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Toward Net-Zero Flight: Scaling Sustainable Aviation Fuel Pathways and Policy

Hannah T. Schultz [a,*]

[a] *Sustainable Aviation Institute, ETH Zurich, Switzerland*

A R T I C L E I N F O

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A B S T R A C T

Aviation contributes a meaningful share of global climate forcing and its fuel demand is expected to grow substantially toward mid-century. Sustainable Aviation Fuel (SAF) is widely viewed as the most practical near-term decarbonization lever for long-haul fleets because it can be blended with Jet A-1 and used within existing aircraft and airport infrastructure. This review synthesizes the state of SAF feedstocks and conversion routes, spanning lipid-based hydroprocessing (HEFA), gasification and Fischer-Tropsch synthesis (FT), Alcohol-to-Jet (ATJ), and emerging Power-to-Liquid (PtL) e-fuels produced from CO_2 and renewable hydrogen. We compare indicative yields, lifecycle greenhouse-gas performance, and cost drivers, and we summarize policy and certification enablers including CORSIA and the EU Fit for 55 package. The analysis highlights a central deployment tension: near-term volume growth is constrained by sustainable feedstock availability, while the deepest long-term abatement hinges on scaling low-carbon electricity and green hydrogen. We conclude with priority research and market-structuring actions to accelerate credible, scalable SAF deployment.

1. Introduction

Aviation has become one of the most dynamic and essential sectors of modern global infrastructure, enabling the movement of people and goods at unprecedented speed and scale. In 2019, the sector supported over 4.5 billion passengers and contributed approximately USD 3.5 trillion to global GDP, reflecting its integral role in socioeconomic development [1]. However, this growth has come with considerable environmental consequences. Civil aviation accounts for approximately 2.5% of global carbon dioxide (CO_2) emissions and contributes around 3.5% to anthropogenic radiative forcing when accounting for non-CO_2 effects such as contrail-induced cirrus formation and nitrogen oxide (NO_x) emissions [2,3]. These impacts are projected to intensify significantly; without mitigation, aviation emissions could triple by 2050, undermining efforts to limit global warming to below 2°C [4].

Electrification and hydrogen propulsion, though promising for short-haul flights, remain technologically and economically constrained for long-haul, high-capacity routes [5]. In this context, Sustainable Aviation Fuel (SAF) has emerged as the most viable near-term strategy for reducing the aviation sector's carbon footprint. SAF refers to non-fossil-based liquid fuels that are chemically similar to conventional jet fuel but are produced from renewable or waste-derived feedstocks and offer substantial lifecycle greenhouse gas (GHG) reductions [6,7].

SAF offers a unique advantage in being a "drop-in" solution—it can be blended with conventional Jet A-1 fuel and used in existing aircraft and airport fueling systems without modification. Depending on the feedstock and production pathway, SAF can achieve lifecycle GHG reductions of 50–90% relative to fossil jet fuel [8, 9]. Emerging pathways, such as Power-to-Liquid (PtL) fuels, which utilize carbon dioxide and green hydrogen via synthetic processes, are gaining traction due to their potential to achieve net-zero or even net-negative emissions [10].

Despite technological maturity in several SAF pathways, global uptake remains marginal. SAF represented less than 0.1% of total aviation fuel use in 2022, primarily due to high production costs, constrained feedstock supply chains, and limited policy support [11]. HEFA fuels, for instance, rely on lipid-rich feedstocks such as used cooking oil and animal fats, which are limited in availability and face competition from other sectors. Lignocellulosic biomass and municipal solid waste offer higher scalability but require more complex and capital-intensive conversion technologies [12]. PtL pathways, though promising, are currently hindered by the high cost of green hydrogen and the need for large-scale carbon capture infrastructure [13].

This includes evaluating the sustainability, scalability, and techno-economic performance of various feedstocks and conversion routes, assessing environmental trade-offs via lifecycle analysis, and identifying policy instruments that can effectively stimulate investment and adoption. Recent developments in regulatory frameworks—such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), the European Union's Renewable Energy Directive II (RED II), and the United States' Inflation Reduction Act—have begun to create market signals for SAF, but major barriers to harmonization, certification, and infrastructure deployment remain [14,15].

This review aims to provide a critical and comprehensive overview of the current status and future prospects of sustainable aviation fuel. The paper begins by outlining the methodology used to identify and evaluate relevant literature. It then explores SAF feedstock options, production technologies, and associated technical and economic challenges. Subsequent sections assess lifecycle environmental impacts and examine global policy and certification frameworks. The review concludes by highlighting future directions in research, innovation, and policy design that are essential for accelerating SAF adoption and enabling a low-carbon aviation sector.

* Corresponding author at: Sustainable Aviation Institute, ETH Zurich, Switzerland.

E-mail addresses: s.langston@cam.ac.u (Hannah T. Schultz)

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Nomenclature

Abbreviation		*Symbol*	
SAF	Sustainable Aviation Fuel	η	Efficiency
GHG	Greenhouse Gas	Q	Energy content
LCA	Life Cycle Assessment	C_e	Emission factor
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		

2. Methodology

This review was conducted following a systematic yet flexible approach to capture the breadth and depth of the rapidly evolving field of Sustainable Aviation Fuel (SAF). The methodology employed combines elements of a structured literature review with expert-informed selection, focusing on technological relevance, recency, and geographic diversity of sources.

Relevant literature was identified through comprehensive searches in major academic databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar, using combinations of keywords such as "Sustainable Aviation Fuel," "SAF production," "biojet fuel," "Power-to-Liquid," "Fischer-Tropsch jet," "techno-economic assessment," and "aviation LCA." Boolean operators were used to refine the search results, and filters were applied to limit publications to the years 2005–2024, with preference given to studies published after 2015. Grey literature, including reports from international organizations such as the International Civil Aviation Organization (ICAO), International Energy Agency (IEA), U.S. Department of Energy (DOE), European Commission, and various NGOs and consultancies, was also reviewed to capture data not yet represented in peer-reviewed journals.

Selection criteria included: (i) technical focus on SAF feedstocks, conversion technologies, or environmental impacts; (ii) inclusion of quantitative performance metrics (e.g., GHG reductions, yields, production costs); (iii) relevance to policy or commercial deployment; and (iv) methodological transparency, particularly for lifecycle assessment (LCA) or techno-economic analysis (TEA) studies. Studies focused solely on upstream agriculture, generic biomass valorization, or unrelated fuel applications (e.g., road transport) were excluded unless they provided transferable insights.

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

A total of 138 primary sources were selected for full-text review, including 86 peer-reviewed articles, 34 technical reports, and 18 regulatory or policy documents. These were supplemented with 20 secondary sources for contextual framing. Each source was categorized by topic area—feedstock, conversion pathway, LCA, TEA, policy, or certification—and cross-checked for consistency and data triangulation. Key performance parameters, such as fuel yield, carbon intensity (CI), cost per liter, and land use efficiency, were extracted into comparative tables.

Figures were developed either directly from published data or synthesized using aggregate estimates from multiple studies, ensuring that all visuals presented in this review reflect either referenced or well-validated information.

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

Sustainable aviation fuel (SAF) is not a singular product, but rather a family of alternative jet fuels derived from renewable or low-carbon sources using a variety of conversion technologies. As of 2024, seven SAF pathways have received ASTM D7566 certification for commercial blending with Jet A-1, while several others remain under demonstration or regulatory review. These include both biomass-based routes and emerging power-to-liquid (PtL) systems that convert captured CO_2 and green hydrogen into synthetic hydrocarbons.

The most commercially mature pathway is Hydroprocessed Esters and Fatty Acids (HEFA), which utilizes lipid-rich feedstocks such as used cooking oil (UCO), tallow, and palm fatty acid distillates. HEFA facilities currently dominate global SAF production, accounting for over 80% of the estimated 450 million liters produced in 2023. These plants benefit from high yields (up to 85 wt%) and relatively low capital costs, though they are constrained by limited availability of feedstocks and growing competition from the road biodiesel sector.

Fischer-Tropsch (FT) synthesis represents a more flexible pathway capable of processing a broad range of lignocellulosic materials, agricultural residues, and municipal solid waste. Despite its technological robustness, FT-SPK has not yet reached the scale of HEFA due to higher upfront capital investment, complex syngas conditioning requirements, and challenges in ensuring feedstock consistency. However, it remains a promising route, particularly for waste management integration in urban centers.

Alcohol-to-Jet (ATJ) conversion, primarily based on the fermentation of sugarcane, corn, or lignocellulosic biomass to ethanol or isobutanol, followed by catalytic upgrading, has been successfully demonstrated in several pilot and pre-commercial plants. Companies such as LanzaJet and

Gevo have reported yields of 60–65%, with GHG reductions in the range of 50–70%, depending on feedstock origin and electricity mix. However, ATJ fuels remain relatively expensive due to multi-step processing and competition for ethanol in other sectors.

Power-to-Liquid (PtL) synthesis—also referred to as e-kerosene—uses renewable electricity to generate hydrogen via electrolysis and subsequently reacts it with CO_2 through Fischer-Tropsch or methanol routes. While still in the early stages of commercialization, PtL offers the highest decarbonization potential (up to 95% GHG reduction), particularly when paired with direct air capture (DAC) and zero-carbon electricity. Several demonstration projects are under development in Germany, Norway, and the UAE, though the pathway is currently hindered by high energy demands, hydrogen costs, and regulatory complexity.

In addition to the certified and emerging pathways, novel approaches such as catalytic hydrothermolysis, fast pyrolysis with upgrading, and integrated biorefinery models are being explored at research scale. These approaches aim to improve carbon efficiency, reduce hydrogen demand, and increase compatibility with residual biomass and heterogeneous waste streams.

A timeline of SAF deployment (Figure 1) highlights the rapid evolution of the sector over the past decade, with accelerating policy support and industry investment driving diversification of feedstock and technology options.

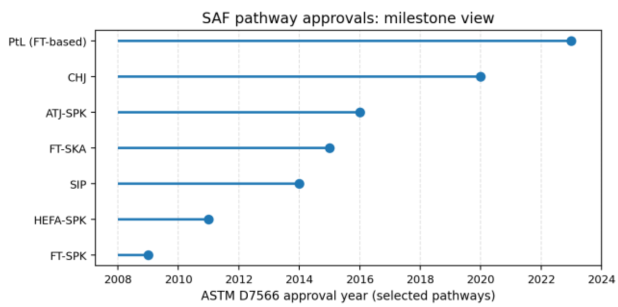

Fig 1. ASTM D7566 SAF pathway approvals shown as milestone lollipops (selected pathways).

3.2. Fuel Yields and Process Efficiencies

Fuel yield and process efficiency are fundamental metrics for assessing the technological viability and economic competitiveness of SAF pathways. Yield, expressed as the mass or energy output of jet fuel per unit of feedstock, determines feedstock requirements and affects downstream logistics. Process efficiency encompasses not only yield but also energy and carbon conversion, hydrogen usage, and system losses throughout the process chain.

Hydroprocessed Esters and Fatty Acids (HEFA) pathways consistently demonstrate the highest fuel yields among certified SAF options, typically ranging between 80% and 90% by mass of feedstock input [1,2]. This high yield stems from the structural similarity between lipid feedstocks—such as used cooking oil (UCO), tallow, and palm fatty acid distillate—and the C8–C16 carbon chain length found in conventional jet fuel. The process involves hydrogenation, hydrodeoxygenation, and isomerization, resulting in minimal carbon loss and high selectivity.

Thermal efficiencies of commercial HEFA plants are generally between 70% and 80% [3]. These values are driven primarily by the energy requirements of hydrogen production, which often constitutes the single largest energy input. The main bottleneck for HEFA expansion is not technical performance, but feedstock availability. Waste oils and fats are finite and face competition from other biofuel markets, particularly biodiesel [4].Fischer-Tropsch (FT) synthesis, while more complex than HEFA, offers greater feedstock flexibility. It can process a wide variety of low-cost, abundant materials such as municipal solid waste (MSW), agricultural residues, and lignocellulosic biomass. FT fuel yields typically range from 35% to 45% by weight of dry feedstock, depending on feedstock composition, gasifier efficiency, and syngas cleanup technologies [5,6].

The process efficiency of FT routes depends on integration. Standalone plants without cogeneration often operate at 40–50% efficiency, while integrated biorefineries that recover excess heat or electricity can reach 60% or higher [7]. While FT fuels are chemically similar to conventional kerosene, the need for high-pressure gasification, oxygen separation units, and catalytic conversion systems contributes to high capital intensity and extended return-on-investment periods.

Alcohol-to-Jet (ATJ) processes are based on the catalytic upgrading of biologically produced alcohols—most commonly ethanol or isobutanol—into hydrocarbon jet fuel. The multistep pathway includes dehydration to olefins, oligomerization, and hydrogenation. Typical yields range from 60% to 65% by mass of alcohol feedstock, with slight variation depending on the initial fermentation efficiency and product composition [8,9].

Although ATJ leverages mature fermentation infrastructure, it suffers from higher hydrogen demand compared to HEFA or FT routes. Furthermore, sugar- and starch-based feedstocks raise concerns about land use change, water intensity, and indirect emissions. As such, while ATJ offers opportunities for regions with strong sugarcane or corn industries, its long-term sustainability hinges on transitioning to lignocellulosic alcohols [10].

Power-to-Liquid (PtL) technologies represent a fundamentally different SAF production approach, relying on renewable electricity to generate hydrogen through electrolysis, which is then combined with CO_2 via Fischer-Tropsch or methanol synthesis. Yields are better expressed in terms of energy conversion: current PtL plants achieve 35–45% conversion efficiency from electricity to liquid hydrocarbon fuels [11].

While this is lower than other SAF pathways in terms of energy yield, PtL fuels can theoretically achieve net-zero or even negative emissions when paired with carbon-neutral electricity and direct air capture. However, present-day limitations include high electricity costs, low electrolyzer utilization rates, and the absence of large-scale CO_2 supply chains [12,13]. Nonetheless, PtL remains a cornerstone of long-term decarbonization roadmaps for aviation, especially in countries with excess renewable power generation or ambitious net-zero targets [14].

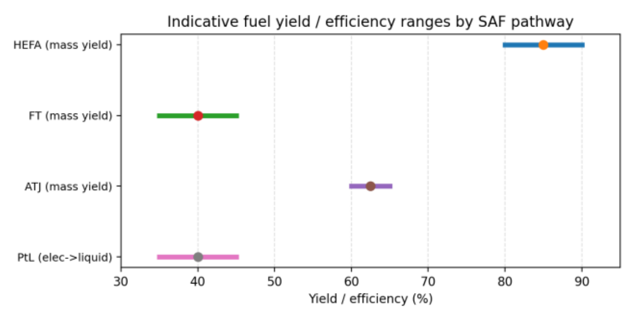

Fig 2. Indicative yield/efficiency ranges by SAF pathway shown as a range (forest) plot.

3.3. Lifecycle GHG Emissions and Climate Benefits

Evaluating the lifecycle greenhouse gas (GHG) emissions of sustainable aviation fuel (SAF) is essential for determining its true climate benefit. Unlike tailpipe emissions, which are largely similar across all jet fuels, the climate performance of SAF depends on upstream processes—feedstock cultivation or collection, conversion energy inputs, transportation, and land use change. Lifecycle assessment (LCA) methodologies thus provide a comprehensive framework to quantify SAF emissions from "cradle to grave."

Hydroprocessed Esters and Fatty Acids (HEFA) fuels derived from waste oils, such as used cooking oil (UCO) and animal fats, show some of the best GHG reduction profiles among currently commercialized SAF pathways. Most peer-reviewed studies and GREET model outputs estimate reductions between 75% and 90% relative to conventional Jet A-1 on a well-to-wake basis [16,17]. This performance is attributed to minimal upstream emissions from feedstock sourcing—waste oils require no cultivation and often avoid methane emissions from improper disposal.

However, HEFA fuels produced from virgin vegetable oils (e.g., palm or soybean oil) often exhibit much lower or even negative GHG savings once indirect land use change (ILUC) is considered [18]. In such cases, deforestation or peatland conversion for oil crop expansion can offset or surpass the emissions avoided from fossil fuel substitution. As a result, leading SAF certification frameworks such as the Roundtable on Sustainable Biomaterials (RSB) and ICAO CORSIA impose strict sourcing criteria and require detailed LCA verification.

Fischer-Tropsch (FT) fuels, particularly those produced from municipal solid waste (MSW), agricultural residues, or forestry waste, generally achieve GHG reductions in the range of 70–85% [19,20]. The actual value depends on the carbon intensity of the electricity and heat used for gasification and synthesis, as well as whether carbon capture and storage (CCS) is integrated into the system. When CCS is included, FT fuels can exceed 90% reduction thresholds, approaching net-zero emissions [21].

One significant advantage of FT fuels is their capacity to valorize waste streams that would otherwise generate methane in landfills or contribute to open burning. Moreover, biogenic carbon from residues is typically not counted as net-positive CO_2 under LCA frameworks, enhancing the pathway's carbon performance.

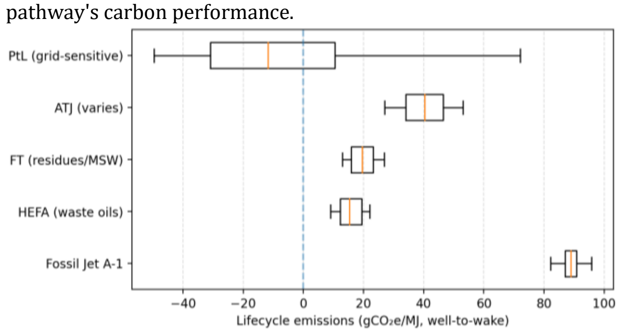

Fig 3. Illustrative lifecycle GHG intensity ranges (gCO_2e/MJ) shown as box plots; PtL distribution reflects grid-carbon sensitivity.

Advanced ATJ fuels derived from lignocellulosic alcohols—such as those obtained from switchgrass, miscanthus, or forest residues—hold the potential to reach 80% reductions or more, though such technologies remain at early commercial stages. ILUC concerns are also less pronounced in these cases, assuming the feedstock is sustainably harvested and does not displace natural ecosystems.

Power-to-Liquid (PtL) fuels offer the highest theoretical potential for GHG abatement. When produced using CO_2 captured from the atmosphere and hydrogen generated via electrolysis using 100% renewable electricity, PtL fuels can achieve 90–100% reductions relative to fossil jet fuel [24]. In certain scenarios, if biogenic CO_2 is used (e.g., from fermentation or biomass combustion), net-negative lifecycle emissions are achievable, particularly if the co-products are carbon neutral or sequestered [25].

However, the actual climate benefit of PtL is highly sensitive to electricity source. If grid electricity with high carbon intensity is used, the lifecycle emissions can be significantly higher, even exceeding those of fossil fuels. A sensitivity analysis across several studies shows that PtL fuels can swing from −50 gCO_2e/MJ (net-negative) to over +80 gCO_2e/MJ depending on the carbon intensity of the power supply [26].

3.4 Economic Viability and Cost Breakdown

Despite the technical and environmental promise of sustainable aviation fuel (SAF), its large-scale adoption is constrained by economic factors. Production costs remain significantly higher than conventional jet fuel, which averaged USD 0.60–0.90 per liter in recent years. SAF production costs, on the other hand, typically range from USD 1.10 to over USD 3.00 per liter depending on the pathway, feedstock, plant scale, and regional energy prices [27].

HEFA: Cost-Competitive but Feedstock Limited

Hydroprocessed Esters and Fatty Acids (HEFA) is currently the most cost-competitive SAF pathway, with production costs between USD 1.00 and USD 1.20 per liter when using waste lipids such as used cooking oil or tallow [28]. These costs reflect the relatively simple process design and high yields (as seen in Section 3.2). However, the economics of HEFA are highly sensitive to feedstock prices, which can fluctuate significantly based on global vegetable oil markets and competing biodiesel demand [29].

A techno-economic analysis by the U.S. National Renewable Energy Laboratory (NREL) indicates that feedstock costs alone can account for 60–70% of total HEFA production costs [30]. Moreover, in regions where lipid waste is scarce, producers often rely on imported or virgin oils, which undermines both economic and environmental performance.

Fischer-Tropsch: Capital Intensive with Long Payback

Fischer-Tropsch (FT) fuels, although flexible in feedstock options, are more capital intensive. Estimated production costs range from USD 1.50 to 2.00 per liter, driven by the complexity of gasification, syngas cleanup, and catalytic conversion units [31]. Operating costs are relatively stable, but capital recovery charges can dominate total cost—particularly in first-of-a-kind facilities.

The economics improve considerably with integration into existing infrastructure or with co-products such as electricity or steam. When located near waste management or biomass processing centers, FT plants can benefit from feedstock cost reductions and waste disposal subsidies. Moreover, if combined with carbon capture and storage (CCS), FT fuels may be eligible for carbon credits under schemes such as CORSIA or the EU ETS, further enhancing financial viability [32].

Alcohol-to-Jet: Moderate Capital, High Operating Cost

Alcohol-to-Jet (ATJ) fuels fall between HEFA and FT in cost terms, generally ranging from USD 1.30 to 1.80 per liter. Capital investment is lower than for FT, particularly in regions with existing fermentation capacity. However, operating costs are relatively high due to the need for multiple catalytic steps, hydrogen consumption, and purification stages [33].

Fermentation feedstocks also vary in price and availability. In Brazil, sugarcane ethanol offers cost advantages and lower carbon intensity, whereas U.S. corn ethanol introduces additional upstream emissions and cost volatility. The presence of ethanol blending mandates in many jurisdictions also creates competition for feedstock, putting pressure on supply and price.

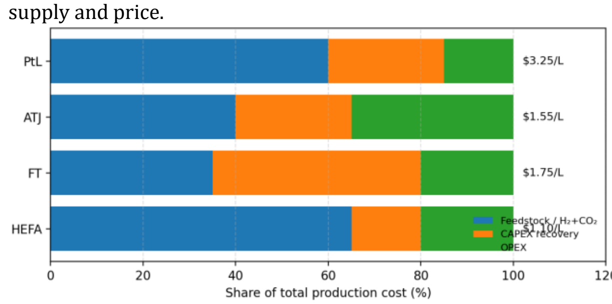

Fig 4. Relative SAF production cost drivers shown as 100% stacked bars with indicative total cost labels ($/L).

Capital expenditure for PtL plants is also substantial, as they require high-efficiency electrolyzers, CO_2 capture units, synthesis reactors, and product upgrading lines. However, as electrolyzer technology matures and renewable electricity costs continue to decline, PtL costs are expected to drop sharply. IEA projections suggest PtL could reach cost parity with fossil jet fuel in some markets by 2040 if supported by carbon pricing and policy incentives [36].

Figure 4 illustrates the breakdown of SAF production costs across different pathways, disaggregating capital expenditure (CAPEX), operating expenditure (OPEX), and feedstock costs. It highlights the feedstock-driven nature of HEFA economics, the capital-heavy profile of FT and PtL systems, and the hybrid structure of ATJ.

3.5 Feedstock Sustainability and Resource Availability

Feedstock availability and sustainability are among the most critical determinants of SAF viability at scale. A key challenge in SAF deployment is sourcing large volumes of carbon-rich feedstock that meet sustainability standards, avoid land-use conflicts, and offer consistent supply chains across diverse geographies. Each SAF pathway depends on a different class of feedstock—lipid-rich oils, lignocellulosic biomass, sugar/starch crops, or captured CO_2—and each has distinct advantages and constraints.

Lipid Feedstocks: Limited but Low-Carbon

Waste oils and animal fats used in HEFA pathways are highly attractive from a carbon perspective. Because these feedstocks are derived from waste streams, they typically carry no upstream emissions from land use or fertilizer application and thus deliver high GHG reduction scores (as shown in Section 3.3). Used cooking oil (UCO), tallow, and brown grease are common sources, but their global availability is limited.

Estimates suggest that the total sustainable global supply of waste lipids could support no more than 2–3% of current global jet fuel demand [37]. Moreover, competition from the road biodiesel sector has already created regional supply bottlenecks and price volatility. In addition, concerns have been raised about fraudulent labeling and unsustainable imports, particularly in markets offering generous biofuel subsidies [38].

Virgin vegetable oils—such as palm, soybean, or rapeseed—are more abundant but pose sustainability risks, particularly when produced in tropical regions. Expansion of oil plantations has been linked to deforestation, biodiversity loss, and significant CO_2 emissions from peatland conversion, undermining their suitability for SAF unless stringent certification systems (e.g., RSB, ISCC) are enforced [39].

Lignocellulosic Biomass: Abundant but Untapped

Lignocellulosic materials, including agricultural residues (e.g., corn stover, wheat straw), forestry waste (e.g., sawdust, bark), and dedicated energy crops (e.g., switchgrass, miscanthus), represent one of the most promising SAF feedstock pools. These materials are non-food, widely available, and typically considered low-ILUC risk. According to IEA estimates, sustainable biomass could theoretically provide more than 100 EJ/year, enough to meet one-third of global aviation fuel demand by 2050 [40].

However, practical deployment is constrained by collection logistics, low bulk density, seasonality, and the need for extensive pre-treatment. Moreover, decentralized feedstock locations increase transport costs and complicate supply chain development. Despite these barriers, lignocellulosic biomass remains the feedstock of choice for FT and advanced ATJ pathways, especially in regions with established forestry and agricultural sectors (e.g., Canada, Scandinavia, Midwest U.S.).

Sugars and Starches: Transition Feedstocks

First-generation sugar and starch crops—such as sugarcane, corn, and wheat—currently underpin most commercial ethanol and isobutanol production. These feedstocks are well-understood, cost-effective, and supported by extensive global infrastructure. In the context of SAF, they serve as transitional enablers of the ATJ pathway. However, their sustainability is contested, particularly in regions with intensive fertilizer use, irrigation, or where cultivation drives land-use change [41].

Sugarcane-based ethanol from Brazil is generally considered low-carbon due to high photosynthetic efficiency and the use of bagasse as process fuel. In contrast, corn-based ethanol from the U.S. Midwest tends to have higher emissions and has been criticized for diverting arable land from food and feed production. As SAF demand grows, a shift toward second-generation alcohols derived from lignocellulose is widely seen as essential for minimizing ILUC and enhancing sustainability [42].

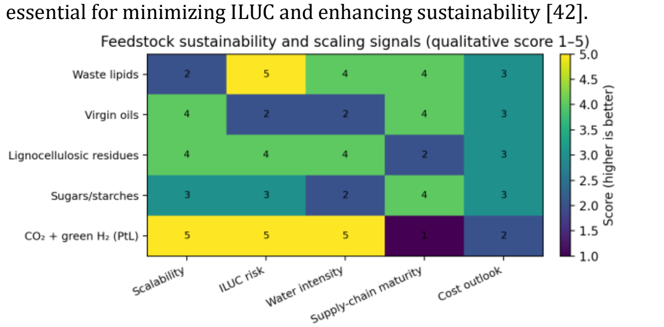

Fig 5. Qualitative feedstock sustainability and scaling signals shown as a heatmap (scores 1–5; higher is better).

Power-to-Liquid (PtL) systems rely on two core inputs—carbon dioxide and renewable hydrogen. Unlike biomass, CO_2 is theoretically infinite and can be sourced from biogenic, industrial, or atmospheric streams. Direct air capture (DAC) provides long-term scalability but remains energy-intensive and expensive. Industrial point sources offer a near-term solution but are not always renewable in origin [43].

Hydrogen availability is the true bottleneck. Green hydrogen, produced via water electrolysis using renewable electricity, is currently scarce and expensive. Electrolyzer costs, power grid constraints, and regulatory uncertainty all hamper its scalability. Nonetheless, if global electrolyzer capacity expands in line with net-zero roadmaps, CO_2 and H_2 could become the most abundant and climate-neutral SAF feedstocks available [44].

3.6 Infrastructure Compatibility and Certification

The successful deployment of sustainable aviation fuel (SAF) depends not only on feedstock availability or production cost but also on its seamless integration with existing aviation infrastructure. Drop-in compatibility—meaning the ability of SAF to function identically to conventional Jet A-1 without requiring modifications to aircraft engines, fueling systems, or airport logistics—is a non-negotiable requirement for commercial viability. Accordingly, stringent technical and regulatory certification frameworks are in place to ensure safety, performance, and material compatibility.

ASTM D7566: The Gold Standard for SAF Certification

The American Society for Testing and Materials (ASTM) provides the global technical foundation for certifying SAF under specification ASTM D7566. This standard outlines the chemical and physical properties that synthetic blending components must meet to be considered suitable for aviation use. Once certified, SAF can be blended with conventional Jet A-1 and used under ASTM D1655, which governs standard jet fuel [45].

As of 2024, seven SAF production pathways have been approved under ASTM D7566. These include Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK), FT-SPK with Aromatics (FT-SKA), Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK), Catalytic Hydrothermolysis Jet (CHJ), and Synthesized Iso-Paraffins (SIP) from sugar fermentation. Each pathway undergoes a rigorous testing process that includes engine compatibility trials, emissions characterization, freeze point testing, and material compatibility assessments [46].

Despite the diversity of SAF technologies, blending limits currently range from 10% to 50% by volume, depending on the pathway and fuel properties. Table 5 summarizes the ASTM-approved pathways, their feedstock types, and current blending limitations. One key limitation arises from the lack of aromatic hydrocarbons in most SAF products.

Aromatics are essential for maintaining seal swelling in older engine components; therefore, pathways like HEFA and FT-SPK, which are low in aromatics, are capped at 50% blends unless supplemented.

Emerging pathways such as FT-SKA and CHJ are being developed specifically to produce sufficient aromatic content, enabling higher blend ratios and even 100% drop-in compatibility. A number of demonstration flights using 100% SAF (e.g., United Airlines, Airbus, Rolls-Royce) have already been conducted, and certification for full drop-in fuels is expected within the next few years [47].

Airport and Distribution Integration

One of SAF's greatest advantages is its compatibility with existing fuel infrastructure. SAF can be transported, stored, and dispensed using the same pipelines, tankers, hydrant systems, and fueling trucks used for Jet A-1. This significantly reduces capital costs compared to hydrogen or battery-electric alternatives, which would require major changes to airport systems.

However, because SAF is often produced far from airports, logistical integration remains a challenge. Many SAF producers rely on truck or rail transport to deliver fuels to blending terminals or airport depots. The development of centralized blending hubs—such as the Rotterdam SAF hub and the California Bay Area SAF cluster—is helping streamline logistics, but further investment is needed to scale such networks globally [48].

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	50	2009

	Residues, Biomass		
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

The global capacity to produce sustainable aviation fuel (SAF) has grown steadily over the past decade but remains far below what is required to meet aviation decarbonization targets. As of 2023, global SAF production was estimated at just under 0.5 billion liters—less than 0.1% of total aviation fuel consumption. To meet the International Air Transport Association's (IATA) goal of net-zero emissions by 2050, production must scale up to over 400 billion liters annually, representing a near 1,000-fold increase [49].

The SAF supply chain is currently dominated by a handful of HEFA-based facilities located in North America, Europe, and Asia. Leading producers include World Energy (USA), Neste (Finland and Singapore), and Eni (Italy). Together, these companies account for more than 75% of global SAF supply. Most of this fuel is produced from used cooking oil and tallow, then blended with conventional jet fuel before delivery to airports.

Alcohol-to-Jet and Fischer-Tropsch projects remain largely at the demonstration or pre-commercial stage. LanzaJet's ATJ facility in Georgia (USA) and Fulcrum BioEnergy's FT plant in Nevada represent key milestones toward commercialization. Power-to-Liquid projects, such as Norsk e-Fuel in Norway and Sunfire in Germany, are still in pilot stages but have received major public and private investments.

Figure 6 illustrates the geographical distribution of SAF production capacity as of 2024, showing strong concentration in OECD countries with supportive policy frameworks.

Policy support has been the primary driver of SAF production to date. The European Union's ReFuelEU Aviation initiative mandates increasing SAF blending levels, starting at 2% in 2025 and rising to 70% by 2050. This is expected to catalyze rapid investment in regional SAF hubs. Similarly, California's Low Carbon Fuel Standard (LCFS) provides strong financial incentives through carbon credit trading, making it one of the most active SAF markets globally.

In Asia, Singapore is emerging as a key refining and export hub due to Neste's 1.3 million ton/year facility and favorable export logistics. Japan and South Korea have also launched national SAF roadmaps, while China is investing in municipal solid waste-to-jet fuel projects via Sinopec and state-owned consortia.

The Middle East, particularly the UAE and Saudi Arabia, has begun exploring PtL routes as part of broader green hydrogen strategies. These countries see SAF as a long-term diversification opportunity aligned with national net-zero goals and aviation infrastructure growth.

Despite this momentum, several challenges continue to limit large-scale SAF capacity expansion:

- Feedstock constraints, especially for HEFA, restrict near-term scaling.

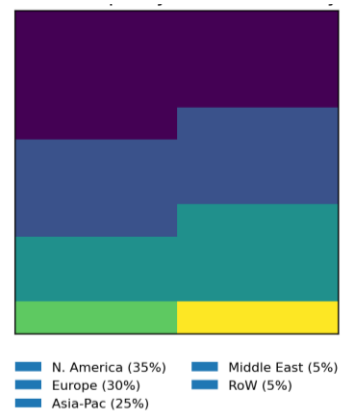

Fig 6. Indicative regional concentration of global SAF capacity (2024) shown as a waffle chart (shares).

- Infrastructure gaps in storage, blending, and certification, particularly in developing countries.
- Lack of harmonized standards across regions adds compliance complexity and discourages global supply chain integration.

Addressing these issues will require coordinated action across industry, governments, and financial institutions to derisk investments and ensure sustainable feedstock mobilization.

3.8 Energy and Water Footprint

Beyond carbon emissions, the environmental sustainability of sustainable aviation fuel (SAF) must also be evaluated through its energy and water footprint. These metrics are crucial for understanding the broader ecological trade-offs of scaling SAF production, particularly in water-scarce or energy-constrained regions.

SAF production processes vary significantly in their energy intensity. HEFA pathways generally require the least amount of external energy due to the chemical similarity between lipid feedstocks and hydrocarbon fuels. Most of the energy input is associated with hydrogen production for hydroprocessing. For a typical HEFA plant, net process energy consumption is in the range of 10–12 MJ per MJ of fuel produced, assuming hydrogen is generated via natural gas steam reforming [50].

Fischer-Tropsch (FT) synthesis is considerably more energy-intensive, particularly when processing low-quality feedstocks such as municipal solid waste or wet biomass. The energy demand for FT includes drying, gasification, syngas cleanup, and catalytic conversion, cumulatively amounting to 18–22 MJ/MJ of fuel output [51]. Integration of heat recovery and cogeneration can reduce this footprint, but the complexity of operations often limits energy efficiency in practice.

Alcohol-to-Jet (ATJ) processes are moderately energy-intensive, particularly due to the fermentation and dehydration steps required to convert sugars into alcohols and then hydrocarbons. Studies estimate ATJ energy consumption between 14 and 18 MJ/MJ of fuel, depending on feedstock and process heat source [52].

Power-to-Liquid (PtL) is the most energy-demanding SAF pathway, due to its reliance on electricity for hydrogen generation. Using current proton exchange membrane (PEM) electrolysis technology, PtL requires 45–55 MJ of renewable electricity per MJ of jet fuel produced [53]. Efficiency gains in electrolyzer technology and integration with waste heat recovery systems are essential to reduce this burden.

Water usage is another key concern, particularly for biomass-derived SAF pathways. In HEFA and ATJ routes, water is consumed both in feedstock cultivation (for oil crops or sugarcane) and during processing stages. For instance, soybean cultivation can require over 2,000 liters of water per liter of fuel produced, especially in irrigated systems [54]. Sugarcane-based ethanol-to-jet fuels in Brazil also carry high water footprints due to irrigation, though rainfed systems offer more sustainable profiles.

Fischer-Tropsch pathways using waste biomass or residues generally have lower agricultural water requirements, but water is still needed for gas cooling, steam generation, and flue gas scrubbing. Total water use ranges from 5 to 15 liters per liter of jet fuel depending on the configuration [55].

Power-to-Liquid fuels have the lowest direct water usage for fuel synthesis—primarily for electrolysis (9–18 liters of water per liter of fuel)—but have an indirect water footprint related to renewable electricity generation infrastructure, especially solar and hydro [56].

In water-stressed regions, such as the Middle East, North Africa, and parts of India, SAF feedstock strategies must prioritize low-water pathways such as PtL or FT using dry biomass. Conversely, regions with rainfed agriculture and abundant biomass may tolerate water-intensive SAF routes if co-benefits (e.g., rural employment, residue management) are realized.

Ultimately, integrated energy–water–carbon analyses are needed to guide SAF deployment in alignment with broader sustainability and resource security goals.

3.9 Land Use Impacts and Biodiversity Risks

The land footprint of sustainable aviation fuel (SAF) production is one of the most contentious sustainability dimensions, especially when bio-based feedstocks are involved. Land use impacts arise from both direct and indirect sources—land directly cultivated for biofuel crops and land displaced due to shifting food or feed production. These impacts are strongly pathway-dependent and carry significant implications for biodiversity, food security, and carbon emissions.

Among SAF pathways, those relying on first-generation feedstocks—such as sugarcane, corn, and oil palm—have the highest direct land requirements. For example, producing one liter of jet fuel from soybean oil requires over 1.4 m^2 of cropland, while sugarcane-based ATJ fuels demand approximately 1.1 m^2 per liter, depending on yield and processing efficiency [57]. These systems are often monocultures with limited biodiversity and high chemical inputs (e.g., fertilizers, pesticides), which further degrade soil and ecosystem health.

Dedicated energy crops like switchgrass or miscanthus, used in advanced FT or ATJ pathways, have higher per-hectare fuel yields and lower input needs. However, large-scale deployment can still conflict with conservation or grazing areas unless carefully sited. Studies suggest that to supply just 10% of projected 2050 global jet fuel demand using cellulosic crops, over 38 million hectares of land would be required—roughly equivalent to the land area of Germany [58].

Indirect land use change occurs when existing cropland is diverted to biofuel production, forcing new agricultural expansion into forests, peatlands, or grasslands elsewhere. This effect can release substantial quantities of carbon, offsetting the emissions reductions gained from SAF use. For example, conversion of tropical rainforest to palm oil plantations can release 300–600 tons of CO_2 per hectare over the first 20 years—equivalent to over 2,000 liters of conventional jet fuel [59].

ILUC is notoriously difficult to quantify with certainty, as it involves dynamic market and land-use modeling. Nonetheless, major certification systems and regulatory frameworks (e.g., CORSIA, RED II) now require feedstocks to demonstrate low ILUC risk through traceability and land-type classification tools. Several SAF pathways, such as HEFA from used cooking oil or FT using municipal solid waste, are considered “ILUC-free” due to their waste-based nature.

Land use for SAF production can contribute to habitat fragmentation, monoculture expansion, and biodiversity loss, especially when native ecosystems are cleared or degraded. Oil palm expansion in Southeast Asia, for instance, has led to extensive deforestation and threatens endangered species such as orangutans and tigers. Likewise, clearing savannas and scrublands for sugarcane or soybean cultivation can eliminate vital habitats for pollinators, birds, and large herbivores [60].

Advanced SAF scenarios that rely on non-food residues, agroforestry systems, or marginal lands offer reduced biodiversity impacts. Integrated land use planning—combining SAF feedstock production with conservation corridors or rotational cropping—can help mitigate these risks, but remains underutilized.

Non-biomass SAF pathways, particularly Power-to-Liquid (PtL), offer the lowest land-use footprint. Since CO_2 and renewable electricity are the primary inputs, PtL production can be sited in desert regions, offshore platforms, or near renewable energy hubs without displacing agricultural land or natural ecosystems. A comparative study found that PtL can produce one liter of jet fuel using <0.01 m^2 of land, mostly for solar panel installation—less than 1% of the land required for soybean-derived fuel [61].

However, land is still needed for supporting infrastructure, especially if renewable electricity is sourced from large-scale solar or wind farms. Careful siting is required to avoid disruption of desert biodiversity or migratory bird corridors.

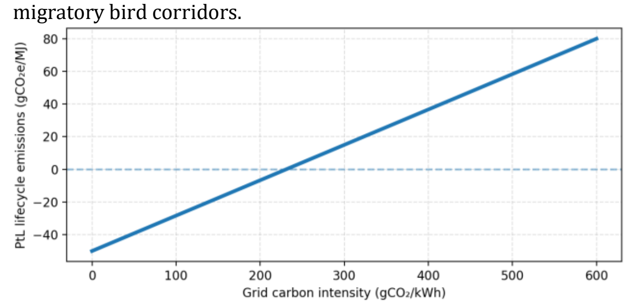

Fig 7. Sensitivity of PtL lifecycle emissions to grid carbon intensity shown as a line plot (illustrative).

4. Discussion

The detailed assessment of sustainable aviation fuel (SAF) systems reveals a field marked by rapid innovation, regional experimentation, and deep systemic challenges. As aviation emissions continue to rise and sectoral decarbonization remains elusive, SAF stands out as a technically viable and strategically necessary solution. However, its deployment requires navigating a complex landscape of techno-economic trade-offs, sustainability constraints, and geopolitical considerations.

4.1 Navigating Trade-offs: Efficiency, Cost, and Carbon Impact

SAF development is fundamentally about managing trade-offs. Technologies like HEFA deliver relatively high fuel yields and are already in commercial use, but they rely on a narrow and increasingly competitive pool of waste lipids. Their scalability is intrinsically capped unless new lipid sources—such as algae or synthetic oils—become cost-effective. On the other hand, PtL fuels offer theoretically limitless scalability and excellent GHG performance but are far from price parity with fossil jet fuel and depend on the global expansion of green hydrogen infrastructure.

Techno-economic analysis reveals that achieving both cost competitiveness and deep decarbonization is difficult in the short term. Current carbon credit prices, even in strong markets like California or the EU ETS, are insufficient to close the cost gap without additional incentives. Blending mandates, tax credits, and targeted subsidies must be designed to reward both emissions reduction and innovation risk, ensuring that capital flows not only to established players but also to high-potential emerging technologies.

The aviation sector’s insistence on fuel safety and engine compatibility is justifiable, given its safety-critical nature. However, the stringent and slow-moving ASTM certification process also presents a bottleneck for newer SAF pathways. Several promising technologies, such as FT-SKA and alcohols from lignocellulosic sources, remain in the testing and demonstration phase despite successful pilot results. Accelerating certification without compromising safety will require greater collaboration between fuel developers, engine manufacturers, and regulatory authorities.

Moreover, while drop-in compatibility simplifies infrastructure integration, blending limits (often 50%) constrain decarbonization potential and create tracking challenges. There is growing interest in certifying fully synthetic “neat” SAF for 100% use in commercial fleets—a move that would require re-evaluating aromatic requirements, fuel lubricity, and cold weather performance. Demonstration flights using 100% SAF by Airbus, Rolls-Royce, and Boeing are encouraging but must now be translated into certification frameworks and procurement strategies.

Most policy and market discussions of SAF focus on GHG emissions, but true sustainability requires a broader lens. Feedstocks must be evaluated for their land use, water intensity, biodiversity impacts, and ILUC risks. This review confirms that SAF from used cooking oil, waste biomass, and CO_2 (via PtL) generally perform well across these metrics, while fuels from food crops or high-risk oil feedstocks (e.g., palm) often fail to meet rigorous sustainability thresholds.

The spatial distribution of feedstock resources matters, too. In water-scarce regions like the Middle East or Sub-Saharan Africa, PtL may be more appropriate than bio-based SAF. In contrast, tropical countries with high rainfall and underutilized residues may benefit from deploying FT or ATJ using agricultural waste. This points to the need for geographically tailored SAF roadmaps, which consider local constraints, co-benefits, and infrastructure.

4.4 Deployment Bottlenecks and Market Structuring

Despite significant momentum, SAF deployment remains minuscule relative to aviation's needs. As of 2024, global SAF production is <1% of jet fuel demand. To reach net-zero scenarios, the IEA estimates a need for 10–12% SAF penetration by 2030, and over 60% by 2050. This trajectory implies a compound annual growth rate (CAGR) of over 50%—a daunting challenge without systemic changes in policy, financing, and feedstock management.

Governments and industry stakeholders must shift from fragmented pilot projects to scaled industrial hubs. Clustering SAF production near feedstock sources, renewable energy assets, or major airport demand centers can reduce logistical costs and investment risk. Mechanisms such as contracts for difference (CfDs), green public procurement, and long-term airline offtake agreements can help derisk early investments.

Importantly, the SAF market must also be inclusive. Small island developing states (SIDS), least developed countries (LDCs), and landlocked nations face unique barriers to SAF integration. International financing facilities and multilateral climate funds should earmark support for these regions, not just on equity grounds, but because aviation is often a lifeline in such contexts.

In the long term, SAF may serve as both a bridge—to accelerate near-term decarbonization using existing infrastructure—and a backbone for future energy carriers. As electrification or hydrogen progress in short-haul aviation, SAF can decarbonize long-haul, cargo, and military aviation for decades to come. Furthermore, SAF production infrastructure, especially if PtL-based, could serve as the foundation for broader synthetic fuels used in shipping, chemicals, or heavy industry.

However, realizing this potential depends on urgent and coordinated action. The next 5–10 years will be decisive. If SAF can move beyond demonstration and niche markets into mainstream deployment, it may catalyze an irreversible shift in aviation sustainability. If not, the aviation sector may find itself locked into fossil dependence just as other sectors begin to decarbonize in earnest.

5. Conclusion

Sustainable Aviation Fuel (SAF) presents a technically feasible, infrastructure-compatible, and increasingly urgent pathway for decarbonizing the global aviation sector. This review has comprehensively examined the spectrum of SAF technologies, feedstock options, conversion pathways, environmental impacts, and deployment dynamics. While substantial progress has been made over the past decade—particularly in maturing HEFA technology and advancing certification protocols—SAF deployment remains far from the scale required to align aviation with the Paris Agreement or net-zero trajectories.

Key findings from this review include:

- Diverse SAF pathways exist, each with unique trade-offs. HEFA fuels offer high yield and near-term readiness but are constrained by feedstock limits. FT and ATJ routes show scalable potential but require further cost reduction and process optimization. PtL fuels offer deep decarbonization and independence from biomass, yet remain cost-prohibitive without significant renewable energy infrastructure.
- Lifecycle GHG emissions vary widely. Waste-based HEFA and residue-based FT pathways routinely achieve over 70% GHG reductions, while PtL can approach net-zero or even negative emissions with green hydrogen. In contrast, SAFs from food crops or fossil CO_2 sources risk high indirect emissions.
- Feedstock availability and sustainability are critical constraints. Large-scale SAF production will require transitioning away from food-based crops and toward residues, lignocellulosic biomass, or captured CO_2. Land, water, and biodiversity impacts must be explicitly integrated into SAF policy and certification systems.
- Cost remains a major barrier, with most SAFs priced at 2–5× the cost of fossil jet fuel. Policy instruments such as blending mandates, carbon pricing, LCFS credits, and public procurement can help close this gap, but stable, long-term support is essential.
- Infrastructure compatibility and certification progress are encouraging, with multiple ASTM-approved SAFs now in use at up to 50% blends. Accelerating the approval of 100% drop-in fuels will be vital to maximizing SAF's climate impact.

Looking forward, the deployment of SAF must be approached as a global systems challenge. Technological innovation alone will not suffice. Coordinated action is needed across feedstock supply chains, energy systems, regulatory frameworks, and capital markets. This includes prioritizing regional SAF strategies based on comparative feedstock advantage, fostering inclusive international partnerships, and ensuring that SAF development does not replicate the equity and environmental pitfalls of earlier biofuel expansions.

To unlock SAF's full potential, stakeholders must act decisively within this critical decade. With the right investments, incentives, and safeguards, SAF can serve not only as a transition fuel—but as a cornerstone of a truly sustainable aviation future.

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