil and palm oil mill effluent". Heavy reliance on palm feedstocks, however, raises its own integration issues (see below). In summary, SAF's integration into the fuel supply chain is feasible in principle via terminal blending and existing logistics, but it demands new coordination, equipment, and assurance processes compared to conventional fuels.

2.2 Policy and Sustainability Frameworks

Regulatory frameworks play a major role in SAF economics by creating demand-pull or incentives. At the international level, the ICAO CORSIA scheme allows airlines to use approved SAF to meet their offsetting obligations. CORSIA defines strict sustainability criteria: SAF must achieve a minimum life-cycle GHG reduction (at least 10% below conventional jet) and must not be made from biomass grown on recently cleared forests, peatlands, wetlands, or other high-carbon-stock lands. In practice, this means feedstocks that cause deforestation or peat drainage (such as new oil-palm plantations on rainforests) are ineligible under CORSIA's carbon-stock test. Correspondingly, any SAF project claiming CORSIA benefits must be vetted by approved sustainability schemes. In Europe, the RED II / ReFuelEU policy compels fuel suppliers to blend increasing shares of SAF (e.g., 2% by 2025, climbing to 70% by 2050) (European Union Aviation Safety Agency [EASA], 2024). SAF used in the EU must meet RED's sustainability and GHG-saving criteria (generally 70–90% cut over fossil) and may earn bonus multipliers if from residues or waste. However, as Ng et al. point out, these policies can have unintended consequences: RED II's current structure (blending mandates and credit multipliers) may skew feedstock markets and "Favor the road and aviation biofuel sectors" unless carefully aligned. In particular, biofuels researchers warn that aggressive aviation mandates could compete with food/biodiesel markets if not managed. Overall, CORSIA and RED II aim to ensure SAF delivers real carbon benefits, but they also elevate costs and restrict feedstock choice. For example, EU policy effectively excludes virgin palm oil as an eligible feedstock (due to ILUC concerns), and CORSIA forbids SAF from palm plantations established after 2008 on carbon-rich land. These regulatory criteria directly impact economic feasibility: any fuel failing the sustainability test will not qualify for credits or mandates, undercutting its value.

2.3 Asia-Pacific Focus: Indonesia and Malaysia

Southeast Asian nations are increasingly evaluating sustainable aviation fuel (SAF) to decarbonize growing air transport, with Indonesia and Malaysia at the forefront of regional efforts. Indonesia has concentrated on biojet blends derived from its vast palm oil industry. In particular, the government and state oil company Pertamina have developed J2.0 and J2.4 biofuels, both based on palm oil, at the Cilacap refinery. These domestically certified fuels exemplify Indonesia's initial SAF pathway, though researchers note that Indonesia is also exploring alternative feedstocks – notably waste cooking oil (UCO) and sugarcane-derived biofuels – to diversify supply and mitigate market risks (Nugroho et al., 2024). Malaysia, by contrast, has fewer indigenous biomass resources for aviation. Its strategy has instead focused on forming industry partnerships and preparing for future production. For example, Malaysia's national oil company Petronas signed a late-2023 agreement with Japan's Idemitsu to "scale-up bio-feedstock possibilities, production cost analysis, and supply chain security" for next-generation SAF. In short, Indonesia leverages its palm oil sector (with an eye toward UCO and sugarcane), whereas Malaysia is building international coalitions and planning infrastructure to develop SAF.

Both countries' SAF plans must balance growth against environmental trade-offs. Relying on palm oil, for example, raises concerns about deforestation and indirect land-use change (LUC). Nugroho et al. (2024) specifically caution that new palm plantations for biojet could trigger carbon-intensive land conversion in Indonesia, potentially negating some of the GHG savings of SAF. Domestic studies have f lagged that converting peatlands or forests to oil palm releases substantial CO_2, a risk if demand for J2 fuels surges. In contrast, UCO feedstock offers clear sustainability advantages, since it repurposes waste oil; however, UCO supplies are limited and competition (for biodiesel, cooking, etc.) may cap its impact. Sugarcane-based SAF generally shows lower life-cycle emissions than vegetable oils, but large-scale sugarcane expansion can also strain land and water resources. Crucially, international certification is a hurdle. Indonesia has certified its J-series fuels domestically, but these certificates do not automatically satisfy ICAO's CORSIA standards. Nugroho et al. (2024) highlight that Indonesia's current sustainability criteria and audit processes may fall short of CORSIA requirements, meaning SAF produced today might not earn carbon credits under the global offsetting scheme. Aligning Indonesia's certification (and Malaysia's future criteria) with CORSIA is therefore essential to ensure that SAF actually delivers net GHG reductions for international f lights. In short, any expansion of bio-SAF must be accompanied by robust land-use policies and chain-of custody tracking so that feedstock cultivation does not undermine climate goals.

Governments and institutions play a pivotal role in translating potential into reality. Both Indonesia and Malaysia have set broad climate targets (including pledges to reach net-zero emissions by mid-century) and have woven biofuels into their renewable energy planning. Indonesia's National Energy Policy and subsequent regulations target substantial biofuel use (e.g. high-percentage biodiesel blending by 2025), implying future mandates could also cover jet fuel. Nugroho et al. (2024) note that Indonesia has issued presidential and ministerial regulations emphasizing renewable fuels, yet consistent SAF-specific policies are still emerging. They recommend that Indonesia strengthen coordination among ministries (energy, transport, environment) and provide financial and technological support to scale SAF production. In Malaysia, policymaking has been more fragmented. While the country has aggressive emissions reductions goals and successful road-transport biofuel mandates, it has no dedicated SAF policy to date. Instead, Malaysian efforts have centered on leveraging state actors: for example, Petronas and research institutes are steering R&D, as seen in the Idemitsu collaboration. Nguyen and Vuong (2024) argue that Malaysia (and other ASEAN nations) needs clearer institutional backing – such as SAF blending targets or subsidies – to attract investment. They also highlight that Malaysia and Singapore currently benefit from better coordination (both have national aviation plans), whereas other countries lag behind. At the regional level, cooperation is deemed crucial. Nguyen and Vuong (2024) emphasize that consistent policies across ASEAN and joint initiatives will accelerate SAF uptake. They point to ASEAN's 2023 Biofuel R&D Roadmap and energy community plans as positive steps, but warn that translation into practice is uneven. In essence, both studies suggest that without ASEAN-wide harmonization – for instance, mutual recognition of sustainability standards and pooled research – neither Indonesia nor Malaysia can fully realize SAF opportunities alone.

3 THE END-OF-LIFE AIRCRAFT

When aircraft reach the end-of-life (EOL) stage, they can't be easily recycled like normal vehicles. According to Airbus, over the next 20 years, air traffic will more than double. This means that demand for new aircraft will increase rapidly. Airbus forecasts that 42,000 new aircraft will be needed by 2043. What's more, 18,460 of them will be used to replace older aircraft, which can also be viewed as EOL aircraft. The green solution for EOL aircraft has been a problem. First, the process for dealing with EOL aircraft should be outlined. When an aircraft reaches its EOL stage, it should be divided into two parts. If the aircraft is a passenger airliner and is worth more than its parts, it can be sold to a country with lenient airworthiness standards, or it can be transformed into a cargo airliner. However, if the aircraft is a cargo airliner and it is worth more than its parts, it can only be sold to a country with loose airworthiness standards. In this way, the carbon emissions of EOL aircraft will not increase. However, not all EOL aircraft can be sold. When the value of an aircraft's parts exceeds the value of the aircraft itself, dismantling should be considered. Furthermore, according to Sainte-Beuve (2012), aircraft will be replaced before the end of their operational life by a new, more efficient type. This will reduce operating costs for airlines, and the green image of EOL aircraft treatment has gradually become a standard for global market competitiveness based on environmental considerations (Siles, 2011). As a result, aircraft dismantling has become a very important stage in the aviation supply chain. Aircraft recycling follows a rigorous process that adheres to environmental regulations. First, certified workers remove the aircraft engine under the guidance of the service manual. Furthermore, according to Airbus, more than 99% of engine parts (CFM) can be recycled. These parts are reconditioned and re-certified so that they can be returned to the aviation materials market without posing safety hazards. After removing all components (electrical, hydraulic systems, etc.), the fuselage can be safely cut up. According to Airbus, the fuselage of the A320 is primarily made of aluminum and Al-Li alloys (72%), steel (9%), and titanium (6%), as shown in Figure 1. All these metals can be used as raw materials in industries beyond aviation. Not only can the mantle be recycled, but the recovered Fibers can also replace newly produced Fibers (Eylem et al., 2013). According to Asmatulu (2013), using carbon fiber as an example, recycled fiber can reduce cost by about 30% and energy consumption by 98% compared to producing new fiber. This circle is a typical Open loop recycle. Many of the materials from the EOL aircraft are suitable for recycling. Consequently, the residual value of the aircraft promotes the recycling of the EOL aircraft. Additionally, the maintenance and production of the aircraft need lots of resources and which will lead to the release of the greenhouse gases (GHG). To reduce the investment, raw material, labour time and carbon emission, the recycling of parts and material from the EOL aircraft is chosen. The third motivation for recycling the EOL aircraft is that when those parts are used in other projects, the total volume of waste is reduced. Then the land that will be used as the landfill decreased. This helps protect the safety of the land and the underground water below that land. The pollution of the underground water is prevented at the source. The air, water, and land are protected due to the recycling of the EOL aircraft.

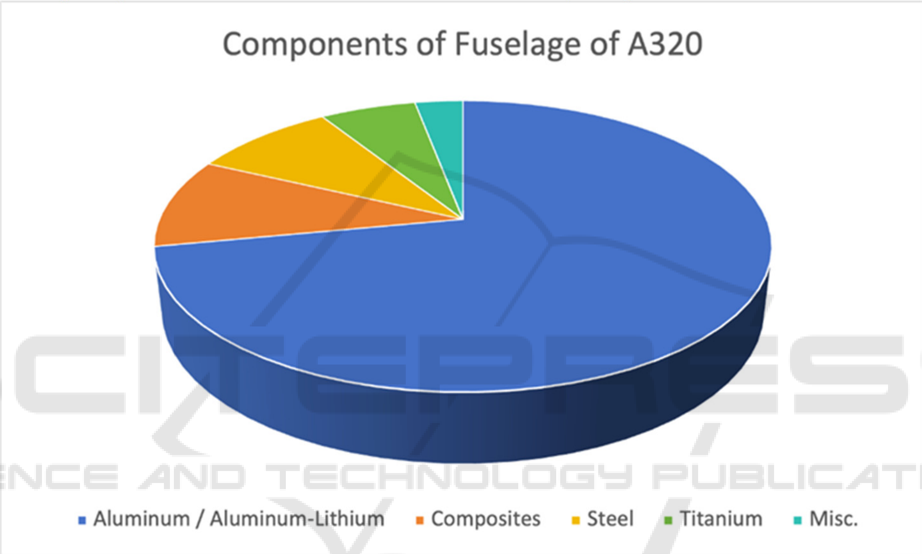

Figure 1: Components of fuselage of A320

4 CONCLUSIONS

In conclusion, while sustainable aviation fuel (SAF) represents a promising path for decarbonizing aviation, significant challenges remain in scaling its production, integrating it into existing supply chains, and aligning it with sustainability frameworks. Technologically, HEFA emerges as the most economically viable SAF pathway, but its dependence on vegetable oils and limited scalability raises long-term concerns. Meanwhile, FT and ATJ offer greater feedstock flexibility but face high capital or operational costs. Despite growing commitments from airlines and governments, SAF currently comprises less than 1% of global jet fuel demand, and production costs remain 2–8 times higher than conventional kerosene, signaling an urgent need for investment, policy consistency, and infrastructure upgrades.

Integration into the fuel supply chain is technically feasible but requires coordination, logistical adaptation, and capital investment, especially in regions lacking pipeline infrastructure. In the Asia-Pacific region, countries like Indonesia and Malaysia hold strategic potential due to abundant palm-based residues; however, this opportunity is counterbalanced by the environmental risks of indirect land-use change. Policies such as CORSIA and RED II provide important guardrails, but their stringent sustainability criteria also limit eligible feedstocks, posing a dilemma for palm-dependent producers. To align with global standards and unlock SAF's full potential, these nations must prioritize nonfood, waste-based inputs and strengthen traceability systems.

In addition, addressing the sustainability of aviation must go beyond fuel. The end-of-life (EOL) treatment of aircraft is emerging as another critical component of the green aviation transition. Recycling aircraft components and materials not only conserves resource and reduces GHG emissions but also mitigates environmental risks such as soil and groundwater pollution. The reuse of metals and carbon fibers exemplifies a circular economic approach that complements SAF development.

Looking ahead, the future of sustainable aviation lies in a multifaceted strategy: accelerating SAF scale-up through policy and financial incentives, ensuring environmentally robust feedstock sourcing, improving logistics infrastructure, and promoting full lifecycle sustainability—including aircraft decommissioning and material recovery. Only through such an integrated approach can the aviation industry effectively reduce its climate impact while maintaining operational resilience and global competitiveness.

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