



From Feedstocks to Flight: Scaling Sustainable Aviation Fuel Through Technology Portfolios, Corporate Ecosystems, Supply Chains, and Decarbonization Integrity

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ABSTRACT

Sustainable aviation fuel (SAF) has moved from a niche alternative-fuel concept toward a central component of aviation decarbonization strategies. Nevertheless, scaling SAF is more complex than increasing production capacity because different pathways depend on fundamentally different combinations of feedstocks, electricity, hydrogen, carbon dioxide, infrastructure, finance, and industrial capabilities. This qualitative literature review synthesizes recent evidence on SAF technologies, resources, techno-economics, lifecycle emissions, supply chains, corporate ecosystems, and market institutions. Particular attention is given to hydroprocessed esters and fatty acids, Fischer-Tropsch fuels, alcohol-to-jet, power-to-liquid/e-SAF, co-processing, and emerging pathways. The review demonstrates that technological maturity does not necessarily imply long-term scalability: mature lipid-based pathways face resource constraints, whereas pathways with larger theoretical resource bases frequently face higher capital requirements, conversion losses, and low-carbon electricity or hydrogen requirements. The analysis further shows that SAF commercialization depends on an increasingly interconnected ecosystem comprising integrated energy companies, specialist fuel producers, technology licensors, project developers, airlines, airports, feedstock suppliers, financiers, and environmental-attribute markets

INTRODUCTION

Aviation represents a particularly difficult sector to decarbonize because commercial aircraft combine stringent requirements for gravimetric and volumetric energy density, reliability, fuel stability, safety, and global infrastructure compatibility. Battery-electric propulsion may become relevant for some short-range operations, while hydrogen could eventually serve selected aircraft categories, but long-haul aviation is likely to retain a substantial requirement for energy-dense liquid fuels for decades. Consequently, sustainable aviation fuel has emerged as a strategically important mechanism for lowering the life-cycle carbon intensity of aviation while continuing to use much of the existing aircraft, airport, storage, and distribution infrastructure. The challenge is not simply to identify fuels that can technically substitute for petroleum-derived kerosene, but to develop alternatives that can be manufactured at very large scale without shifting unacceptable environmental burdens elsewhere in energy, land, water, or material systems (Doliente et al., 2020; Dahal et al., 2021; Abrantes et al., 2021; Bergero et al., 2023).

The significance of SAF is amplified by the broader climate profile of aviation. Aviation climate impacts are not restricted to carbon dioxide released during combustion. Nitrogen oxides, soot, water vapor, and persistent contrail cirrus contribute additional climate forcing, meaning that a comprehensive decarbonization strategy must evaluate both life-cycle greenhouse-gas emissions and atmospheric effects occurring at altitude. Recent studies therefore caution against interpreting a nominal percentage reduction in life-cycle CO₂ emissions as an exhaustive measure of climate performance. Grewe et al. (2021), Voigt et al. (2021), Bräuer et al. (2021), Dray et al. (2022), and Lee et al. (2023) collectively demonstrate that fuel composition, operational conditions, and non-CO₂ effects influence the climate outcome of aviation technologies.

The contemporary SAF landscape is also technologically heterogeneous. Hydroprocessed esters and fatty acids (HEFA) convert oils and fats into paraffinic hydrocarbons and currently represent the most technologically mature pathway. Fischer-Tropsch (FT) routes can transform syngas derived from lignocellulosic biomass, waste, or renewable hydrogen and carbon dioxide into liquid hydrocarbons. Alcohol-to-jet (ATJ) pathways convert alcohol intermediates such as ethanol or isobutanol into jet-range molecules. Power-to-liquid (PtL) or e-SAF configurations combine renewable electricity, electrolytic hydrogen, and captured carbon to produce synthetic aviation fuels. Other pathways based on hydrothermal liquefaction, pyrolysis, lignin conversion, algae, microbial processes, and hybrid catalytic systems continue to develop. These routes differ not only in technology readiness but also in feedstock demand, electricity consumption, hydrogen use, capital intensity, yield, fuel properties, and life-cycle emissions (Ng et al., 2021; Shahriar and Khanal, 2022; Watson et al., 2024; Zahid et al., 2024; Jiang et al., 2026).

This diversity means that the term “SAF” can obscure important distinctions. A liter of fuel derived from used cooking oil through HEFA is not environmentally, economically, or institutionally equivalent to a liter produced from dedicated vegetable oils, forestry residues, municipal waste, ethanol, renewable hydrogen and captured CO₂, or emerging lignin resources. Reported life-cycle results depend strongly on methodological boundaries, direct and indirect land-use assumptions, electricity sources, hydrogen production, treatment of co-products, and allocation procedures. Even fossil jet fuel itself has geographically variable life-cycle emissions, illustrating why credible benchmarking requires carefully defined system boundaries rather than a single universal comparison value (Kolosz et al., 2020; Seber et al., 2022; Jing et al., 2022; Bell et al., 2025).

Economics create a second layer of heterogeneity. Technology maturity does not guarantee cost competitiveness, and a pathway with attractive life-cycle performance may nevertheless remain constrained by feedstock price, electricity price, hydrogen cost, plant scale, utilization rate, capital expenditure, financing conditions, and co-product revenues. Contemporary literature reports substantial differences in minimum jet fuel selling prices and stresses that comparing pathways without harmonizing assumptions can produce misleading conclusions. Costs can also change materially when projects are integrated with existing refineries, pulp mills, hydrogen systems, or other industrial facilities (Brandt et al., 2020; Gonzalez-Garay et al., 2022; Rojas-Michaga et al., 2023; Chireshe et al., 2025; Farooq et al., 2025; Saeed et al., 2026).

The industry-actor map that motivated this review illustrates another frequently overlooked characteristic of SAF development: it is not an industry composed solely of fuel manufacturers. Firms associated with SAF include integrated oil and energy companies, renewable-fuel producers, technology licensors, refinery-process specialists, synthetic-fuel developers, waste-conversion companies, distributors, and intermediaries. Airlines, airports, logistics companies, feedstock aggregators, electricity suppliers, hydrogen producers, financiers, and corporate fuel buyers complete the wider ecosystem. Consequently, lists of prominent SAF companies should not automatically be interpreted as rankings because these organizations occupy different positions in the value chain. The more analytically relevant question is how their capabilities combine to transform feedstocks and low-carbon energy into certified fuel delivered to aircraft, a multi-stakeholder perspective increasingly emphasized in economic and supply-chain research (Xu et al., 2025; Liang et al., 2025).

The literature has become extensive but remains fragmented. Some studies concentrate on chemical pathways, others on feedstock availability, combustion characteristics, techno-economic analysis, life-cycle assessment, supply-chain optimization, or market formation. The proliferation of specialized reviews makes interdisciplinary synthesis increasingly necessary. Wandelt et al. (2025) identify this fragmentation explicitly and emphasize recurring challenges related to feedstock availability, scaling, sustainability, coordination, and certification. Watson et al. (2024) and Xu et al. (2025) similarly demonstrate the

need to connect technologies with economics, emissions, policy, supply-chain dynamics, and markets rather than analyzing these dimensions independently.

Accordingly, this article asks six questions. First, how do SAF feedstocks and conversion pathways differ in technological maturity, scalability, economics, resource requirements and lifecycle performance? Second, how is the emerging industrial ecosystem structured across established energy companies, specialists, licensors, project developers, airlines and supporting actors? Third, what trade-offs distinguish HEFA, FT, ATJ, PtL and emerging routes? Fourth, how do market institutions, certification arrangements and demand mechanisms affect commercialization? Fifth, under what conditions can SAF deliver credible aviation decarbonization once electricity, hydrogen, land use, coproduct allocation and non-CO₂ effects are considered? Sixth, which combinations of technology, supply-chain integration, financing and partnerships can help close the gap between announced capacity and fuel actually delivered to aircraft?

The central argument developed in this article is that large-scale SAF deployment is fundamentally a system-coordination challenge. There is no universally optimal feedstock or conversion pathway. Instead, viable scale-up depends on alignment among resource availability, conversion technology, capital, energy, logistics, sustainability accounting, certification and demand. This system perspective shifts the analytical focus from identifying a single “winning” technology toward understanding complementary pathway portfolios and the conditions under which they can produce credible climate benefits.

LITERATURE REVIEW

1. SAF as a Socio-Technical Decarbonization System

SAF is commonly defined around two related but distinct characteristics: technical suitability for aviation and lower life-cycle environmental impact relative to fossil-derived jet fuel. These characteristics should not be conflated. Technical qualification addresses properties such as freezing point, density, thermal stability, combustion characteristics, and compatibility with existing engines and infrastructure. Sustainability assessment examines the origin and use of carbon, energy, land, water, and other inputs across the life cycle. A technically acceptable fuel is therefore not automatically environmentally preferable. Conversely, an environmentally attractive molecule cannot be deployed commercially unless it satisfies demanding aviation fuel specifications and certification requirements (Yang et al., 2021; Yadav and Kumar, 2026).

The “drop-in” concept is especially important. Aviation differs from many road-transport applications because replacing the entire global aircraft fleet and fuel-handling infrastructure would require enormous capital and time. SAF pathways producing hydrocarbons compatible with conventional jet fuel can therefore exploit established infrastructure while gradually reducing the fossil component. This compatibility helps explain the strategic significance of SAF even when alternative propulsion technologies continue to develop. Co-processing in conventional refineries may also provide an intermediate deployment route by sharing existing process assets, although life-cycle attribution and accounting require careful treatment (Liu and Yang, 2023). At the

same time, compositional differences—particularly aromatic content—remain important for material compatibility, seals, combustion behavior, particulate formation, and blending limitations (Dahal et al., 2021; Harper et al., 2022; Corbin et al., 2022; Yadav and Kumar, 2026).

2. HEFA: Commercial Maturity and the Lipid Constraint

HEFA converts triglycerides and fatty acids into hydrocarbons through reactions including hydrogenation, deoxygenation, hydrocracking, and isomerization. Its principal strength is technological maturity. Existing refinery knowledge, hydrotreating equipment, and established oil-processing logistics can facilitate commercial deployment. This explains why HEFA has played an outsized role in early SAF supply. However, the pathway's maturity should not be confused with unlimited scalability. Waste oils and fats are finite, geographically uneven, and already demanded by other industries, while the sustainability of crop-derived oils depends heavily on agricultural practice and land-use effects (Ng et al., 2021; Seber et al., 2022; Song et al., 2023; Zahid et al., 2024; Jiang et al., 2026).

Hydrogen is another critical variable. Hydroprocessing requires hydrogen for removing oxygen and adjusting molecular structure. If this hydrogen is derived from fossil-intensive production, the lifecycle advantage of the resulting SAF can be eroded. Conversely, renewable hydrogen can improve carbon performance but may raise costs and create competition for scarce electrolytic hydrogen. Research on in-situ hydrogen generation and process integration therefore demonstrates that the distinction between “feedstock” and “energy input” becomes blurred in advanced SAF systems (Pipitone et al., 2023; Song et al., 2023).

3. Fischer-Tropsch and the Opportunity to Use Heterogeneous Carbon Resources

FT pathways expand the feedstock base because syngas can be produced from lignocellulosic biomass, residues, selected wastes, or combinations of renewable hydrogen and captured carbon. Gasification followed by syngas cleaning, conditioning, FT synthesis, and upgrading can generate high-quality hydrocarbons, while integrated configurations can exploit residues that are difficult to convert through lipid-based routes. Forest residues and other woody materials have consequently attracted considerable attention in life-cycle and techno-economic research (Ringsred et al., 2021; Rojas-Michaga et al., 2022; Dietrich et al., 2024; Almena et al., 2024).

The disadvantage is increased system complexity. Biomass must be collected, conditioned, and transported; gasification plants involve high temperatures and demanding gas-cleaning requirements; and economies of scale can conflict with the low volumetric density and dispersed geography of biomass. The optimal configuration may therefore not be a single enormous biorefinery. Chireshe et al. (2025) demonstrate why logistics and decentralized or partially decentralized production configurations can materially change economic outcomes, while Liang et al. (2025) show that supply-chain optimization must integrate feedstock selection, conversion technology, transportation, and airport demand.

4. Alcohol-to-Jet

ATJ provides another bridge between established biofuel industries and aviation. Ethanol, isobutanol, and other alcohols can be dehydrated, oligomerized, and hydrogenated to produce jet-range hydrocarbons. The attractiveness of ATJ depends partly on whether low-carbon alcohol production already exists at commercial scale in a region. Where agricultural, cellulosic, or industrial alcohol supply chains are established, ATJ may leverage existing assets and skills. However, the life-cycle performance of the final fuel remains closely linked to how the alcohol is produced, including agricultural emissions, land-use effects, and process-energy requirements (Brandt et al., 2020; Gonzalez-Garay et al., 2022; Zhang et al., 2025).

This illustrates a recurring pattern in SAF analysis: the conversion pathway alone does not determine sustainability. Identical upgrading technology can produce fuels with very different carbon intensities when the intermediate alcohol originates from different feedstocks or energy systems.

5. Power-to-Liquid and e-SAF

PtL potentially changes the resource basis of SAF more radically. Water electrolysis produces hydrogen, while carbon is supplied through concentrated biogenic streams, industrial capture, or direct air capture. These inputs can be converted into synthesis gas and subsequently hydrocarbons through FT chemistry, or routed through methanol and methanol-to-jet processes. In theory, PtL reduces dependence on scarce lipid feedstocks and can be geographically located wherever sufficiently abundant low-carbon electricity is available. In practice, this pathway transfers the principal scarcity problem from biomass toward renewable electricity, electrolytic hydrogen, captured carbon, and capital (Drünert et al., 2020; Grim et al., 2022; Freire Ordóñez et al., 2022; Rojas-Michaga et al., 2023; Eyberg et al., 2024).

Electricity is particularly consequential because electrolysis and synthetic-fuel conversion are energy intensive. PtL produced using carbon-intensive grid electricity can lose much of the climate rationale motivating its deployment. The location and temporal sourcing of electricity therefore become environmental variables rather than merely economic ones. Rojas-Michaga et al. (2023) show how upstream electricity emissions materially affect well-to-wake global-warming performance, while Freire Ordóñez et al. (2022) demonstrate that location-specific renewable resources influence both economics and environmental outcomes.

6. Emerging Feedstocks and Conversion Systems

Resource diversification is one response to the limitations of mature pathways. Municipal and industrial wastes may provide carbon streams while simultaneously addressing waste-management problems. Agricultural and forestry residues can expand lignocellulosic supply without deliberately cultivating fuel crops, although residue extraction must be constrained by soil, ecological, and competing-use considerations. Hydrothermal liquefaction is attractive for wet feedstocks because it may avoid energy-intensive drying. Algae could theoretically produce high yields without occupying conventional cropland, but nutrient, cultivation, harvesting, and energy requirements remain decisive (Prussi et al., 2021; Emmanouilidou et al., 2023; Usman et al., 2023).

Lignin is another increasingly important candidate. Conventional lignocellulosic biorefineries often focus on carbohydrate conversion, whereas lignin contains aromatic structures potentially valuable for aviation fuels. Recent research explores catalytic depolymerization and upgrading strategies that could improve whole-biomass utilization and help produce aromatic components useful for future high-SAF blends. However, results depend strongly on process integration, hydrogen recovery, and allocation assumptions (Weyand et al., 2025; Zhang et al., 2025).

7. Lifecycle Assessment and Carbon Integrity

Life-cycle assessment is essential because carbon released from an aircraft engine is only one component of fuel climate performance. Feedstock production, fertilizer, harvesting, electricity, hydrogen, processing, transportation, refining, land-use change, and co-product treatment can all materially affect the final result. Kolosz et al. (2020) identify system boundaries and allocation methods as persistent sources of variability. Seber et al. (2022) demonstrate the importance of land-use assumptions for vegetable-oil pathways, while Ringsred et al. (2021) show the sensitivity of forest-residue fuel carbon intensity to hydrogen sources and co-product allocation.

A second issue is the baseline. Jing et al. (2022) found substantial geographic variation in life-cycle emissions from petroleum jet fuel, indicating that the fossil comparator is not completely uniform. This matters because percentage reduction claims depend on the carbon intensity against which SAF is measured. Bell et al. (2025) further demonstrate the value of linking specific fuel pathways with flight-level carbon metrics rather than treating SAF carbon intensity in isolation.

Negative-emission configurations complicate interpretation further. Combining biogenic carbon with carbon capture and geological storage can produce modeled life-cycle outcomes below zero under specified boundaries. Rojas-Michaga et al. (2022), Ahlström et al. (2023), Almena et al. (2024), and Rojas-Michaga et al. (2025) illustrate opportunities to couple SAF production with carbon capture. Such results should nevertheless be interpreted carefully because negative values depend on the durability of storage, counterfactual biomass fate, water and energy requirements, and attribution of captured biogenic carbon.

8. Non-CO₂ Effects and Fuel Composition

Fuel chemistry can influence climate impacts after combustion. Low-aromatic SAF blends generally produce less soot because they contain fewer soot-forming aromatic compounds. Flight and combustion experiments provide evidence of reductions in particulate emissions and contrail ice-crystal numbers under particular conditions. Voigt et al. (2021) observed substantial reductions in soot and ice-particle number concentrations when low-aromatic SAF blends were burned, while Bräuer et al. (2021) found lower ice-number concentrations and contrail optical depth. Combustor and engine studies by Harper et al. (2022) and Corbin et al. (2022) likewise reinforce the relationship between composition and particulate emissions.

These findings do not imply that SAF automatically eliminates aviation non-CO₂ climate forcing. Contrail formation remains dependent on atmospheric conditions, engine technology and operational characteristics. Lee et al. (2023) therefore emphasize considerable uncertainty in assessing the total climate implications of hydrocarbon-fuel strategies. The analytical lesson is that lifecycle CO₂ and non-CO₂ benefits should be treated as related but separate dimensions rather than collapsed into a single unqualified sustainability claim.

9. Economics, Logistics and Demand

Techno-economic performance is determined by far more than conversion yield. Capital expenditure, feedstock price, co-product value, hydrogen, electricity, plant utilization, scale, location, and financing assumptions can alter minimum selling prices. Brandt et al. (2020) demonstrate the economic importance of co-product choices, while Chireshe et al. (2025) show how logistics, plant configuration, and external renewable hydrogen can influence SAF economics. The most recent comparative evidence similarly shows that feedstock cost, process integration, by-product valuation, capital-cost estimation, and financial assumptions are major determinants of observed cost dispersion across SAF studies (Watson et al., 2024; Farooq et al., 2025; Saeed et al., 2026).

Supply-chain configuration therefore constitutes part of the production technology rather than an afterthought. Martinez-Valencia et al. (2021) argue that no single supply-chain architecture is appropriate for all SAF systems. Ebrahimi et al. (2022) and Masum et al. (2023) use optimization approaches to demonstrate how feedstock geography, transport, facility placement, incentives, and demand locations influence system outcomes. Recent synthesis further emphasizes that scalable SAF supply chains require coordinated optimization across feedstocks, conversion technologies, transportation, and airport demand (Liang et al., 2025). Demand also matters because airlines face higher fuel costs while attempting to operate in highly competitive markets. Xu et al. (2022) show that passenger willingness to pay for lower-carbon aviation is therefore economically relevant. More recently, book-and-claim systems have been analyzed as mechanisms allowing environmental attributes to be separated contractually from the physical movement of SAF, potentially reducing logistical inefficiencies when physical fuel delivery to every airport is impractical (Uy and San Juan, 2024).

METHODOLOGY

1. Review Design

This study adopts a qualitative integrative literature-review methodology rather than a systematic literature review or meta-analysis. The objective is not to claim exhaustive retrieval of every publication on SAF or to calculate pooled quantitative effects. Instead, the approach integrates evidence from technological, engineering, lifecycle, economic, logistics, combustion, market and aviation-climate literatures in order to develop an interdisciplinary interpretation of SAF scale-up.

This methodological choice responds to the nature of the research problem. A narrow systematic review focused, for example, exclusively on HEFA life-cycle emissions or minimum selling prices could apply tightly defined inclusion criteria and produce a quantitative synthesis. The present study instead asks how technology, resources, firms, infrastructure, and environmental accounting interact. Such a question requires interpretive synthesis across bodies of literature employing heterogeneous units of analysis and methodologies. Wandelt et al. (2025) and Xu et al. (2025) show that contemporary SAF scholarship is fragmented across technical, environmental, economic, supply-chain, and policy domains, supporting the value of an integrative framework.

2. Literature Identification and Selection

The review prioritizes peer-reviewed journal literature published from 2020 through 2026. Relevant studies were conceptually grouped using combinations of terms including “sustainable aviation fuel,” “biojet fuel,” “HEFA,” “Fischer-Tropsch,” “alcohol-to-jet,” “power-to-liquid,” “e-SAF,” “life cycle assessment,” “techno-economic assessment,” “feedstock,” “supply chain,” “contrail,” “particulate emissions,” “book-and-claim,” and “aviation decarbonization.” Priority was placed on studies published in established journals in energy, environmental science, fuels, process engineering, transport, climate and sustainability research.

Selection was relevance driven rather than mechanically exhaustive. Papers were retained when they contributed evidence to one or more of seven analytical dimensions: technology; resources; economics and finance; supply chains; corporate ecosystems; environmental integrity; and market or institutional conditions. Recent critical reviews were used to map broad debates, while primary lifecycle, techno-economic, supply-chain and combustion studies were used where greater specificity was required.

The supplied company infographic was treated separately from the peer-reviewed evidence. It served as an initial industry-actor mapping device, not as evidence that the included organizations represent the objectively largest, most sustainable or highest-performing SAF companies. This distinction is necessary because producers, technology licensors, integrated oil companies, distributors and project developers perform different economic functions and cannot legitimately be ranked on a single common metric without a separate company-level methodology.

3. Thematic Coding

The literature was interpreted using both deductive and inductive thematic coding. Deductive categories followed seven dimensions defined in the analytical framework: technology maturity, resource availability, techno-economics, supply chains, industrial actors, environmental integrity, and institutions. Inductive interpretation identified cross-cutting relationships that repeatedly appeared in the literature, particularly resource substitution, pathway complementarity, carbon-accounting sensitivity, first-of-a-kind risk, infrastructure coordination, and the gap between nominal production capacity and deliverable low-carbon fuel.

Because this study is a qualitative integrative review rather than a systematic review, a PRISMA flow diagram was not used. Methodological transparency was instead maintained by specifying the temporal scope, thematic logic, evidence hierarchy, selection principles, and analytical framework used to organize the literature.

RESULT

1. SAF Is Better Understood as a Portfolio than as a Single Technology

The most consistent finding across the literature is that SAF pathways occupy different positions along a trade-off frontier. HEFA offers high technological readiness and relatively straightforward integration into existing refinery systems but faces constraints associated with sustainable lipid availability. FT can utilize a broader range of lignocellulosic and waste carbon but requires complex gasification and syngas-processing infrastructure. ATJ can leverage established alcohol industries but inherits the upstream carbon characteristics of alcohol production. PtL provides a route away from biomass dependence but imposes very large demands on low-carbon electricity, hydrogen, and carbon capture. Emerging systems may unlock additional feedstocks but generally face lower technology readiness and greater financing risk (Shahriar and Khanal, 2022; Watson et al., 2024; Ismael et al., 2025; Yadav and Kumar, 2026; Jiang et al., 2026).

This finding undermines a simple sequential narrative in which an older SAF pathway is eventually replaced by a technologically superior new pathway. A more plausible long-term structure is a portfolio in which pathways coexist because regional resource endowments differ. Regions with abundant waste lipids may deploy HEFA; forestry regions may favor biomass-to-liquid; regions with inexpensive low-carbon electricity may eventually support e-SAF; and areas with established low-carbon ethanol industries may find ATJ attractive. The key determinant becomes local alignment between resources, technology and infrastructure rather than pathway identity alone.

Figure 1 synthesizes these interdependencies across five linked layers – resources, conversion, industrial actors, logistics, and aviation demand – while treating finance, certification, life-cycle assessment, sustainability verification, and standards as cross-cutting enablers. This systems view clarifies that airline demand sits at the downstream end of a broader resource, technology, and institutional network.



Figure 1. SAF Industrial Ecosystem: From Resources to Flight

Figure 1 emphasizes that the SAF transition extends far beyond refinery conversion. The physical pathway begins with carbon, hydrogen and energy resources, but commercial delivery requires conversion equipment, project development, financing, certification, logistics and airline demand. Consequently, a bottleneck in any one layer can constrain the entire chain. This helps explain why headline production capacity can overstate the quantity of SAF that ultimately becomes available to aircraft.

2. Feedstock Availability Becomes the First Major Scaling Boundary

The near-term attractiveness of waste lipids is simultaneously their principal long-term weakness: their supply is limited. As production expands, competition for used cooking oil, animal fats, and similar residues can increase procurement cost and extend transportation distances. Crop oils can enlarge the resource pool, but environmental integrity becomes more dependent on agricultural practices and land-use consequences. Seber et al. (2022) show how methodological treatment of direct land-use change contributes substantial uncertainty to vegetable-oil SAF life-cycle results.

Lignocellulosic materials appear considerably more abundant but create a different logistical challenge. Agricultural residues, forestry residues, and heterogeneous wastes have low bulk density and geographically dispersed supply. Harvesting, preprocessing, storage, and transport can therefore become major system components. Masum et al. (2023) demonstrate why feedstock geography and biorefinery placement should be incorporated directly into SAF supply-chain optimization, while Martinez-Valencia et al. (2021) and Liang et al. (2025) emphasize that environmental value and system performance depend on how supply networks are configured and optimized.

Emerging feedstocks reduce some constraints while introducing others. Algal systems can theoretically reduce direct competition with conventional cropland but require careful management of nutrients, cultivation energy, and harvesting. Wet wastes may be particularly compatible with hydrothermal processes, while lignin valorization can improve carbon utilization in forest-based biorefineries. No feedstock is therefore “waste” in an economic sense once significant demand develops; competing uses and opportunity costs eventually become relevant (Prussi et al., 2021; Usman et al., 2023; Weyand et al., 2025; Jiang et al., 2026).

3. Energy and Hydrogen Become Feedstocks in Advanced Pathways

A major conceptual shift occurs as SAF production moves from conventional biofuels toward deeply decarbonized synthetic systems. Renewable electricity is no longer simply a utility; it effectively becomes a feedstock. The same is true for hydrogen. In PtL production, electricity determines hydrogen cost and much of overall energy efficiency. In biomass-based systems, supplemental renewable hydrogen can increase carbon utilization by preventing biogenic carbon from leaving the process as CO₂.

Grim et al. (2022) frame electrification as both an opportunity and a risk because electricity-intensive routes can improve carbon utilization while creating dependence on large supplies of low-carbon power. Chireshe et al. (2025) similarly report that renewable hydrogen supplementation can increase SAF yield in particular FT configurations. The broader implication is that future SAF industries will increasingly compete not only for biomass but also for clean electricity and hydrogen with steel, chemicals, road transport, power storage, and other decarbonizing sectors.

Figure 2 visualizes the principal resource substitutions across HEFA, ATJ, FT-BTL, PtL/e-SAF, and emerging routes. It highlights how greater technological maturity does not necessarily coincide with lower resource intensity or fewer scale-up constraints.



Figure 2. Technology–Resource Trade-Off Matrix for Major SAF Pathways

Figure 2 shows why maturity and scalability are not synonymous. HEFA is commercially mature but faces a relatively narrow feedstock pool. PtL has a potentially broader carbon resource base but requires very large quantities of renewable electricity and hydrogen. FT occupies an intermediate position, with large theoretical biomass resources offset by complex logistics and capital requirements. The resulting structure supports a diversified technology portfolio rather than a single pathway dominating every region.

4. The Cost Gap Is a Systems Problem

SAF cost discussions frequently focus on conversion technology, yet the reviewed evidence shows that cost emerges from the entire system. Feedstock price can dominate mature pathways; electricity dominates many PtL configurations; capital and financing become especially important for first-of-a-kind facilities; and co-products may materially alter economic performance. Brandt et al. (2020) demonstrate that changing co-product strategies can significantly reduce modeled jet-fuel selling prices in a forest-residue ATJ system, while Farooq et al. (2025) show that feedstock costs and methodological assumptions are major drivers of MJSP variability across pathway studies. PtL provides a particularly clear example. Rojas-Michaga et al. (2023) found the evaluated PtL system to be strongly OPEX-intensive because of electricity consumption, with direct-air-capture equipment also materially contributing to capital costs. Eyberg et al. (2024) show that process configuration matters when comparing FT and methanol-to-jet PtL routes. These studies indicate that statements such as “e-SAF is expensive” are incomplete without specifying renewable-electricity price, electrolyzer assumptions, CO₂ source, utilization rate, and process architecture.

Recent harmonized literature strengthens this conclusion. Saeed et al. (2026) report a broad range of minimum fuel selling prices across SAF pathways after economic normalization, while Farooq et al. (2025) find that feedstock costs, by-product credit valuation, process design, capital-cost estimation, and financial assumptions materially affect MJSP comparability. Together, these analyses show why cost and environmental performance should be assessed jointly rather than treated as independent rankings.

5. Carbon Integrity Is Conditional

The literature does not support the proposition that all fuels carrying the SAF label provide equivalent climate benefits. Life-cycle performance is conditional on feedstock origin, process configuration, allocation method, land-use effects, hydrogen, electricity, and the carbon counterfactual. This explains why reported outcomes can range from relatively modest improvements to deep reductions or even modeled net-negative emissions under carbon-capture configurations (Kolosz et al., 2020; Rojas-Michaga et al., 2022; Almena et al., 2024; Bell et al., 2025; Rojas-Michaga et al., 2025; Saeed et al., 2026).

Used cooking oil illustrates one relatively favorable pathway when genuine waste feedstock is used and upstream burdens remain limited. By contrast, crop-based fuels may be more sensitive to land-use assumptions. Forest-derived pathways depend on counterfactual residue management, forest carbon accounting and hydrogen. PtL relies on electricity and CO₂ provenance. Carbon

captured from a fossil facility, biogenic source and direct air capture do not have identical long-run carbon implications.

Figure 3 summarizes the carbon-integrity chain from feedstock origin through aircraft combustion and separates life-cycle GHG accounting from non-CO₂ atmospheric effects. This distinction is essential because the two accounting lenses capture different mechanisms and should not be collapsed into a single unqualified climate metric.

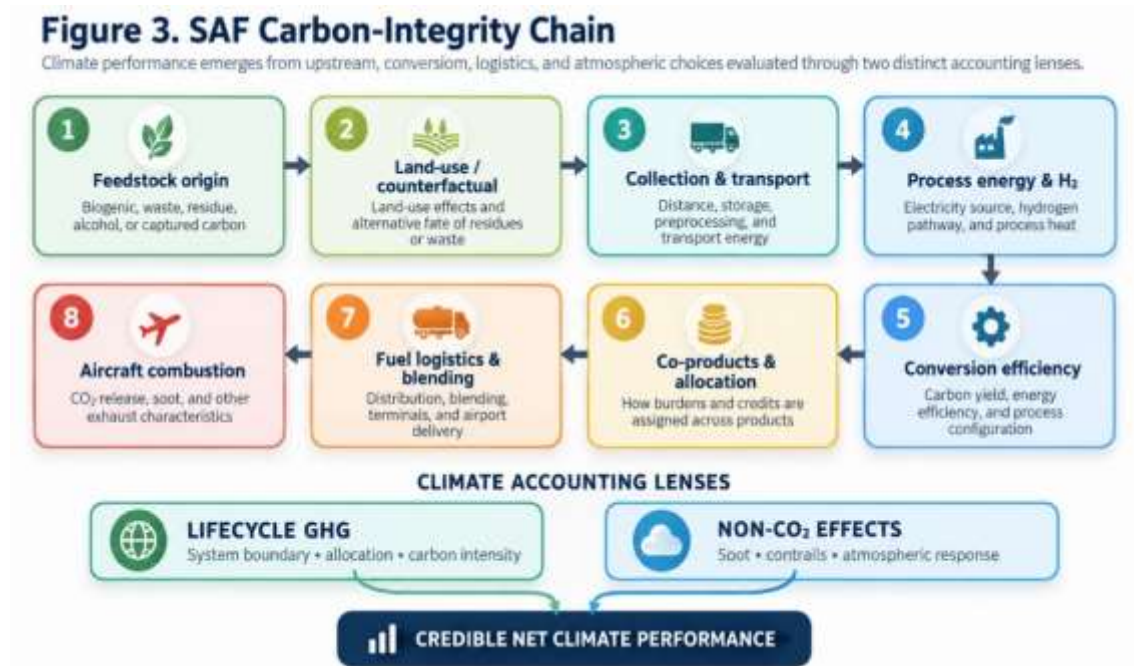


Figure 3. SAF Carbon-Integrity Chain

The important implication of Figure 3 is that environmental integrity cannot be added retrospectively to an otherwise completed fuel project. It is embedded in the project's resource and engineering choices from the beginning. A pathway using high-carbon electricity or unsustainable feedstock cannot necessarily be transformed into a low-carbon product merely through downstream certification.

6. SAF May Also Influence Non-CO₂ Climate Effects

Experimental evidence indicates that fuel composition can produce additional environmental effects beyond life-cycle fossil-carbon substitution. Voigt et al. (2021) reported reductions in soot and contrail ice-crystal concentrations using lower-aromatic alternative fuel blends. Bräuer et al. (2021) likewise observed reductions in ice-number concentration and contrail optical depth. Combustor and engine studies by Harper et al. (2022) and Corbin et al. (2022) reinforce these findings, while airport-level analysis indicates that SAF blending can also affect combined energy and emissions outcomes in aviation operations (Liu et al., 2024). These results are particularly relevant because contrail cirrus forms an important component of aviation's total climate forcing. Fuel-composition optimization could therefore become a second environmental design objective alongside lifecycle carbon intensity. However, atmospheric outcomes remain conditional on meteorology and flight conditions, and the field

still contains material uncertainty. The strongest interpretation is consequently not that SAF eliminates contrail effects, but that certain fuel compositions may create additional mitigation opportunities that deserve integration into future fuel and flight optimization (Grewe et al., 2021; Lee et al., 2023).

7. The Corporate Landscape Is an Ecosystem Rather than a Ranking

The initial industry-actor map used to motivate this review included integrated energy companies such as TotalEnergies, Eni, Shell, bp, Repsol, Phillips 66, OMV, Moeve, Valero, Marathon, and ExxonMobil; renewable-fuel specialists such as Neste and World Energy; technology and project developers such as LanzaJet, Gevo, Velocys, DG Fuels, Twelve, INERATEC, and Air Company; and technology providers including Honeywell UOP and Topsoe. These examples are used illustratively rather than as a ranking or an exhaustive market census. The analytically relevant issue is the capability each type of actor contributes to the emerging SAF value chain.

Integrated refiners can bring existing hydrotreating equipment, procurement systems, trading capabilities, terminals, and customer relationships. Technology licensors allow conversion technologies to diffuse across multiple plants without requiring the licensor to own every facility. Specialist developers may accept technology and project risks that incumbent refiners would initially avoid. Airlines contribute demand certainty through offtake arrangements, while financial institutions and infrastructure operators determine whether facilities can move from engineering concepts to operational assets. This multi-actor structure is consistent with recent management and supply-chain reviews that identify stakeholder coordination as a central condition for SAF scale-up (Xu et al., 2025; Liang et al., 2025).

Figure 4 maps the complementary corporate archetypes around a SAF production project, including feedstock suppliers, technology licensors/EPC firms, financiers, traders and distributors, certification bodies, airport fuel systems, and end users. The figure highlights commercialization as a coordination problem rather than a contest among directly comparable firms.



Figure 4. Corporate Archetypes within the SAF Ecosystem

Figure 4 helps explain why SAF commercialization depends heavily on partnerships. Few organizations simultaneously possess feedstocks, proprietary conversion technology, financing capacity, refinery infrastructure, fuel-distribution networks and guaranteed aviation demand. Vertical integration can solve some coordination problems, but strategic alliances and long-term contracting remain central mechanisms for assembling complementary capabilities.

8. From Announced Capacity to Delivered Fuel

The most important scale-up distinction is between nominal project announcements and sustained commercial fuel delivery. A project can be technically credible yet fail to secure feedstock. It can secure feedstock yet fail to reach financial close. It can reach financial close and encounter construction delays. It can begin production but face certification, distribution or offtake problems. Each stage therefore constitutes a potential attrition point.

Figure 5 converts these sequential requirements into a scale-up constraint cascade. The cascade makes explicit that progress can be delayed at any stage between sustainable resource availability and durable airline or corporate demand.



Figure 5. SAF Scale-Up Constraint Cascade

The cascade highlights a central result of the review: the usable quantity of SAF is determined by the tightest binding constraint, not by theoretical production potential alone. This distinction is particularly important when evaluating future supply projections.

DISCUSSION

RQ1: Why Technology Performance Cannot Be Separated from Resources

The first research question asks how pathways differ in maturity, scalability, economics, resource needs and lifecycle performance. The evidence demonstrates that these variables interact rather than move together. HEFA scores strongly on technical maturity but poorly on unconstrained feedstock scalability. PtL has a potentially large long-run resource base but relatively demanding electricity and hydrogen requirements. Biomass FT can access widely distributed lignocellulosic carbon but faces logistics and capital constraints. ATJ can benefit from established alcohol industries but inherits the carbon intensity and sustainability of alcohol production.

The relevant analytical unit is therefore not simply “HEFA” or “FT,” but feedstock–technology–energy–location configuration. A HEFA plant processing genuine waste oils with low-carbon hydrogen can have a substantially different lifecycle profile from the same process using land-intensive crop oil and fossil-derived hydrogen. Likewise, an FT facility using residues and renewable hydrogen differs from one using higher-carbon inputs. PtL using dedicated low-carbon electricity is conceptually different from PtL drawing marginal power from a carbon-intensive grid.

This point is strengthened by the latest global assessment of feedstocks and processes. Jiang et al. (2026) conclude that mature approved routes depend on only part of the available biomass and waste resource and that expansion will require additional conversion technologies capable of processing more heterogeneous feedstocks. The result supports portfolio diversification rather than technological monoculture.

RQ2: The SAF Industry Is Defined by Complementary Capabilities

The second research question concerns the industrial ecosystem. The supplied infographic initially appears to depict competitors, but a closer industrial interpretation reveals multiple complementary roles. The business model of a refinery owner differs fundamentally from that of a process licensor; an e-fuel technology developer differs from an aviation-fuel distributor; and a specialist project developer differs from an integrated multinational energy company.

This distinction matters because industry concentration cannot be inferred simply by counting company names or announced projects. A technology provider can influence many facilities without owning their fuel production. Conversely, a large integrated energy company can operate refineries, distribution infrastructure and airline supply relationships while licensing technology from another organization. Corporate-network analysis may therefore reveal more about the structure of SAF commercialization than conventional producer rankings.

The importance of multi-actor coordination is consistent with the supply-chain and management literature. Ng et al. (2021) emphasize collaboration in facilitating biojet uptake, Martinez-Valencia et al. (2021) argue that SAF value-chain design requires systemic rather than isolated plant optimization, and Xu et al. (2025) identify multi-stakeholder supply-chain dynamics as a major theme in the contemporary economic and management literature. Liang et al. (2025) further show that integrated optimization across feedstocks, conversion, transport, and end-user demand is central to scalable deployment.

RQ3: No Pathway Wins Every Criterion

The third research question evaluates trade-offs among HEFA, FT, ATJ, PtL and emerging pathways. The literature provides no defensible basis for a universal ordering. HEFA has commercial advantages but limited sustainable lipid supply. FT expands the biomass base but is capital intensive. ATJ can exploit alcohol infrastructure but depends heavily on upstream alcohol economics and emissions. PtL offers a non-biological carbon pathway but faces high electricity requirements and currently challenging economics. Emerging systems could improve resource efficiency but face technological and financing uncertainty.

A better decision framework therefore uses multiple criteria simultaneously: feedstock abundance; life-cycle greenhouse-gas intensity; technology readiness; capital requirements; production cost; hydrogen demand; renewable-electricity demand; logistics; fuel properties; co-product opportunities; and compatibility with regional infrastructure. Recent comparative evidence also shows that techno-economic conclusions are sensitive to feedstock costs, by-product credits, capital-cost estimation, process integration, and financial assumptions, reinforcing the case for multi-criteria

rather than single-indicator assessment (Farooq et al., 2025). The analytical result is not indecision; it is recognition that regional optimization can produce different answers.

This conclusion also explains why technology portfolios can increase resilience. Dependence on a single pathway exposes the industry to one dominant resource bottleneck. Diversification allows waste oils, residues, alcohols, renewable power and captured carbon to contribute according to local comparative advantages.

RQ4: Market Architecture Determines Who Bears the Cost Premium and Risk

The fourth question concerns institutions and commercialization. SAF projects frequently involve costs exceeding those of conventional fuel, meaning that someone must absorb or redistribute the premium. That cost can be allocated among producers, governments, airlines, passengers, corporate customers or environmental-attribute buyers. The structure of incentives therefore determines not merely the amount of SAF demanded but also which projects can secure finance.

Offtake agreements are especially important because they transform uncertain future demand into a contractible revenue expectation. A long-term airline purchase commitment can reduce market risk, although the contract must still allocate exposure to feedstock prices, policy changes, and production underperformance. Book-and-claim mechanisms address a different problem: physical SAF does not necessarily need to be transported to the precise airport associated with the purchaser if environmental attributes can be credibly recorded and retired elsewhere. Uy and San Juan (2024) demonstrate the potential importance of combining physical and virtual procurement in airline fuel planning.

Consumer demand is another part of this architecture. Xu et al. (2022) show that willingness to pay for lower-carbon aviation is not automatic and depends on behavioral and contextual factors. This limits the extent to which airlines can simply transfer the entire SAF premium to passengers without affecting demand or competitiveness.

The article does not prescribe one political or regulatory model. Rather, the literature shows that institutional design affects project incentives, risk allocation, market formation, and the credibility of environmental claims. Comparative evaluation should therefore focus on observed effects, distribution of costs, administrative design, and interactions among policies rather than treating any one instrument as inherently preferable (Watson et al., 2024; Bardon and Massol, 2025; Xu et al., 2025).

RQ5: Credible Decarbonization Requires Boundary Discipline

The fifth question addresses the environmental conditions under which SAF can legitimately be considered a decarbonization measure. The first requirement is robust lifecycle accounting. Carbon reduction should not be inferred solely from the renewable character of a feedstock. Cultivation inputs, transport, refining energy and land-use effects can materially alter outcomes. Second, low-carbon hydrogen and electricity are increasingly central. This is true not only for PtL but for hydroprocessing and advanced biomass pathways. As

SAF systems become more integrated with hydrogen and renewable electricity, carbon accounting must track energy sourcing more precisely.

Third, co-product treatment must be transparent. Brandt et al. (2020), Ringsred et al. (2021), Kolosz et al. (2020), and Weyand et al. (2025) collectively demonstrate that allocation decisions can materially change economic or environmental results.

Fourth, avoided emissions and negative emissions should be separated conceptually. Carbon capture can produce strong climate performance in modeled SAF systems, but the accounting must explain whether benefits arise from substitution of fossil fuel, permanent storage of biogenic carbon, avoided waste emissions, or a combination. Ahlström et al. (2023), Almena et al. (2024), and Rojas-Michaga et al. (2025) illustrate the potential of integrated capture configurations, while also underscoring the need for explicit system boundaries and transparent treatment of energy, water, and carbon-storage assumptions.

Finally, non-CO₂ effects should remain visible. The evidence that low-aromatic fuels can reduce soot and contrail ice particles is promising, but lifecycle carbon reductions and contrail mitigation are conceptually distinct benefits. Treating them separately will reduce the risk of double counting.

RQ6: Closing the Announcement-to-Delivery Gap

The sixth question asks how the industry can transform potential capacity into delivered fuel. The synthesis suggests five conditions.

First, feedstock or energy supply must be secured for the expected operating life of the facility. A technically complete plant without adequate resource supply will operate below capacity and face higher unit costs.

Second, technology risk must be aligned with financing structures. Mature refinery conversions face different risks from first-of-a-kind gasification or e-fuel plants. Capital providers therefore require different risk-sharing arrangements.

Third, offtake should provide sufficiently predictable revenue. Without credible demand, even technically attractive projects can struggle to reach financial close. Fourth, infrastructure must connect the production site to the aviation market. Pipeline access, blending facilities, terminals, road or marine logistics and airport fuel systems can become binding constraints.

Fifth, certification and environmental attributes must be sufficiently credible to prevent double claiming and sustain buyer confidence. This requires traceable chain-of-custody rules, transparent life-cycle accounting, and governance arrangements that preserve the uniqueness of environmental claims across physical and book-and-claim transactions (Uy and San Juan, 2024; Xu et al., 2025).

The constraint-cascade model developed in Figure 5 integrates these findings. It helps explain why production forecasts based only on plant announcements can overstate probable output. Each additional constraint between project announcement and routine commercial production introduces attrition.

The SAF Scale-Up Viability and Integrity Framework

The seven-dimensional synthesis is presented in Table 1, which integrates technology, resources, economics and finance, supply chains, the corporate ecosystem, environmental integrity, and market institutions. Each dimension is linked to principal variables and a central question so that pathway viability can be assessed consistently across contexts.

Seven dimensions linking technical feasibility, commercial viability, and environmental credibility.

Dimension	Principal variables (examples)	Central question
1 Technology From concept to certified fuel	- Technology readiness level (TRL) - Fuel yield and properties (e.g., energy density, freeze point) - Conversion efficiency and feasibility - Certification status (e.g., ASTM D7568)	Can the pathway reliably produce aviation-quality fuel?
2 Resources Securing sustainable inputs	- Feedstock availability and sustainability (waste, biomass, etc) - Renewable power, hydrogen, and CO₂ supply - Water use and critical materials - Competition with other sectors (food, materials, other fuels)	Are sufficient sustainable inputs available?
3 Economics and finance Pathways to profitability	- Capital expenditure (CAPEX) and operating expenditure (OPEX) - Minimum jet fuel selling price (MJFSP) - Financing structures and risk allocation - Co-products and revenue diversification	Can the project become bankable?
4 Supply chain Moving fuel to users	- Feedstock collection and transport - Plant siting and infrastructure - Blending, storage, and distribution - Airport readiness and logistics integration	Can fuel reach users efficiently?
5 Corporate ecosystem Creating value for users	- Producers, technology licensors, and EPC contractors - Airlines, airports, and fuel distributors - Investors, off-takers, and strategic partnerships - Governance and alignment of incentives	Are complementary capabilities coordinated?
6 Environmental integrity Delivering real climate benefits	- Lifecycle greenhouse-gas (GHG) emissions - Land use and biodiversity impacts - Non-CO₂ effects (e.g., contrails, NO_x, soot) - Allocation methods and chain of custody	Does the pathway deliver credible climate benefits?
7 Market and institutions Shaping durable demand	- Policy frameworks and mandates (e.g., SAF blending targets) - Standards and certification schemes (e.g., CORSIA, ISB, ISCC) - Contracts, offtake agreements, and market incentives - Carbon markets and revenue for environmental attributes	Can production obtain durable market demand?

Abbreviations: TRL = technology readiness level; CAPEX = capital expenditure; OPEX = operating expenditure; MJFSP = minimum jet fuel selling price; ASTM = American Society for Testing and Materials; CORSIA = Carbon Offsetting and Reduction Scheme for International Aviation; ISB = International Sustainability Benchmark; ISCC = International Sustainability and Carbon Certification.

Figure 8. SAF Scale-UP Viability and Framework

The framework explains why optimizing only one dimension can produce a misleading conclusion. For example, maximizing conversion yield is not necessarily advantageous if it requires carbon-intensive hydrogen. Minimizing production cost can reduce sustainability if it induces problematic feedstock sourcing. Maximizing lifecycle carbon savings may be commercially ineffective if capital costs prevent financing. True scalability occurs where the dimensions become mutually compatible.

Implications for Developing and Emerging Economies

Although much SAF literature focuses on Europe and North America, the integrated framework is especially relevant to emerging economies. Regions with large agricultural, forestry or waste resources could participate in future SAF supply chains, but the highest economic value may not arise from exporting raw feedstock. Development of domestic preprocessing, refining, hydrogen, renewable energy, certification and technical capabilities could retain more value locally.

At the same time, large-scale feedstock demand may create trade-offs with food systems, existing bioenergy markets, smallholder livelihoods, biodiversity, and land use. A resource theoretically classified as “available” should therefore not automatically be considered environmentally or socially surplus. Gautam et al. (2023) demonstrate the importance of examining agricultural carbon

management alongside SAF viability, while global-scale research increasingly emphasizes resource heterogeneity and logistics (Jiang et al., 2026).

For countries with abundant renewable electricity, e-SAF creates a different industrial opportunity. Instead of exporting electricity indirectly through energy-intensive materials alone, renewable power could potentially be transformed into hydrogen and synthetic hydrocarbons. The feasibility of such strategies would nevertheless depend on renewable-power additionality, infrastructure, water, cost of capital and access to reliable CO₂ sources.

Research Agenda

The first research priority is harmonized pathway comparison. Recent literature repeatedly demonstrates that differences in economic and life-cycle assumptions can be as important as differences in technologies themselves. Common treatment of plant life, discount rate, feedstock cost, electricity, hydrogen, allocation, by-product valuation, and carbon baselines would improve comparability across studies (Watson et al., 2024; Farooq et al., 2025; Saeed et al., 2026).

Second, the field needs more operating data from commercial facilities. Engineering models remain essential, but actual performance at scale will provide information on capacity factors, maintenance, catalyst life, feedstock variability, product yields and costs that simulation alone cannot fully capture. Third, corporate-network research should complement engineering studies. The rapid emergence of joint ventures, technology licensing, airline offtake, environmental-attribute markets, and cross-sector partnerships creates a rich opportunity to investigate how industrial structure affects scale-up. Recent economic and management literature identifies multi-stakeholder supply-chain dynamics and international coordination as major areas for further research (Xu et al., 2025).

Fourth, feedstock competition requires dynamic rather than static assessment. Waste resources that are inexpensive at low demand may become scarce and expensive under large-scale deployment. Similarly, electricity and hydrogen opportunity costs change as other industries decarbonize. Fifth, more spatial analysis is required. Resource availability, electricity carbon intensity, feedstock transport and airport demand are geographic variables. Spatially explicit assessments can therefore produce more realistic deployment maps than universal technology assumptions.

Sixth, future studies should integrate life-cycle CO₂ with aviation non-CO₂ effects while preserving methodological separation. The experimental evidence from Voigt et al. (2021), Bräuer et al. (2021), Harper et al. (2022), and Corbin et al. (2022) makes fuel composition an increasingly important research frontier.

Seventh, researchers should distinguish more clearly between announced, financed, under-construction, operational, and delivered capacity. This distinction would improve the quality of SAF supply projections and help connect project-pipeline analysis with real supply-chain bottlenecks identified in recent optimization research (Liang et al., 2025).

Finally, rapidly developing pathway research should continue examining hybrid biochemical, thermochemical, and electrochemical configurations. Recent syntheses by Zhang et al. (2025), Yadav and Kumar (2026), and Jiang et al. (2026) suggest that greater carbon efficiency may ultimately emerge from integrated rather than strictly separated pathway families.

CONCLUSIONS AND RECOMMENDATIONS

Sustainable aviation fuel has become one of the most important technological options for reducing aviation's dependence on fossil kerosene, but SAF should not be understood as a homogeneous product or a single technology. HEFA, Fischer-Tropsch, alcohol-to-jet, power-to-liquid and emerging pathways differ fundamentally in their resource bases, technological maturity, capital requirements, energy consumption and environmental profiles.

The central conclusion of this review is that SAF scale-up is simultaneously a technology problem, a resource-allocation problem, a financing problem, a logistics problem and an environmental-integrity problem. Technological maturity alone cannot guarantee large-scale deployment. Mature pathways may be limited by feedstock; resource-rich pathways may be limited by conversion efficiency; technically promising projects may fail to become bankable; and apparently low-carbon fuels may lose environmental credibility if electricity, hydrogen, land-use change or lifecycle boundaries are inadequately addressed.

The corporate landscape should likewise be interpreted as an ecosystem rather than as a ranking of fuel producers. Integrated energy companies, renewable-fuel specialists, technology licensors, e-fuel developers, airlines, airports, feedstock providers, financiers and certification systems provide complementary capabilities. Commercial scale is therefore likely to emerge through networks and partnerships rather than through isolated firms operating complete value chains.

The SAF Scale-Up Viability and Integrity Framework developed in this review integrates seven dimensions—technology, resources, economics and finance, supply chains, corporate ecosystems, environmental integrity, and market institutions. Its central implication is that a viable SAF project must satisfy all seven dimensions simultaneously. Weakness in one dimension can constrain the entire system.

A diversified pathway portfolio consequently appears more robust than dependence on any single technology. Near-term commercial expansion may continue to rely strongly on mature lipid pathways, while lignocellulosic, waste-based, alcohol-derived and synthetic e-SAF systems broaden the long-run resource base. The ultimate contribution of SAF to aviation decarbonization will depend less on the number of technologies or projects announced than on the volume of fuel that can be produced, certified, financed, transported and consumed while delivering demonstrably credible lifecycle climate benefits.

FURTHER STUDY

This research still has limitations, so further studies are needed on the topic 'From Feedstocks to Flight: Scaling Sustainable Aviation Fuel through Technology Portfolios, Corporate Ecosystems, Supply Chains, and Decarbonization Integrity' to improve this research and add insights for both the author and readers.

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