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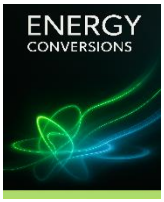

Towards Net-Zero Aviation: A Critical Review of Sustainable Aviation Fuel Pathways and Scale-Up Constraints

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ABSTRACT

Aviation is one of the most difficult sectors to decarbonize because long-range flight still depends on high-energy-density liquid fuels. Sustainable aviation fuel (SAF) has therefore emerged as the principal near-term decarbonization option, but its real climate value depends on feedstock origin, conversion route, energy inputs, and deployment scale. This review synthesizes the state of knowledge on the major SAF pathways—including hydroprocessed esters and fatty acids (HEFA), Fischer–Tropsch (FT), alcohol-to-jet (ATJ), and power-to-liquid (PtL)—and compares their feedstocks, fuel yields, lifecycle greenhouse gas performance, production costs, certification status, and infrastructure readiness. Particular attention is given to the trade-offs among technological maturity, resource availability, land and water pressures, hydrogen demand, and electricity carbon intensity. The analysis also examines how policy instruments such as CORSIA and regional blending mandates shape investment signals and market formation. The review shows that no single pathway can satisfy future aviation demand on its own: mature lipid-based routes can support near-term growth, whereas deep long-term decarbonization will require large-scale expansion of residue-based and synthetic fuels. Progress in certification, feedstock governance, and industrial scale-up will be decisive for meaningful SAF penetration.

1. Introduction

Aviation is indispensable to contemporary mobility and trade, yet it remains one of the most challenging sectors to decarbonize. Before the pandemic, air transport moved billions of passengers annually and underpinned trillions of dollars in economic activity, but that connectivity has been accompanied by a substantial climate burden [1]. Commercial aviation contributes a meaningful share of global CO_2 emissions, and its total warming effect is even larger when non-CO_2 effects such as contrails and nitrogen oxides are considered [2,3]. Without strong mitigation, sectoral emissions could expand markedly by mid-century and compromise wider climate targets [4].

Alternative propulsion concepts are advancing, but their applicability is uneven across the fleet. Battery-electric systems remain constrained by energy density, while hydrogen introduces storage, certification, and infrastructure challenges that are especially difficult for long-haul and wide-body operations [5]. Within this context, sustainable aviation fuel (SAF) is widely regarded as the most practical near- to medium-term decarbonization route because it can reduce lifecycle emissions while remaining compatible with existing turbine technology [6,7].

SAF is best understood as a portfolio of fuels rather than a single product. Depending on the feedstock and conversion route, it can be produced from waste lipids, lignocellulosic residues, sugars, alcohols, captured CO_2, and renewable hydrogen. Its principal strategic advantage is drop-in use: SAF can be blended with conventional Jet A-1 and distributed through today's aircraft and airport fuel systems with little or no hardware modification. Reported lifecycle GHG reductions generally range from roughly 50% to 90%, with the upper end associated with waste-derived and synthetic low-carbon pathways [8,9].

Despite this promise, current deployment remains marginal relative to aviation fuel demand. Production is held back by the high cost of low-carbon fuel manufacture, limited availability of sustainable feedstocks, competition from other sectors for waste oils and biomass, and the slow pace of certification and project finance closure [10–13]. These constraints mean that the central question is no longer whether SAF is technically possible, but how rapidly different pathways can be expanded without shifting environmental burdens elsewhere.

At the same time, the policy environment is becoming more consequential. Frameworks such as ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), the European Union's renewable fuel mandates, and U.S. incentive structures are beginning to create stronger demand signals [14,15]. Even so, persistent fragmentation across regions, inconsistent sustainability criteria, and uneven infrastructure readiness continue to complicate market formation and investment decisions.

This review therefore provides a critical assessment of SAF from a systems perspective. It examines feedstock classes, conversion pathways, environmental performance, cost drivers, certification requirements, and deployment readiness, and it identifies the technical and institutional conditions most likely to accelerate SAF adoption at scale.

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Nomenclature

Abbreviation	
SAF	Sustainable Aviation Fuel
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
HEFA	Hydroprocessed Esters and Fatty Acids
FT	Fischer-Tropsch
ATJ	Alcohol-to-Jet
PtL	Power-to-Liquid
ASTM	American Society for Testing and Materials
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation

Symbol	
η	Efficiency
Q	Energy content
C_e	Emission factor

2. Methodology

The review was designed as a structured evidence synthesis intended to capture both the technical depth and the policy breadth of the SAF literature. Rather than relying on a purely narrative survey, the methodology combined systematic searching, rule-based screening, and thematic synthesis so that engineering, economic, and regulatory evidence could be interpreted within a common framework.

Literature was collected from Scopus, Web of Science, ScienceDirect, and Google Scholar using search combinations built around terms such as "sustainable aviation fuel," "biojet fuel," "HEFA," "Fischer–Tropsch jet," "alcohol-to-jet," "power-to-liquid," "life cycle assessment," and "techno-economic analysis." Boolean operators and date filters were used to improve relevance, with primary emphasis placed on publications from 2005–2024 and stronger weighting given to studies published after 2015.

Peer-reviewed papers were supplemented with authoritative grey literature from ICAO, IEA, the U.S. Department of Energy, the European Commission, and related institutional sources in order to capture certification updates, policy developments, and industrial deployment data that are not always reported in journal articles. Only sources that provided sufficient methodological transparency or directly relevant quantitative information were retained for detailed analysis.

Table 1. Literature Sources and Inclusion — summarizes the number of SAF-related articles identified and included from each major database and grey literature source.

Database/Source	Articles Identified	Articles Included
Scopus	48	28
Web of Science	42	24
ScienceDirect	55	35
Google Scholar	61	31
IEA Reports	10	8
ICAO Reports	8	6

Eligibility criteria focused on four dimensions: direct relevance to SAF feedstocks or conversion routes; availability of quantitative indicators such as fuel yield, lifecycle emissions, or production cost; usefulness for understanding commercialization or policy design; and transparency of analytical boundaries, especially in LCA and TEA studies. Studies centered exclusively on upstream agriculture, non-aviation fuels, or generic biomass valorization were excluded unless they offered transferable insights.

The final corpus was coded by topic area—including feedstocks, pathways, lifecycle impacts, techno-economics, certification, and market development—and key metrics were extracted into comparative tables. Figures in this manuscript were then redrawn from the synthesized evidence base to present the comparative trends more clearly and in a consistent visual format.

Table 2. Selection Criteria for Inclusion — outlines the methodological inclusion rules and corresponding reasons for exclusion.

Criteria	Included Studies (n=138)	Excluded if
Technical focus on SAF	Yes	Focused only on upstream agriculture
Quantitative performance data	Yes	Lacked specific data on SAF yields or emissions
Relevance to policy or deployment	Yes	Covered non-aviation fuels only
Transparency of LCA/TEA methods	Yes	No methods or unclear LCA boundaries
SAF feedstock or conversion scope	Yes	Focused solely on fossil or unrelated processes

3. Results

3.1. Overview of SAF Pathways and Deployment Status

SAF encompasses several families of low-carbon jet fuels derived from renewable or waste-based carbon sources. By 2024, multiple pathways had progressed through ASTM D7566 approval, while others were advancing through demonstration and pre-certification stages. Taken together, these routes illustrate that SAF commercialization is not a single-technology transition but a widening portfolio strategy.

Hydroprocessed esters and fatty acids (HEFA) remain the most mature commercial pathway. Using feedstocks such as used cooking oil, tallow, and related lipid streams, HEFA plants benefit from comparatively high conversion yields and relatively well-understood process configurations. For that reason, HEFA still supplies the largest share of global SAF output.

The strength of HEFA lies in process simplicity and near-term deployability, but its expansion is bounded by feedstock scarcity. Waste lipids are finite, geographically uneven, and increasingly contested by road transport and renewable diesel markets. As SAF demand rises, this feedstock ceiling becomes a structural limitation rather than a temporary market hurdle.

Fischer–Tropsch (FT) routes offer a broader feedstock base because they can convert lignocellulosic biomass, agricultural residues, and municipal solid waste into synthetic paraffinic kerosene. That flexibility makes FT attractive for long-term scale-up, especially where waste management and biomass logistics can be integrated. Its slower diffusion to date is mainly a consequence of capital intensity, syngas conditioning complexity, and the challenge of establishing reliable large-volume feedstock supply chains.

Alcohol-to-jet (ATJ) pathways occupy an intermediate position. They draw on ethanol or isobutanol production platforms and then upgrade those intermediates through dehydration, oligomerization, and hydrogenation. ATJ benefits from links to established fermentation industries, but its economics remain sensitive to feedstock choice, hydrogen demand, and the number of upgrading steps required.

Power-to-liquid (PtL) fuels, often discussed as e-kerosene, represent the most synthetic end of the SAF spectrum. These routes use renewable electricity to generate hydrogen and combine it with concentrated or captured CO_2 to form liquid hydrocarbons. Although commercial deployment is still limited, PtL has become central to long-term aviation decarbonization scenarios because it is not inherently constrained by biomass availability.

Other emerging options—including catalytic hydrothermolysis, upgraded fast pyrolysis oils, and integrated biorefinery concepts—seek to improve carbon efficiency, broaden feedstock tolerance, or reduce external hydrogen demand. Their commercial contribution remains small today, but they highlight the continuing diversification of the SAF innovation landscape.

Figure 1 presents a lollipop-style chronology of certification and market milestones, showing how the sector has moved from a small number of approved routes to a broader and more investment-intensive technology portfolio.

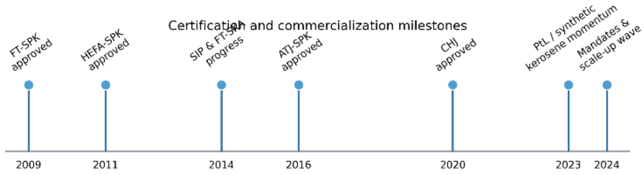

Fig 1. Lollipop chronology of SAF certification and commercialization milestones.

3.2. Fuel Yields and Process Efficiencies

Fuel yield and overall process efficiency are foundational indicators of SAF viability because they determine feedstock demand, energy use, and cost exposure across the value chain. High-yield pathways reduce pressure on scarce resources, whereas low-yield pathways generally require stronger policy support or lower-cost inputs to remain competitive.

HEFA typically delivers the highest liquid fuel yield among commercial SAF pathways, often reaching approximately 80–90% on a feedstock-mass basis [1,2]. This strong performance reflects the structural similarity between lipid feedstocks and jet-range hydrocarbons, which limits carbon losses during upgrading.

Process efficiencies for HEFA are also comparatively favorable, but they remain strongly influenced by the source and cost of hydrogen [3]. Accordingly, the main bottleneck for HEFA is not conversion chemistry but the limited and increasingly expensive pool of sustainable lipid feedstocks [4].

FT pathways generally produce lower jet fuel yields than HEFA, commonly in the range of roughly 35–45% of dry feedstock input depending on gasifier design, syngas quality, and downstream integration [5,6]. Even so, the pathway gains strategic value from its ability to utilize low-cost residues and heterogeneous solid wastes.

Where heat recovery, cogeneration, or broader biorefinery integration are implemented, FT process efficiency can improve substantially [7]. Without such integration, however, gasification-based schemes remain energy intensive and capital heavy, which slows their commercial rollout.

ATJ pathways usually deliver intermediate performance, with fuel yields often reported near 60–65% of alcohol feed input [8,9]. Their appeal lies in the availability of fermentation know-how, but the pathway still carries penalties associated with multiple upgrading steps and relatively high hydrogen consumption.

PtL systems are better interpreted through electricity-to-fuel efficiency than through mass yield. Current plants commonly convert only about 35–45% of input electrical energy into liquid hydrocarbons [11], yet the pathway remains compelling because it can couple aviation fuel supply to low-carbon power systems rather than to biogenic carbon availability.

The dumbbell comparison in Figure 2 shows this contrast clearly: HEFA leads on direct fuel yield, ATJ occupies a middle position, FT sacrifices yield for feedstock flexibility, and PtL trades conversion efficiency for the prospect of very deep decarbonization.

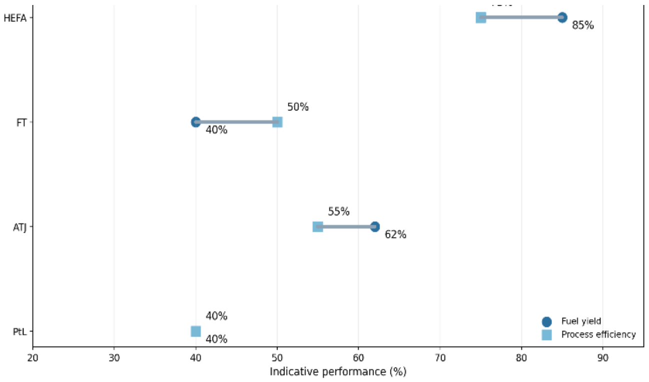

Fig 2. Dumbbell comparison of indicative yield and process efficiency across major SAF pathways.

3.3. Lifecycle GHG Emissions and Climate Benefits

Lifecycle greenhouse gas assessment is essential because the climate value of SAF is determined far more by upstream processes than by tailpipe CO_2 alone. Feedstock cultivation or collection, hydrogen supply, electricity source, transport logistics, land-use change, and process heat all influence the final well-to-wake balance.

Waste-based HEFA pathways generally show some of the strongest near-term GHG performance among commercial SAF routes.

When derived from used cooking oil or animal fats, HEFA can often achieve reductions on the order of 75–90% relative to conventional jet fuel because upstream cultivation burdens are limited and waste diversion may avoid additional emissions [16,17].

That result does not apply uniformly across all lipid feedstocks, however. HEFA produced from virgin vegetable oils can perform much worse once indirect land-use change is considered, particularly where oil crop expansion is linked to deforestation or peatland disturbance [18].

FT fuels produced from municipal solid waste, forestry residues, or agricultural residues typically achieve large lifecycle savings as well, commonly around 70–85% under favorable assumptions [19,20].

Their performance depends on the carbon intensity of process energy and on whether carbon capture is integrated into the gasification and synthesis train.

With carbon capture and storage, some FT configurations can approach or exceed the highest reduction bands reported in the literature [21].

ATJ performance is more variable, often ranging from roughly 40% to 70% depending on both feedstock origin and process energy mix. As a result, the same pathway label can represent very different climate outcomes across regions and supply chains.

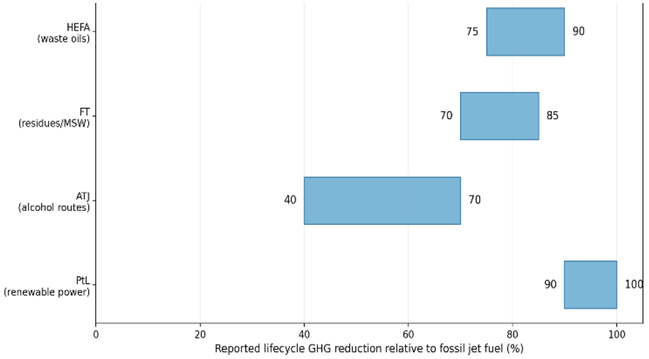

Fig 3. Range-based comparison of reported lifecycle GHG reductions for major SAF pathways.

Sugarcane-derived alcohols processed in low-carbon energy systems generally outperform corn-based routes, while lignocellulosic alcohols offer a pathway to deeper reductions if commercial maturity can be improved [22,23].

PtL fuels offer the highest theoretical abatement potential because carbon is introduced through CO_2 and hydrogen rather than through biomass, and because the pathway can be paired with renewable electricity and direct air capture [24,25].

Their actual performance, however, is extremely sensitive to power-sector carbon intensity. If electrolyzers are supplied with carbon-intensive grid electricity, PtL can lose much of its climate advantage or even underperform conventional fuels [26].

Figure 3 therefore presents lifecycle performance as reduction ranges rather than as single-point values, emphasizing that pathway labels alone are poor predictors of climate benefit.

The central implication is that SAF policy should reward verified lifecycle outcomes, not only pathway type or feedstock category.

3.4 Economic Viability and Cost Breakdown

Economic performance remains the most immediate barrier to large-scale SAF deployment. Even when technical feasibility is established, most pathways still produce fuel at a substantial premium to fossil jet fuel, especially under volatile feedstock and electricity markets [27].

HEFA is currently the closest pathway to commercial cost competitiveness, with reported production costs often near USD 1.0–1.2 per liter when low-cost waste lipids are available [28].

That advantage is fragile because HEFA economics are dominated by feedstock price. In many assessments, oils and fats account for the majority of total production cost, which means that competition for waste lipids can quickly erode the pathway’s cost lead [29,30].

FT pathways are typically more capital intensive, with production costs often estimated around USD 1.5–2.0 per liter depending on scale, feedstock quality, and plant integration [31].

Their economics improve when waste-handling fees, cogenerated utilities, or carbon credits can be captured, but first-of-a-kind plants still face long payback periods and significant financing risk [32].

ATJ pathways generally occupy an intermediate cost band. Existing fermentation infrastructure can reduce some capital requirements, yet the cost of upgrading alcohol intermediates and supplying hydrogen keeps total fuel cost elevated [33].

Regional context also matters strongly for ATJ. Sugarcane-based systems may be more favorable where low-cost ethanol already exists, while corn-based routes face added emissions and feedstock market competition.

PtL remains the most expensive major SAF option, with many recent estimates extending from roughly USD 2.5 per liter to well above USD 4.0 per liter [34].

The dominant cost driver is green hydrogen, which can contribute more than half of total production cost when electricity prices or electrolyzer utilization are unfavorable [35].

Even so, PtL costs are expected to decline as renewable power becomes cheaper, electrolyzer deployment expands, and synthetic fuel plants move down the learning curve [36].

Because of this cost structure, long-term contracts, carbon pricing, tax credits, and capital support are not peripheral policy tools; they are central conditions for market formation.

Figure 4 uses stacked bars to distinguish the relative contributions of feedstock or carbon input, operating expenditure, and capital recovery across the principal pathways.

The comparison highlights a feedstock-led HEFA cost profile, a capital-heavy FT profile, a mixed ATJ structure, and the electricity-and-hydrogen burden that currently defines PtL.

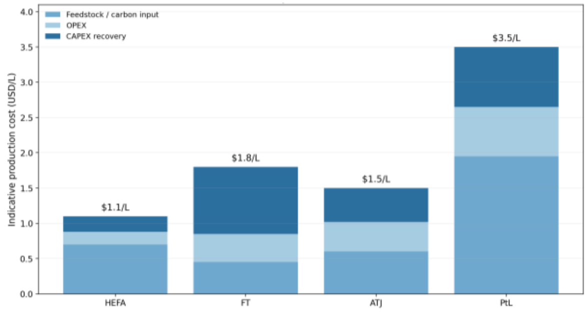

Fig 4. Stacked cost profiles showing indicative CAPEX, OPEX, and feedstock or carbon-input shares by pathway.

3.5 Feedstock Sustainability and Resource Availability

Feedstock availability is the pivot around which SAF scalability turns. A pathway may be technically robust and environmentally attractive, but if its carbon source cannot be supplied at sufficient volume under acceptable sustainability criteria, it cannot support aviation-scale deployment.

Waste lipids used in HEFA are attractive because they typically carry low upstream burdens and can deliver strong lifecycle GHG performance.

Their global supply, however, is limited; most assessments conclude that waste oils and fats can satisfy only a small fraction of total jet fuel demand, while competition from renewable diesel and biodiesel further tightens the market [37,38].

Virgin vegetable oils are more abundant, but they introduce much greater sustainability risk because they can be associated with deforestation, peatland degradation, and biodiversity loss unless sourcing controls are exceptionally stringent [39].

For that reason, the apparent scale advantage of crop oils is not equivalent to a sustainable scale advantage.

Lignocellulosic biomass represents one of the largest long-term renewable carbon pools for SAF production. Agricultural residues, forestry wastes, and some energy crops can support FT and advanced ATJ pathways without directly competing with food markets [40].

Yet this potential is not frictionless. Low bulk density, dispersed supply, seasonal availability, and pre-treatment requirements increase logistics cost and complicate continuous industrial operation.

Sugars and starches currently function mainly as transitional feedstocks for ATJ because they are supported by established fermentation infrastructure.

Their sustainability profile varies substantially: Brazilian sugarcane can be comparatively favorable, whereas more input-intensive crop systems may carry higher land-use, water, and indirect emission burdens [41,42].

The long-term strategic direction is therefore toward second-generation alcohols derived from lignocellulosic resources rather than continued dependence on food-grade feedstocks.

PtL routes replace biomass dependence with dependence on CO_2 and renewable hydrogen. In principle, CO_2 can be sourced from biogenic streams, industrial emissions, or direct air capture.

Direct air capture offers the strongest long-term scalability narrative, but at present it remains energy intensive and expensive [43].

Hydrogen is the more immediate bottleneck. The availability of low-cost green hydrogen will determine how quickly PtL can transition from niche demonstration to large-scale supply [44].

The bubble chart in Figure 5 summarizes this trade-off between sustainable resource potential and deployment difficulty, showing that high theoretical potential does not automatically translate into easy near-term scale-up.

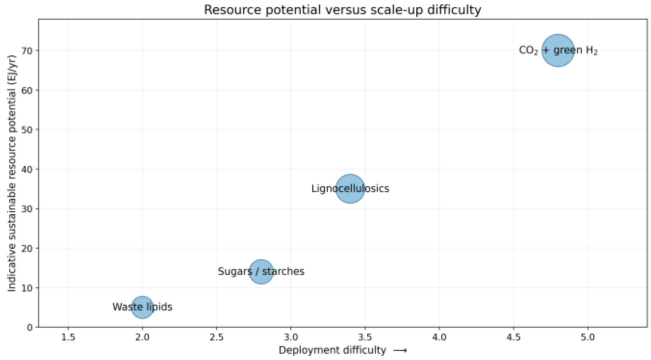

Fig 5. Bubble plot of indicative sustainable resource potential versus deployment difficulty for major SAF feedstock classes.

3.6 Infrastructure Compatibility and Certification

Infrastructure compatibility and certification are decisive because aviation fuel adoption is governed by safety, material compatibility, and operational reliability as much as by carbon performance.

ASTM D7566 remains the primary technical gateway for SAF approval. It defines the properties required for synthesized blending components before they can enter commercial aviation fuel pools under conventional jet fuel specifications [45].

By 2024, several pathways—including HEFA, FT-based routes, ATJ, catalytic hydrothermolysis, synthesized iso-paraffins, and PtL-derived synthetic kerosenes—had either secured approval or advanced through important approval milestones [46].

This progress demonstrates that the certification system can evolve, but it also underscores how long and evidence-intensive the process is for emerging fuels.

Blend limits remain pathway specific, often because many SAF products contain too little aromatic content to fully replicate all functions of fossil kerosene in legacy fuel systems.

That is why several approved pathways are presently capped at 10–50% blend ratios, while aromatic-containing routes are being pursued to enable higher fractions and ultimately neat SAF use.

Recent demonstration flights with 100% SAF have shown that higher-blend or neat-fuel operation is technically plausible, but widespread commercial use will still depend on standards development, materials validation, and fleet-wide acceptance [47].

A major advantage of SAF is that it can usually move through existing airport storage, pipeline, and hydrant systems, avoiding the radical infrastructure overhaul that would accompany hydrogen or battery-electric aviation.

The remaining challenge is not basic compatibility but logistics: fuel production often occurs far from airports, so transport, blending, certification documentation, and chain-of-custody management all become critical parts of the deployment problem.

In practice, certification progress and supply-chain integration must advance together if approved SAF pathways are to move from isolated projects to routine airport fuel supply.

Table 5. ASTM-Certified SAF Pathways and Blending Limits

Pathway	Feedstock Type	Max Blend Limit (%)	ASTM Approval Year
HEFA-SPK	Used Cooking Oil, Animal Fats	50	2011
FT-SPK	MSW, Agricultural Residues, Biomass	50	2009
FT-SKA	Same as FT-SPK, but with aromatics	100	2015
ATJ-SPK	Sugars, Starches, Alcohols	50	2016
CHJ	Oils via hydrothermolysis	50	2020
SIP	Sugar fermentation (farnesene)	10	2014
PtL (FT-based)	$CO_2 + H_2$ via FT synthesis	50	2023

3.7 Regional and Global Production Capacity

Global SAF production capacity has expanded rapidly in percentage terms, yet it remains very small in absolute terms compared with aviation fuel demand.

Output in 2023 was still well below 1% of total jet fuel consumption, while long-term net-zero scenarios imply the need for hundreds of billions of liters per year by mid-century [49].

The current market is dominated by a small number of HEFA-oriented producers operating mainly in North America, Europe, and selected Asian refining hubs.

ATJ and FT projects are progressing, but many remain at demonstration or early commercial scale, which means that their contribution to aggregate supply is still modest.

Figure 6 recasts regional production capacity as a circular comparison, illustrating the strong concentration of SAF supply in policy-active OECD markets and the still limited contribution of most other regions.

Policy remains the primary driver of that regional pattern. Mandates such as ReFuelEU Aviation, low-carbon fuel incentives in North America, and strategic industrial support have created the clearest market signals for project developers.

Asia is emerging as an increasingly important hub through refinery upgrades, export-oriented production, and national roadmaps in countries such as Singapore, Japan, South Korea, and China.

The Middle East is pursuing a different strategic position, with growing interest in PtL aligned to renewable electricity and green hydrogen ambitions.

Several barriers continue to restrict the pace of capacity growth.

Near-term expansion is limited by sustainable lipid availability, which means that HEFA cannot carry the entire scale-up burden on its own.

At the same time, FT and PtL projects face heavy capital requirements and depend on durable policy certainty or long-term offtake agreements to reach financial close.

Infrastructure for storage, blending, traceability, and certification is also unevenly distributed, particularly outside the most advanced aviation fuel markets.

Finally, fragmented regional rules and inconsistent sustainability requirements complicate international trade and discourage the development of globally integrated supply chains.

The capacity challenge is therefore not simply a matter of building more plants; it is a market-structuring challenge that links industrial policy, feedstock governance, and infrastructure planning.

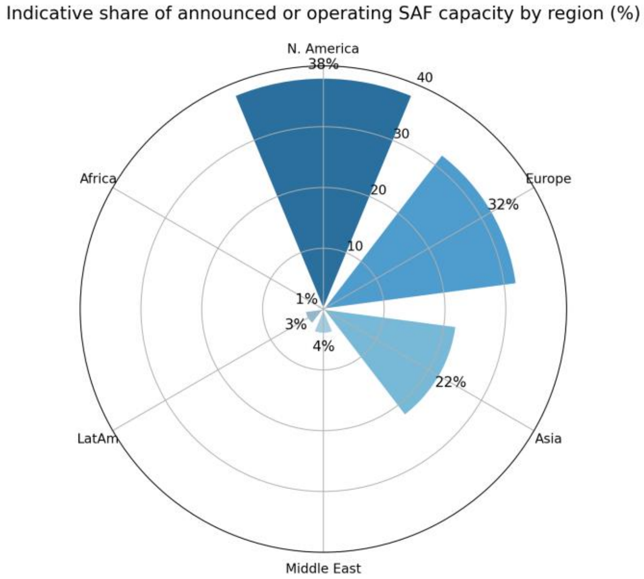

Fig 6. Circular regional comparison of indicative announced or operating SAF production capacity in 2024.

3.8 Energy and Water Footprint

Beyond carbon intensity, SAF pathways must also be evaluated through their broader energy and water footprints. These metrics are particularly important in regions where energy systems are still carbon intensive or where water scarcity can constrain industrial expansion.

HEFA generally exhibits the lowest process energy demand among the major pathways because it upgrades molecules that are already relatively close to jet-range hydrocarbons.

Its overall burden nevertheless depends strongly on how hydrogen is produced; low-carbon hydrogen can improve environmental performance, whereas fossil-derived hydrogen weakens it.

FT routes are more energy intensive because they require feedstock preparation, gasification, syngas cleanup, and catalytic synthesis in sequence [51].

Their performance improves when waste heat is recovered or when the facility is integrated into a broader industrial energy system, but the baseline process remains demanding.

ATJ pathways sit between HEFA and FT: fermentation can be mature and efficient, yet dehydration, oligomerization, and finishing steps still impose notable energy penalties.

PtL is typically the most electricity-intensive option because hydrogen generation dominates the energy balance. That characteristic is not inherently disqualifying, but it means that PtL scale-up is inseparable from the availability of abundant low-cost renewable power.

Water demand adds another layer of differentiation. Bio-based routes may consume water both in feedstock production and within the fuel conversion process, which can be significant for irrigated crops or wet biomass systems.

FT pathways based on residues avoid much of the agricultural water burden associated with dedicated crops, although process water is still needed for cooling, cleaning, and gas handling.

PtL often has lower direct water demand for synthesis than irrigated biomass systems, but electrolysis still requires purified water and the supporting renewable power infrastructure can carry its own regional water implications.

These trade-offs matter sharply in arid and water-stressed regions, where low-water pathways or desalination-integrated industrial systems may be more appropriate than conventional biomass-dependent routes.

Accordingly, SAF planning should be based on integrated energy–water–carbon assessment rather than on carbon metrics alone.

3.9 Land Use Impacts and Biodiversity Risks

Land-use performance remains one of the most contested dimensions of SAF sustainability because carbon savings can be undermined if fuel expansion drives cropland conversion, habitat loss, or indirect market-mediated land change.

First-generation feedstocks such as oil crops, corn, and sugar crops usually impose the largest direct land requirements, especially when high volumes are needed for aviation-scale supply.

Dedicated energy crops can offer better yield per hectare and potentially lower input intensity than conventional food crops, but they still require careful siting if biodiversity loss and land competition are to be minimized.

Indirect land-use change (ILUC) arises when existing agricultural land is diverted toward fuel production and displaced food or feed demand drives expansion elsewhere.

Although ILUC is difficult to quantify precisely, it cannot be treated as negligible because it can materially alter the climate case for some biomass-based pathways.

Certification systems increasingly attempt to address this risk through feedstock eligibility rules, traceability requirements, and exclusion of high-risk land categories.

Biodiversity concerns extend beyond carbon accounting. Large monocultures, habitat fragmentation, and pressure on high-value ecosystems can all accompany poorly governed biofuel expansion.

Residue-based pathways, agroforestry systems, and carefully managed marginal-land strategies generally present lower biodiversity pressure and are therefore more consistent with robust sustainability governance.

Among the major options, PtL has the lowest intrinsic land-use dependence because its primary inputs are CO_2 and renewable electricity rather than biomass carbon.

Figure 7 provides a heat-map style sustainability screening across land, water, feedstock scale, and commercialization readiness, illustrating that the most scalable pathways are not always the easiest to deploy and that the lowest-land options can remain highly energy dependent.

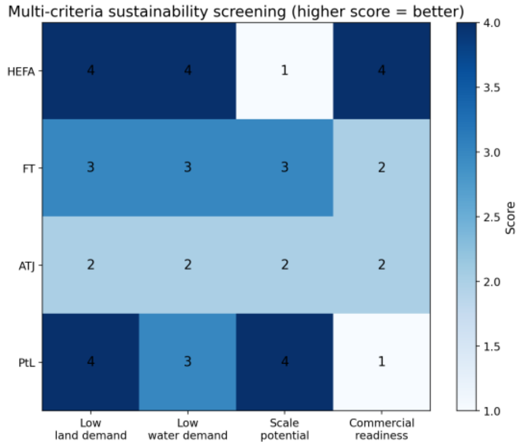

Fig 7. Heat-map screening of major SAF pathways across land, water, scalability, and readiness criteria.

4. Discussion

The evidence synthesized in this review shows that SAF development is best understood as a systems transition rather than a single-fuel substitution. Each pathway resolves one constraint while intensifying another: HEFA offers strong near-term practicality but limited feedstock scale, FT broadens the resource base at the expense of capital complexity, ATJ leverages fermentation infrastructures but still faces cost and sustainability variability, and PtL promises deep decarbonization while depending on abundant renewable electricity and green hydrogen.

4.1 Systems-Level Trade-offs

The central trade-off in SAF deployment is the tension between near-term feasibility and long-term scalability. Pathways that are commercially closest today are not necessarily those most capable of serving future aviation demand, whereas pathways with the strongest long-run decarbonization logic still require major upstream energy and infrastructure transitions.

HEFA illustrates this pattern clearly: it is commercially proven and often climate beneficial, yet it relies on a narrow pool of sustainable lipids that cannot plausibly satisfy a large fraction of global jet demand.

PtL sits at the opposite end of the spectrum. Its carbon and land-use profile can be exceptionally strong, but only when low-carbon electricity, hydrogen, and CO_2 supply chains are available at very large scale.

FT and advanced ATJ routes therefore deserve particular attention as bridging options because they can expand the carbon resource base through residues and wastes while avoiding exclusive dependence on lipid markets.

The review also indicates that cost competitiveness and climate performance do not automatically align. Policy support must therefore reward verified lifecycle outcomes and not merely the existence of a nominal SAF project or pathway label.

Certification is another strategic bottleneck. Aviation cannot compromise on fuel safety, yet protracted qualification timelines can delay the market entry of otherwise promising fuels and slow the accumulation of operational experience.

A broader definition of sustainability is equally necessary. Carbon metrics must be evaluated alongside land occupation, water demand, biodiversity pressure, and feedstock governance if SAF is to avoid reproducing the unintended consequences associated with earlier biofuel expansion.

For that reason, regional SAF strategies should be differentiated: biomass-rich regions may favor FT or advanced ATJ, while regions with strong renewable power potential and limited land or water may be better suited to PtL-led pathways.

4.2 Deployment Bottlenecks and Market Formation

Despite rising political and industrial interest, SAF deployment remains far below the scale required for meaningful sectoral decarbonization. Scaling from pilot projects to mainstream fuel supply will require a pace of industrial expansion that is unusual even by energy-transition standards.

The transition now depends less on proof of concept and more on market design. Long-term offtake agreements, contracts for difference, tax incentives, loan guarantees, and carbon-price support are essential to move capital toward first-of-a-kind and early commercial plants.

Industrial clustering can further reduce risk by locating SAF production near feedstock sources, renewable energy assets, CO_2 supply, or major airport demand centers, thereby lowering logistics costs and improving infrastructure utilization.

International coordination will also matter. Without greater alignment in sustainability criteria, certification practice, and accounting rules, SAF markets may fragment into regional niches rather than maturing into a globally tradable low-carbon fuel system.

An equitable transition should remain part of this agenda. Countries with limited fiscal space or weaker fuel infrastructure may otherwise be excluded from SAF adoption despite being highly dependent on aviation connectivity.

The next decade will therefore determine whether SAF becomes a genuine decarbonization pillar for long-haul aviation or remains confined to premium low-volume markets.

Success will depend on coordinated advances in feedstock mobilization, clean hydrogen deployment, certification, infrastructure, and durable policy support.

5. Conclusion

Sustainable aviation fuel remains the most practical decarbonization option currently available for much of global aviation, particularly for long-haul operations where direct electrification and hydrogen face substantial constraints. The literature reviewed here confirms that SAF can deliver meaningful lifecycle emissions reductions, but it also shows that those reductions are conditional rather than automatic.

No single SAF pathway is sufficient on its own. HEFA is important for near-term market growth, FT and advanced ATJ can expand the sustainable carbon resource base, and PtL is likely to be indispensable for deep long-term decarbonization once renewable electricity and green hydrogen become more widely available.

Climate performance varies strongly with feedstock source, electricity mix, hydrogen pathway, and land-use effects. Accordingly, SAF governance should prioritize measured lifecycle performance and robust sustainability safeguards rather than broad pathway labels alone.

The same principle applies to scale. Feedstock availability, logistics, land and water constraints, certification timelines, and financing conditions all determine whether a pathway can move beyond demonstration and contribute meaningfully to global fuel supply.

Economic barriers remain substantial, especially for capital-intensive or electricity-intensive routes. Stable demand signals and risk-sharing instruments will therefore be essential if private investment is expected to deliver commercial-scale plants at the pace required.

At the infrastructure level, progress is encouraging: existing aircraft and fuel systems can absorb increasing quantities of approved SAF, and continued movement toward higher blend limits or neat-fuel approval could significantly strengthen the decarbonization impact of deployment.

Looking ahead, SAF should be approached as an integrated industrial strategy linking energy, carbon management, land stewardship, and aviation operations rather than as a narrow fuel-substitution exercise.

Pathway choice should be regionally differentiated, policy frameworks should reward verified sustainability performance, and international cooperation should reduce fragmentation in standards and market access.

If those conditions are met, SAF can evolve from a promising mitigation option into a central pillar of net-zero aviation.

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