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# Sustainable Aviation Fuels Versus Conventional Jet Fuel: Emissions, Climate Effects, and Deployment Challenges A Comparative Review

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**Abstract:** Sustainable aviation fuel (SAF) is being developed as a lower-lifecycle-greenhouse-gas (GHG) alternative to conventional petroleum-derived aviation turbine fuel. Its environmental performance, however, is not uniform: it depends on feedstock origin, conversion pathway, process energy, hydrogen source, transport, land-use effects, and lifecycle-assessment (LCA) assumptions. This structured narrative review compares SAF with conventional Jet A-1 across lifecycle GHG emissions, selected non-$CO_2$ climate effects, fuel pathways and technical compatibility, production scale, cost, feedstock constraints, and policy. Particular attention is given to the ECLIF3 flight campaign, which measured 35% fewer soot particles and 56% fewer contrail ice particles per unit mass of fuel burned for 100% HEFA-SPK than for the reference Jet A-1 under the tested cruise conditions. A global climate-model simulation in the same study estimated a 26% reduction in contrail radiative forcing for a modelled 2018 fleet scenario; this is a model result, not a direct measurement of global temperature change. IATA estimated SAF production at approximately 1 million tonnes in 2024 and projected 1.9 million tonnes in 2025 and 2.4 million tonnes in 2026, equivalent to approximately 0.6% and 0.8% of jet-fuel consumption in 2025 and 2026, respectively. The review finds that SAF can deliver substantial lifecycle GHG reductions when produced through well-performing pathways, but its deployment is constrained by price premiums, finite sustainable feedstocks, conversion capacity, and inconsistent LCA assumptions. SAF should therefore be evaluated pathway by pathway and deployed alongside aircraft-efficiency improvements, operational measures, and other climate-mitigation strategies.

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## 1.Introduction

Commercial aviation influences the climate through carbon dioxide ($CO_2$) released during fuel combustion and through non-$CO_2$ processes involving nitrogen oxides ($NO_x$), water vapour, soot, sulphur-containing particles, and contrail cirrus. The magnitude and relative importance of these effects depend on the climate metric, time horizon, atmospheric conditions, and uncertainty treatment. Lee et al. (2021) estimated that non-$CO_2$ effects accounted for approximately 66% of aviation's net effective radiative forcing in 2018. This figure describes a contribution to a climate-forcing metric; it is not a share of aircraft exhaust mass, fuel consumption, or total greenhouse-gas emissions. Contrail cirrus, $CO_2$, and $NO_x$ were identified as major contributors, while several aerosol-related effects remain uncertain.

SAF is an umbrella term for aviation turbine fuels produced from eligible non-fossil or recycled-carbon sources and meeting relevant technical and sustainability requirements. Pathways include hydroprocessed esters and fatty acids (HEFA), alcohol-to-jet (ATJ), gasification followed by Fischer–Tropsch synthesis (FT), and power-to-liquid (PtL) processes. These routes differ in feedstock, energy demand, maturity, fuel properties, cost, and lifecycle GHG

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intensity. Consequently, statements about SAF should identify the pathway and comparison basis rather than imply that all fuels marketed as sustainable perform identically (Watson et al., 2024; Shahriar & Khanal, 2022).

This review compares SAF with conventional Jet A-1 across lifecycle emissions, non-$CO_2$ effects, technical compatibility, supply and cost, feedstock sustainability, and policy. It prioritizes peer-reviewed research and authoritative institutional sources, while distinguishing measured findings from modelled estimates, industry forecasts, and regulatory targets.

**Table-1. Comparative Summary of Sustainable Aviation Fuel (SAF)**

| Dimension | Conventional Jet A-1 | Sustainable aviation fuel (SAF) |
|---|---|---|
| Carbon accounting | Fossil-derived carbon; combustion transfers geological carbon to the atmosphere as $CO_2$. | Lifecycle performance depends on feedstock, conversion route, process energy and land-use effects. |
| Lifecycle GHGs | Reference baseline for like-for-like LCA. | Can be substantially lower for selected pathways; reductions are pathway- and methodology-specific. |
| Soot and contrails | Emissions depend on fuel composition, engine and operating conditions. | Some low-aromatic/low-Sulphur SAFs can reduce soot and contrail ice formation; effects are not universal. |
| $NO_x$ | Primarily influenced by combustor design and operating conditions. | No universal reduction factor; compare under equivalent engine and test conditions. |
| Technical use | Established fuel specification and global supply infrastructure. | Certified blending components have pathway-specific limits under ASTM specifications. |
| Supply and price | Large-scale established supply chain. | Production remains a small share of jet-fuel use and generally carries a price premium. |

## 2. Review Methodology

This article adopts a structured narrative-review approach rather than a systematic review or meta-analysis. The evidence base was assembled from peer-reviewed studies and authoritative institutional material published primarily between 2016 and 2026. Sources include research in Atmospheric Environment and Atmospheric Chemistry and Physics; guidance and datasets from the International Civil Aviation Organization (ICAO), the European Commission, the U.S. Department of Energy (DOE), and the International Air Transport Association (IATA); and technical summaries of ASTM-qualified fuel pathways.

Evidence was organised into five themes: (1) lifecycle GHG emissions and accounting boundaries; (2) exhaust emissions and contrail effects; (3) fuel pathways, standards, and aircraft compatibility; (4) production, feedstocks, and cost; and (5) policy and market development. Quantitative findings were retained where the source, metric, and comparison were identifiable. Flight measurements, lifecycle estimates, industry production forecasts, and regulatory targets were not pooled because they represent different evidence types and cannot be treated as directly comparable observations.

The review is not systematic. A reproducible database-by-database search protocol, formal screening flow diagram, duplicate-removal procedure, and quantitative risk-of-bias assessment were not conducted. The conclusions should therefore be interpreted as a critical synthesis of selected evidence rather than an exhaustive census of the SAF literature.

## 3. Lifecycle Greenhouse-Gas Performance

The principal climate rationale for SAF is the potential to reduce lifecycle GHG emissions relative to fossil-derived jet fuel. A lifecycle assessment extends beyond the aircraft engine and may include feedstock cultivation or collection, processing, transport, fuel conversion, distribution, combustion, and direct or indirect land-use change. ICAO's CORSIA methodology expresses fuel lifecycle emissions in grams of $CO_2$-equivalent per megajoule and

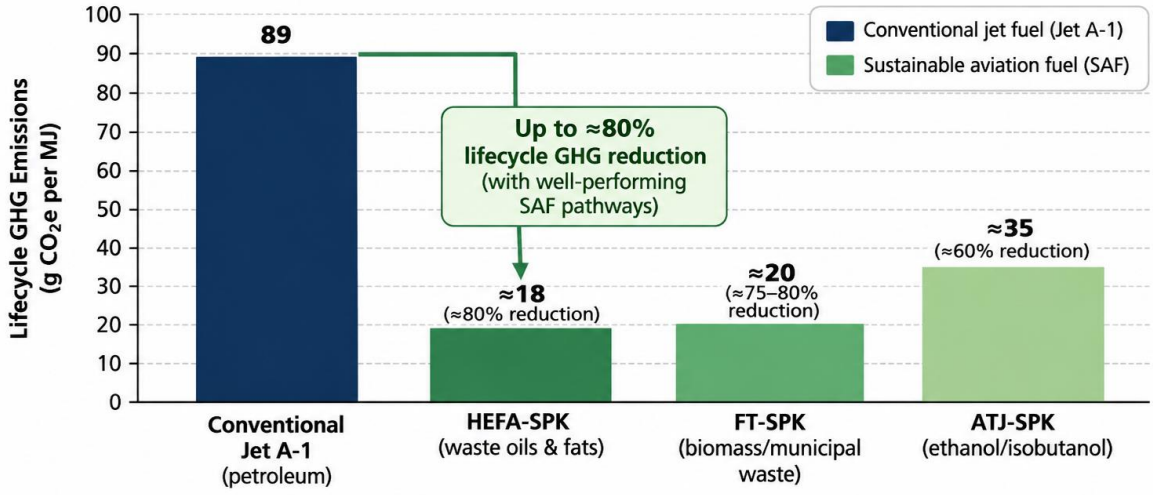
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accounts for core lifecycle emissions and applicable land-use effects and credits. The resulting value is therefore dependent on the defined system boundary and the applicable accounting method (ICAO, n.d.-b).

IATA reports that some SAF pathways can achieve lifecycle carbon reductions of around 80%, particularly when suitable waste- and residue-based feedstocks are used. This should be treated as an indicative result for favourable pathways, not as a guaranteed attribute of every SAF. The literature reports a wide range of outcomes because feedstock, conversion technology, electricity and hydrogen sources, co-product allocation, transport, and land-use assumptions vary. Watson et al. (2024) likewise identify substantial variation in cost and emissions estimates across technologies and studies.

**Figure 1. Lifecycle Greenhouse-Gas (GHG) Emissions: Conventional Jet Fuel vs. SAF Pathways**




***Note:*** *Values are indicative lifecycle estimates (g $CO_2$e per MJ) from the literature, illustrating typical reductions of ≈60–80% for favorable SAF pathways compared with conventional Jet A-1. Actual results vary with feedstock, conversion process, energy source, and lifecycle-assessment (LCA) assumptions.*

A critical distinction is that a lifecycle GHG reduction is not equivalent to the same percentage reduction in direct $CO_2$ emitted by an aircraft. Hydrocarbon SAF still releases $CO_2$ during combustion. The lifecycle benefit arises from the carbon source and the emissions associated with producing and supplying the fuel, as evaluated under a specified accounting framework. Claims of very high reductions should therefore state whether they refer to well-to-wake GHG emissions, combustion emissions, or another metric.

The choice of feedstock is especially important. Waste oils, fats, and residues may offer favourable results when their collection and alternative uses are properly accounted for. Conversely, purpose-grown crops can create emissions and ecological burdens through land-use change, fertiliser use, water demand, and competition with food or ecosystems. Even waste feedstocks are not impact-free: they have finite supply and may already serve other markets. The sustainability case must be established across the full supply chain, not inferred solely from the renewable origin of the carbon.

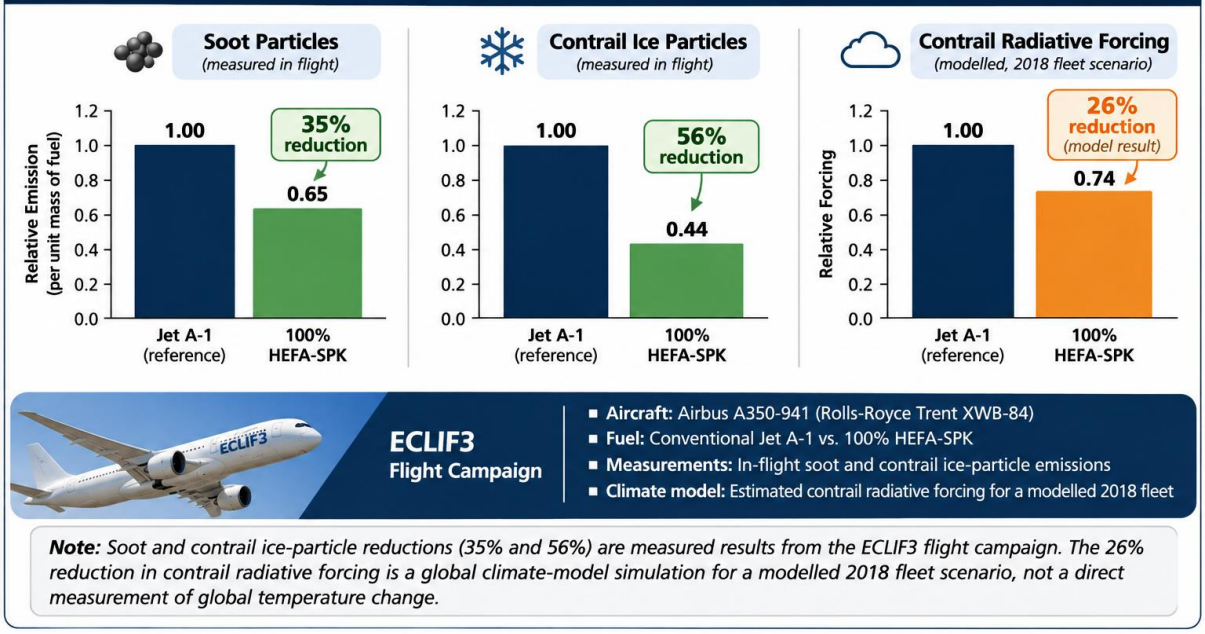
## 4. Non-$CO_2$ Emissions and the ECLIF3 Case Study

Aviation's non-$CO_2$ climate effects include contrail cirrus and chemically mediated effects associated with $NO_x$. Their magnitude depends on altitude, temperature, humidity, time of day, engine conditions, fuel composition, and flight trajectory. Contrails form when water vapour in aircraft exhaust mixes with sufficiently cold and humid ambient air; persistent contrails can evolve into cirrus-like cloud. Their net radiative effect varies with atmospheric and solar conditions. Fixed percentage allocations to $CO_2$, contrails, $NO_x$, and soot should therefore be avoided unless the metric, reference period, and uncertainty are clearly stated (Lee et al., 2021).

A notable experimental study is the ECLIF3 flight campaign reported by Märkl et al. (2024). An Airbus A350-941 equipped with Rolls-Royce Trent XWB-84 engines was operated using conventional Jet A-1 and 100% HEFA-SPK in a research campaign. A DLR Falcon 20 research aircraft sampled the exhaust plume and young contrails. Under the measured cruise conditions, the researchers reported a 35% reduction in soot particle number and a 56% reduction in contrail ice-particle number per mass of fuel burned for 100% HEFA-SPK compared with the reference Jet A-1.

The same study used global climate-model simulations to estimate a 26% decrease in contrail radiative forcing for a modelled 2018 fleet scenario. This result is a modelled estimate and should not be described as a directly measured reduction in global warming. The study provides evidence that fuel composition can influence soot emissions and contrail ice formation, but the size of the climate benefit depends on atmospheric conditions, engine characteristics, fuel composition, and modelling assumptions. It concerns a specific HEFA-SPK fuel and experimental campaign; it should not be generalized on every SAF pathway.

**Figure 2. ECLIF3 Experiment: Non-$CO_2$ Effects of 100% HEFA-SPK vs. Jet A-1**
Measured changes in particle emissions and modelled contrail climate effect




***Note:*** *Soot and contrail ice-particle reductions (35% and 56%) are measured results from the ECLIF3 flight campaign. The 26% reduction in contrail radiative forcing is a global climate-model simulation for a modelled 2018 fleet scenario, not a direct measurement of global temperature change.*

The available evidence does not justify assigning a universal $NO_x$ or particulate-matter reduction percentage to all SAF. $NO_x$ formation is strongly influenced by combustor temperature, pressure, design, and operating conditions, while particulate emissions depend on fuel composition and measurement method. Lower Sulphur content can reduce Sulphur-related emissions, but the magnitude depends on the Sulphur content of the fuels being compared. Future comparative tests should report engine type, operating point, blend ratio, ambient conditions, particle metric, and uncertainty.

## 5.Technical Compatibility and Fuel Pathways

SAF is generally designed to function as a drop-in aviation fuel after production and certification under applicable specifications. ASTM D7566 defines approved synthetic blending-component pathways and their conditions of use. The U.S. DOE Alternative Fuels Data Center summarises approved routes including FT-SPK, HEFA-SPK, hydroprocessed fermented sugars to synthetic isoparaffins, FT-SPK with aromatics, and ATJ-SPK, each with its own feedstock requirements and blending limit (U.S. DOE, n.d.).

For example, the DOE pathway summary lists maximum blend limits of 50% for FT-SPK, HEFA-SPK, FT-SPK/A, and ATJ-SPK, while certain other pathways have lower limits. The applicable ASTM edition and specification must be checked before publication or operational use because approvals and limits can change. A general statement that all SAF can be used neat at 100% in commercial service would therefore be inaccurate. The 100% HEFA-SPK use in ECLIF3 was part of a research campaign and should not be confused with unrestricted commercial approval.

Pathways differ in energy density, aromatic content, Sulphur content, cold-flow behaviour, thermal stability, and production requirements. These properties influence fuel handling, combustor behaviour, and emissions. Any claim about aircraft range or payload should be supported by pathway-specific fuel-property data and should distinguish gravimetric from volumetric energy density.

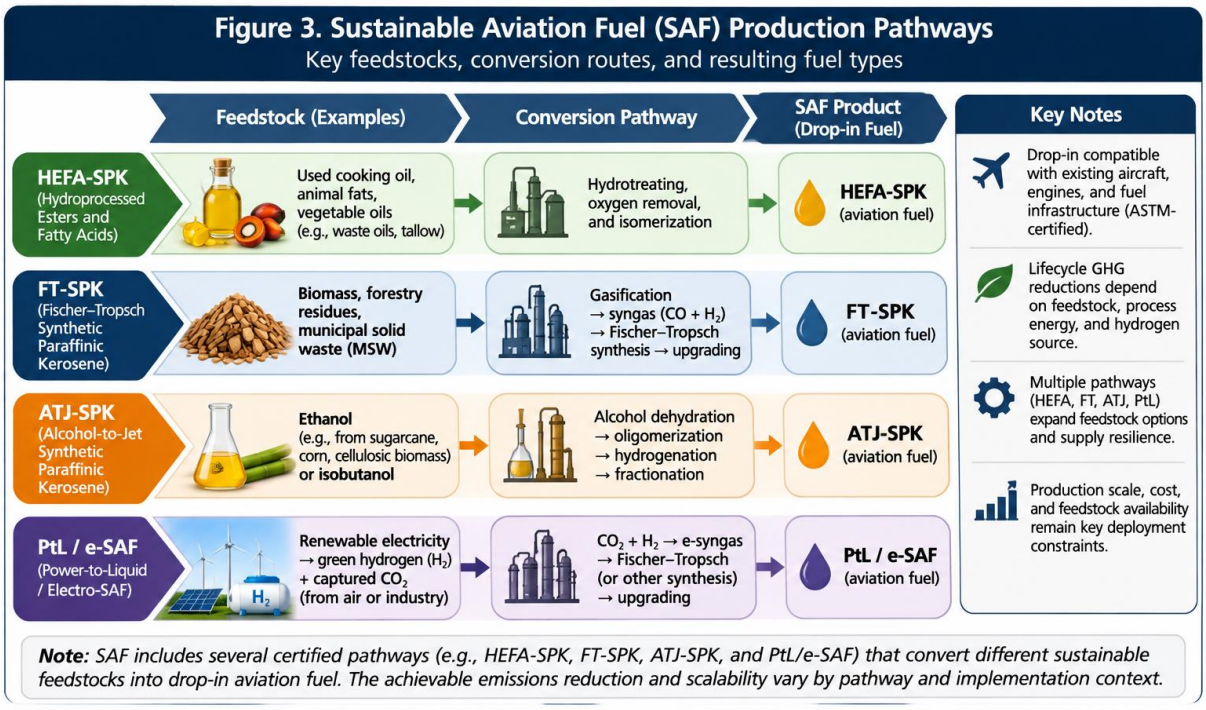
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**Table-2. Types of Sustainable Aviation Fuels**

| Pathway | Typical feedstock | Conversion route | Key consideration |
|---|---|---|---|
| HEFA-SPK | Used cooking oil, animal fats, vegetable oils | Hydrotreating, hydrocracking and isomerisation | Commercially mature; constrained by sustainable lipid availability. |
| FT-SPK | Forestry/agricultural residues, municipal solid waste, eligible biomass | Gasification followed by Fischer–Tropsch synthesis | Can use a broader range of solid feedstocks; capital and process complexity are significant. |
| ATJ-SPK | Ethanol or Isobutanol from eligible biomass or waste-derived sources | Alcohol dehydration, oligomerisation and upgrading | Potential to use established alcohol supply chains; lifecycle result depends strongly on alcohol source. |
| PtL / e-SAF | Low-carbon electricity, hydrogen and captured $CO_2$ | Electrolysis, $CO_2$ conversion and synthesis (often FT) | Potentially low lifecycle intensity with additional renewable electricity; high electricity and capital requirements. |

The pathway descriptions above are simplified categories rather than complete process specifications. Actual eligible feedstocks, process configurations, and blend limits must be checked against the relevant ASTM annex and sustainability scheme (U.S. DOE, n.d.; Bhatt et al., 2023).



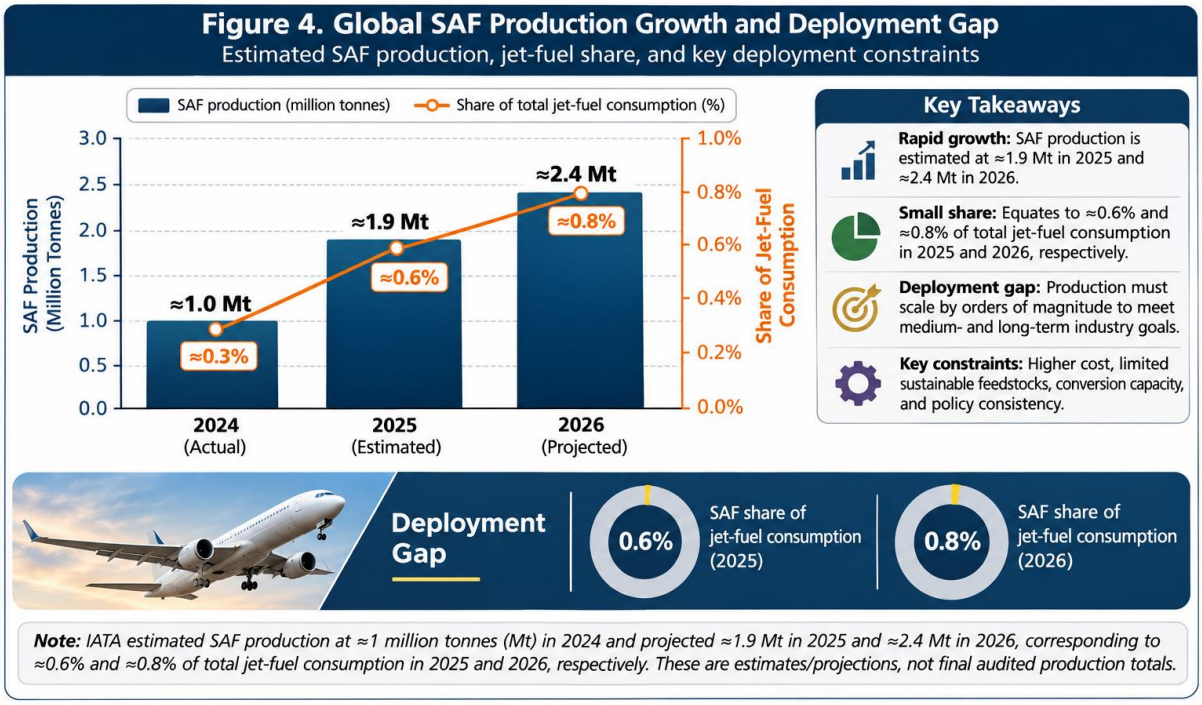

## 6. Production, Cost, and Feedstock Constraints

SAF remains a small share of global aviation fuel supply. In December 2025, IATA estimated production at approximately 1 million tonnes in 2024, expected 1.9 million tonnes in 2025, and projected 2.4 million tonnes in 2026. IATA estimated these volumes at approximately 0.6% of total jet-fuel consumption in 2025 and 0.8% in 2026. The 2025 and 2026 figures are estimates or projections, not final audited production totals, and should be labelled accordingly (IATA, 2025).

The scale-up challenge is substantial. IATA indicates that annual SAF supply would need to expand to hundreds of millions of tonnes by 2050 in its net-zero pathway. Such projections are scenario-dependent and should not be

interpreted as guaranteed demand or production. They nevertheless illustrate the distance between current output and long-term sectoral ambitions.

Cost is another major constraint. IATA reported that SAF prices were approximately twice those of fossil jet fuel on average and could be up to five times higher in some mandated markets in its 2025 assessment. These ratios are market estimates, not universal production-cost constants. Comparisons should specify year, geography, currency, pathway, and whether the figure refers to production cost, wholesale price, or the price paid by an airline. Techno-economic reviews also show that assumptions about feedstock prices, plant scale, financing, co-product allocation, and energy inputs can materially alter estimated minimum selling prices (Watson et al., 2024; Chireshe et al., 2025).




Feedstock availability is not unlimited. Used cooking oil, animal fats, agricultural and forestry residues, municipal waste, and other potential inputs have different sustainability constraints and competing uses. Expanding crop-based feedstocks without safeguards may create risks related to land-use change, biodiversity, water use, fertiliser emissions, and food systems. Waste-derived feedstocks also have finite supply and may already be used in other sectors. Large-scale deployment is therefore likely to require a portfolio of pathways rather than dependence on a single feedstock.

Production capacity must also be reported carefully. Announced project capacity, nameplate capacity, operational capacity, and actual annual output are different quantities. A facility may produce several renewable products rather than SAF alone, and announced expansions may be delayed. A global supply assessment should rely on a consistent dataset and should not infer total production from a small selection of plants. The U.S. SAF Grand Challenge roadmap similarly emphasises feedstock innovation, conversion technology, supply-chain development, policy analysis, and end-use enablement as linked requirements for scale-up (U.S. DOE et al., 2022).

## 7.Policy and Market Development

### 7.1 ReFuelEU Aviation

ReFuelEU Aviation, established by Regulation (EU) 2023/2405, requires aviation-fuel suppliers to provide increasing minimum shares of SAF at covered EU airports. The European Commission identifies a 2% SAF share from 2025 and 70% by 2050, together with a synthetic aviation-fuel sub-mandate that begins in 2030 and reaches 35% by 2050. These targets apply within the regulation's defined scope and sustainability criteria; the overall SAF share should not be conflated with the synthetic-fuel sub-target (European Commission, n.d.; European Union, 2023).

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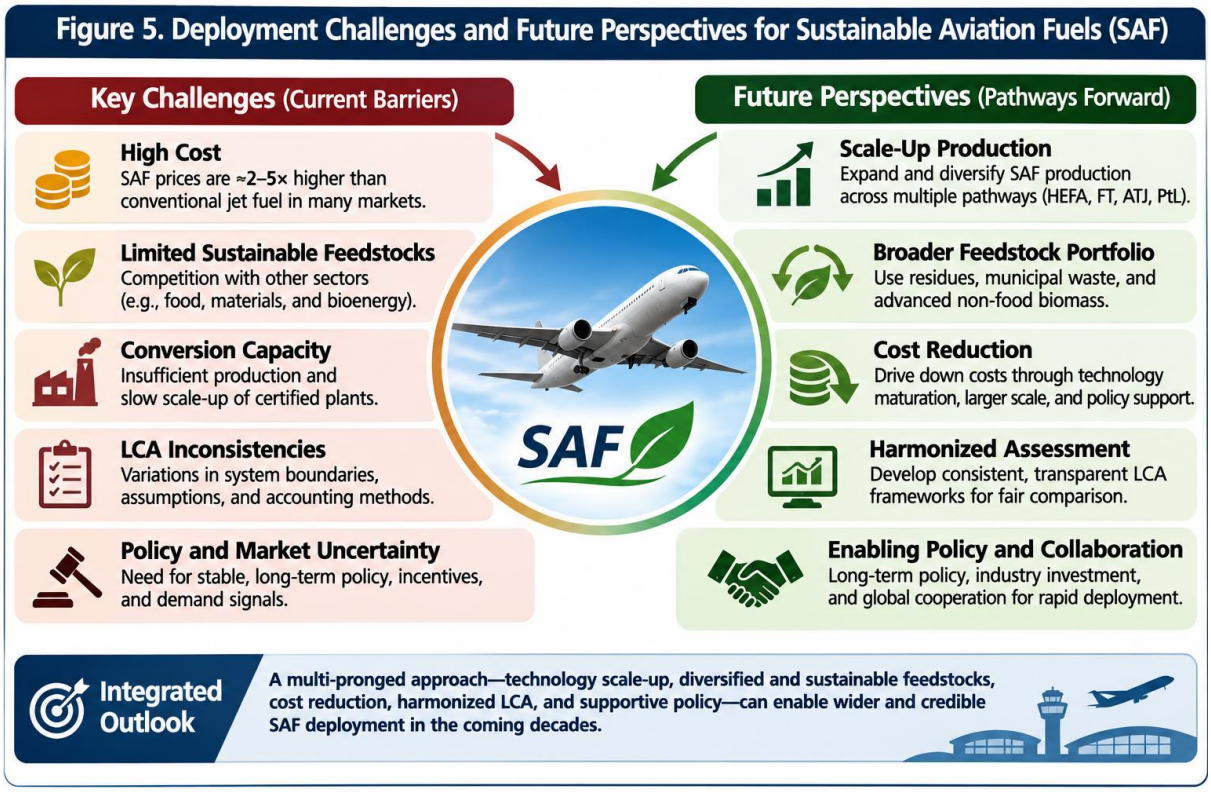
### 7.2 CORSIA

ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) allows aircraft operators to reduce offsetting requirements through the use of CORSIA-eligible fuels that meet applicable sustainability and lifecycle-emissions requirements. Eligibility is not automatic for any fuel marketed as sustainable. Certification, feedstock eligibility, lifecycle emissions values, and the applicable ICAO methodology are central to substantiating claims (ICAO, n.d.-a; ICAO, n.d.-b).

### 7.3 United States policy and investment support

In the United States, federal policy has supported SAF through tax incentives, research funding, grants, and the interagency SAF Grand Challenge. The Grand Challenge roadmap identifies six linked action areas, including feedstock innovation, conversion technology, supply chains, policy and valuation, enabling end use, and public communication (U.S. DOE et al., 2022). Tax-credit provisions and eligibility conditions can change through legislation; any detailed account of current incentives should therefore cite the applicable statutory text or current official guidance and specify the relevant tax year.

Mandates can create demand certainty, while tax incentives, public funding, long-term offtake agreements, and revenue-support mechanisms can reduce investment risk. However, policies should be assessed against actual production, verified lifecycle performance, feedstock sustainability, and the risk of shifting environmental burdens upstream or across sectors.




## 8. Discussion

The evidence supports a balanced assessment. SAF can reduce lifecycle GHG emissions substantially when produced through favourable pathways, but the magnitude of the reduction is not uniform. The ECLIF3 campaign provides experimental evidence that one HEFA-SPK fuel reduced measured soot and contrail ice-particle numbers under specified cruise conditions. Its modelled fleet-level contrail radiative-forcing result is informative but remains dependent on assumptions and should not be presented as a measured global climate outcome.

The distinction between per-unit performance and sector-wide impact is central. A fuel may have a favourable lifecycle intensity yet contribute only modestly to total aviation emissions while production volumes remain low. Conversely, rapid expansion without credible feedstock safeguards or low-carbon process energy could erode the environmental benefit. SAF deployment must therefore be judged by both lifecycle intensity and the quantity of genuinely sustainable fuel delivered.

SAF should be considered one component of a wider mitigation portfolio. Improvements in aircraft and engine efficiency, operational optimisation, air-traffic management, and targeted avoidance of strongly warming contrail conditions can address different parts of aviation's climate impact. These measures are complementary rather than direct substitutes for lifecycle fuel decarbonisation. Research priorities include pathway-specific LCA using harmonised assumptions, improved feedstock inventories, full-scale operational demonstrations, and repeated emissions measurements across engine types and atmospheric conditions.

## 9. Limitations of This Review

This review is a structured narrative synthesis, not a systematic review or meta-analysis. It does not provide a complete database search protocol, a formal quality appraisal of every included study, or pooled estimates across SAF pathways. Several market and production figures are based on industry estimates and projections and may change as new data become available. The ECLIF3 results are specific to the fuels, engine, flight conditions, and measurement campaign studied. In addition, LCA results may not be directly comparable where studies use different system boundaries, co-product allocation methods, energy assumptions, or land-use-change treatments. Further research across pathways, engine types, atmospheric conditions, and commercial operations is required.

## 10. Policy and Market Development

Sustainable aviation fuels offer a credible route to reducing aviation's lifecycle GHG emissions, but the size of the benefit depends on feedstock, conversion pathway, process energy, hydrogen source, land-use effects, and the lifecycle methodology applied. The ECLIF3 study provides important evidence that 100% HEFA-SPK reduced measured soot and contrail ice-particle numbers relative to reference Jet A-1 during the tested conditions; its estimated fleet-level reduction in contrail radiative forcing is a model result and should be interpreted accordingly.

The principal barriers to broad deployment are limited production, higher prices, sustainable feedstock constraints, conversion capacity, and the need for robust lifecycle verification. Policymakers and industry should support multiple pathways, strengthen harmonised lifecycle accounting, and align incentives with demonstrable emissions reductions and sustainability safeguards. SAF can make an important contribution to aviation decarbonisation, but it is not a complete solution on its own and should be integrated with efficiency, operational, and other climate-mitigation measures.

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## 12. Conflict of Interest

The author declares no competing conflict of interest.

## 13. Declaration on the Use of Artificial Intelligence (AI)

No fuArtificial Intelligence (AI)-assisted tools were used during the preparation of this manuscript to support grammatical correction, sentence restructuring, language refinement, and improvement of overall readability and clarity. AI tools were also employed to assist in generating relevant charts, graphical representations, and illustrative images for the presentation of concepts discussed in the manuscript. The use of AI was limited to language enhancement and visual-content development. The author remains solely responsible for the originality, accuracy, interpretation, verification, and scientific integrity of the manuscript, including the validation of all data, references, findings, and generated visual materials. AI tools were not considered authors or contributors to the scientific interpretation or conclusions of this work. The author has reviewed and takes full responsibility for the final submitted version of the manuscript.

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No funding was issued for this research.

## 15. Author Biography

**Manvick Kapoor** is an emerging student researcher with a strong interest in scientific exploration, technological innovation, and the future of sustainable aviation. Currently pursuing his academic journey at The Scindia School, Gwalior, India, he is passionate about understanding complex scientific challenges and exploring research-driven solutions to global problems. His research interests include sustainable aviation fuels, aerospace technology, environmental sustainability, and the advancement of cleaner and more efficient aviation systems.

Through his research and academic pursuits, he seeks to contribute to the evolving landscape of aerospace science and sustainable technological development. He believes that meaningful scientific progress begins with curiosity, critical thinking, and the courage to explore questions beyond conventional boundaries. As an aspiring researcher, he is committed to continuous learning, knowledge creation, and contributing to a future where scientific innovation serves both humanity and the environment.