

Feedstocks, production paths, availability and costs of SAF

Renata ADAMI,^{1,2†} Nicole D'AVANZO¹, Patrizia LAMBERTI,^{2,3} Maria SARNO,^{1,2} Vincenzo TUCCI^{2,3}

¹Department of Physics "E.R. Caianiello" (DF), University of Salerno, Fisciano (SA), Italy

²Interdepartmental Centre Research Centre for NANOMaterials and nanoTEchnology (NANO_MATES), Fisciano (SA), Italy

³Department of Information, Electrical Engineering and Applied Mathematics (DIEM), University of Salerno, Fisciano (SA), Italy

radami@unisa.it – ndavanzo@unisa.it – plamberti@unisa.it – msarno@unisa.it – vtucci@unisa.it

[†] radami@unisa.it

Abstract

The aviation sector is responsible for about 3% of global CO₂ emissions and is now facing much pressure to decarbonize. Sustainable Aviation Fuels (SAF) are a drop-in alternative to conventional jet fuel, nevertheless, their usage on a large scale is strongly affected by feedstock diversity, production efficiency, availability, and cost competitiveness. First-generation feedstocks like vegetable oils undergo criticism for potential land-use conflicts, whereas second-generation alternatives, such as agricultural residues, mitigate Indirect Land-Use Change risks. Emerging pathways utilize renewable hydrogen and captured CO₂. Up to now, there are several pathways approved by ASTM for SAF production, though global SAF production in 2023 reached less than 0.1% of aviation fuel demand. SAF costs are still an obstacle to diffusion, since they remain 2-5 times more than conventional jet fuel. Strategic investments, policy support, and cross-sector collaboration are essential to unlock its potential.

1. Introduction

According to the latest IPCC (Intergovernmental Panel on Climate Change) synthesis report, rapid decarbonization of aviation is essential to remain within the 1.5 °C carbon budget, especially for sectors with no immediate electrification alternative [1]. Sustainable Aviation Fuel (SAF) has emerged as the principal near-to-mid-term decarbonization lever for aviation, especially for long-range aircrafts, yet its scalability depends on resolving interdependent challenges, such as feedstock sustainability, production pathway maturity, regional availability variations, and cost competitiveness. Ensuring long-term feedstock sustainability requires a shift from limited first-generation oils to more abundant second-generation sources such as lignocellulosic biomass and organic waste. Current production is largely dependent on HEFA pathways and lipid-based feedstocks, which are limited in availability and unevenly distributed. To ensure long-term viability, international institutions such as ICAO (International Civil Aviation Organization) stress the need to diversify toward waste-derived and lignocellulosic biomass feedstocks, alongside synthetic options using captured CO₂ [2]. Meanwhile, alternative conversion routes, such as Fischer–Tropsch (FT), Alcohol-to-Jet (AtJ), and Power-to-Liquid (PtL), must overcome technological, economic, and regulatory barriers to scale [3]. SAF supply remains concentrated in a few geographic areas, constrained by regional infrastructure, policy frameworks, and feedstock logistics [4]. Finally, SAF production costs remain significantly higher than those of fossil Jet Fuel (JF), requiring targeted innovation, economies of scale, and stable investment frameworks to close the gap between them [5]. This paper analyses these challenges and their implications for SAF deployment toward 2030 and gives some projections beyond.

2. Feedstocks

SAF can be produced from a variety of feedstocks, which are broadly categorized based on their origin and economic value. The main categories are oil-based (such as waste cooking oil, vegetable oil, and animal oil), lignocellulosic biomass and waste streams. Feedstocks also vary in availability, conversion efficiency, and environmental impact. The main source for SAF production is the oil-based feedstocks. Vegetable oils (soy, palm) and animal oils (tallow), despite their abundance, face strict EU RED III sustainability criteria to limit the Indirect Land Use Change (ILUC) and

deforestation risks; therefore, used cooking oil, also known as Waste Cooking Oil (WCO) has become an important feedstock. In 2023, over 500'000 tonnes of SAF were produced from WCO, driven by U.S. tax credits under the Inflation Reduction Act (\$1.25–1.75/gal) and the EU ReFuelEU mandate, which requires fuel suppliers to blend increasing percentages of SAF with traditional JF, starting at 2% in 2025 and reaching 70% in 2050 [6]. The industrial sector expects that WCO and tallow will supply 40% of all SAF feedstock by 2030 [7]. There is also a growing interest in lignocellulosic biomass, referring to agricultural residues (wheat straw, corn stover), forestry residues, and energy crops (miscanthus, switchgrass). Lignocellulose holds a great sustainable potential (>100 EJ/year) for aviation fuel, but the International Energy Agency (IEA) expects it to supply <1% of the 13 Mt/year biojet feedstock demand in 2030, equivalent to a 70% increase from 2023. Over 90% will, on the other hand, come from waste oils [8-10]. Advanced catalytic processing techniques may overcome lignin recalcitrance. Catalysts capable of performing hydrodeoxygenation, isomerization, and selective aromatic synthesis are under active development, with promising results in terms of fuel properties and hydrogen efficiency [11].

Last-generation feedstocks, such as algae, prioritize non-competition with cropland and boast theoretical yields of 30'000 L/ha·yr. Despite this potential, scaling is hindered by cultivation/harvesting costs, that are 5-10 times above conventional terrestrial biomass pathways [12]. PtL SAF is also promising. PtL synthesizes green H₂ and captured CO₂ using FT or methanol-to-jet processes, and also in this case the costs are an obstacle: PtL's energy intensity remains 4-5 times higher than bio-based SAF pathway.

The global inclination in using distinct feedstocks is driven by the different regional policies, which also affect the pathways for SAF production. Ensuring the sustainability of SAF feedstocks requires compliance with internationally recognized certification frameworks. The Roundtable on Sustainable Biomaterials (RSB), for instance, provides a science-based standard for assessing environmental and social criteria across multiple feedstock types [13]. In the United States, the Renewable Fuel Standard (RFS) enhancements and Inflation Reduction Act (IRA) tax credits economically favour the established lipid-based feedstocks (primarily WCO, animal tallow, and soybean oil) by incentivizing their conversion into hydro-processed esters and fatty acids (HEFA)-SAF. On the contrary, the European Union's ReFuelEU Aviation mandate and revised Renewable Energy Directive (RED III) prioritize advanced feedstocks: lignocellulosic agricultural residues (e.g., straw, forestry residues) and PtL electrofuels, while explicitly disincentivizing palm oil derivatives through low sustainability certification limits. Asia-Pacific initiatives focus on pilot-scale waste valorization, converting municipal solid waste (MSW) and sewage sludge into SAF via gasification/FT or anaerobic digestion pathways, aligning with circular economy principles to address urban waste management challenges [14].

3. Production pathways

SAF production technologies differ in maturity, cost, and feedstock flexibility. In figure 1 the state of ASTM status qualification of SAF is reported [15].

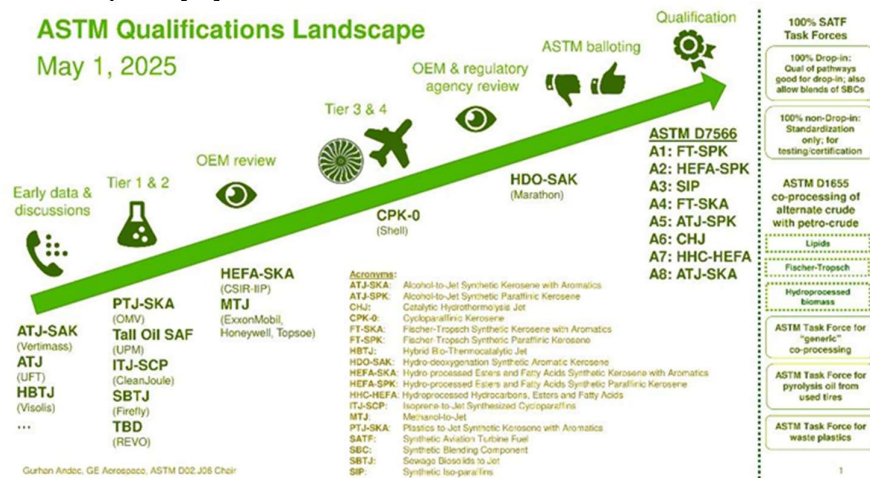


Figure 1: Current Fuels in the D4054 Qualification Process [15]

Among the 8 SAF production pathways approved by ASTM [16], FT-SPK (Fischer-Tropsch Synthesized Paraffinic Kerosene), HEFA (Hydroprocessed Esters and Fatty Acids), FT-SPK with aromatics, ATJ-SPK (Alcohol-to-Jet Synthesized Paraffinic Kerosene), Fats, Oils, and Greases Coprocessing (table 2) are likely to contribute to 3 billion Gallons by 2030.

Table 1: SAF production pathways approved by ASTM likely contributing to 3 billion Gallons by 2030

Pathway	Feedstocks	Chemical Process	Blending limit
D7566 Annex A1 (FT-SPK)	Biomass, municipal solid waste, agricultural and forest wastes, energy crops	Lignocellulosic biomass is converted to syngas using gasification, and then an FT synthesis reaction converts the syngas to JF.	50%
D7566 Annex A2 (HEFA)	Triglyceride feedstocks such as vegetable oils (e.g., jatropha, camelina); animal oils; waste fat, oil, and greases (e.g., yellow or brown greases); or algae feedstocks	Hydroprocessing followed by hydroisomerization and hydrocracking	50%
D7566 Annex A4 (FT-SPK with aromatics)	Same as A1	Gasification followed by SPK and aromatics by FT synthesis. The process is similar to FT-SPK ASTM D7566 Annex A1, but with the addition of aromatic components	50%
D7566 Annex A5 (ATJ-SPK)	Alcohols are derived from cellulosic (e.g., corn stover), sugar, or starch feedstock via fermentation or gasification	Conversion of alcohols (isobutanol and ethanol) into a drop-in fuel through dehydration, hydrogenation, oligomerization, and hydrotreatment.	50%
D1655 Annex A1.2.2.1 (Fats, oils, and greases coprocessing)	Same as A2	Fats, oils, and greases coprocessing with petroleum intermediates for SAF production.	5%

SAF production influences technological pathways at varying maturity levels. HEFA, employs hydrotreatment of triglycerides/free fatty acids (80-220°C, 0.7-4 bar) over noble metal catalysts (e.g., Pt, Ni), followed by isomerization to produce n-alkanes. Recent innovations include 3D-printed reactor internals that enhance thermal management and Pt/SAPO-11+Al₂O₃ catalysts that can achieve 60% jet-range selectivity. It operates Technology Readiness Level (TRL) 8-9 [17]. FT synthesis utilizes syngas from biomass, MSW, or PtL sources, with a target of 3 Ggal/yr SAF by 2030. New research related to ambient-temperature electrochemical FT on Cu-In/Sn electrodes enables single-step C₂-C₇ hydrocarbon synthesis, reducing energy demands [18].

Particular attention has been given in the last year to ATJ-SPK, and to the other approved alcohol-based process ATJ-SKA (Alcohol-to-Jet Synthesized Kerosene with Aromatics), since they foresee the use of renewable feedstock (lignocellulose, alcohols) for fuel production. AtJ converts ethanol/methanol via zeolite-catalyzed oligomerization; European pilots report 15% carbon efficiency gains through integrated fermentation-upgrading. Their properties and quality satisfy the specification requirements of JF. AtJ-SKA may be successfully used blended in higher amounts compared to AtJ-SKP, furthermore, the physical-chemical properties of blended JFs are very close to conventional JFs [19].

Concerning PtL, renewable H₂ and captured CO₂ are catalytically converted (FT/methanol-to-jet) using renewable energies, with European cost projections indicating €1.21/L by 2030, that might fall to €0.71/L by 2050 [20]. Some industrial deployments like Pine Bend Refinery aim for 60 Mgal/yr PtL-SAF by 2025, scaling to 1 Ggal/yr with renewable power integration [21].

4. Availability and costs

SAF represents the most scalable near-term option and despite the exponential production growth, remains critically constrained, representing only ~0.2% of global JF demand in 2023 (600 million Liters, 0.5 Mt) [22]. While IATA data indicate a projected tripling to 1.875 billion Liters (~0.53% of demand) in 2024 and 2.7 billion Liters (0.7%) in 2025 [23], this volume constitutes only 6% of total renewable fuel output[18]. Regional disparities further shape the supply landscape: Europe, that hosts 53% of global capacity, produced 1.04 Mt in 2024 and expects 1.6 Mt in 2025 [24] under ReFuelEU's binding mandates [25]. On the other hand, Asia-Pacific faces policy-demand misalignment, with capacity doubling to 3.5 Mt by end-2025 but enforceable SAF mandates delayed until 2026-2027 [26]. North America, driven by U.S. Inflation Reduction Act (IRA) incentives, is projected to supply 44% of global SAF by 2030 [27]. In table 2 the analysis of the trend in SAF production in the last 5 years is reported. It can be noticed that in 2024 1.3 billion Liters of SAF have been produced, that covers 11% of the Renewable Fuel (RF) output. It is expected that the production will double in 2025.

Table 2: trend in SAF production

Year	2019	2020	2021	2022	2023	2024	2025
Estimated SAF Output in Million tonnes (Mt)	<0.02	0.05	0.08	0.24	0.45-0.5**	1	2.1
					(625 billion liters or 3% of RF output)	(1.3 billion liters, 11% of global RF)	(2.7 billion liters, 13% of RF)
Global Jet Fuel (Mt)	287	157	189	233	286*	301	401
SAF % of Global Jet Fuel	<0.01 %	0.03 %	0.04 %	0.1%	0.2%*	0.3%	0.7%

The main problem to be faced is related to the still low production of SAF: available SAF meets only 0.5–0.7% of global demand through 2025 [28], and SkyNRG forecasts a 23 Mt annual shortfall by 2035 due to HEFA feedstock limitations and slow technology diversification [24]. On the other hand, Asia's SAF production capacity estimated to reach 3.5 Mt by end of 2025, might influence near-term price erosion until appropriate policies are activated [26].

The main factors that affect the availability of SAF are summarized in table 3.

Table 2: trend in SAF production

Factor	Impact
Feedstock constraints	HEFA-based oil/fat feedstocks are limited and under competition
Policy consistency	Mandates (EU ReFuelEU, U.S. RFS expansion, Asia mandates) are central to scaling supply
Infrastructure, registry	Launch of IATA's SAF Registry in 2025 enables transparent accounting and tradeability
Cost, offtake	High SAF premium (2-5 times kerosene) limits airline purchasing; offtake deals and co-processing incentives are essential.

In its 2021 SAF Roadmap, IATA projected that SAF could account for up to 65% of the aviation sector's CO₂ reductions needed by 2050, with an estimated 7.9 billion Liters required annually by 2030 [29]. Despite expanding policy support and accelerating technological progress, SAF remains substantially more expensive than conventional Jet A-1. As of 2025, the average production cost of SAF is estimated to range between €1.00–2.50 per Liter, depending on the pathway, plant size, feedstock, and location. Scientific and economic analyses suggest that a multidimensional

optimization strategy-spanning scale-up, infrastructure integration, catalytic innovation, and regulatory incentives, could reduce this cost gap over the next decade.

Economies of scale remain a fundamental lever for cost reduction. According to Habermeyer et al., a 100 MW-scale Power Biomass-to-Liquid (PbTL) facility in northern Europe could achieve cost reductions of over 35% compared to small-scale installations, particularly when integrated with regional district heating and carbon reuse systems [30].

Co-processing biogenic intermediates within existing fossil fuel refining infrastructure is another practical short-term measure to reduce SAF production costs. This approach avoids full greenfield investment and enables partial SAF deployment using existing hydrotreaters, hydrogen supply, and utilities. Although not suitable for all pathways, co-processing offers 15-30% cost reductions in HEFA- and HTL-derived intermediates, particularly under ASTM Annex A6 guidelines [31].

Feedstock cost is the main contributor to SAF price, in especially for HEFA and lignocellulosic routes. Recent analysis by the ICCT (International Council on Clean Transportation) found that achieving the EU's 2035 ReFuelEU Aviation target will require sourcing up to 20 Mt of dry biomass annually, with highly localized supply chains needed to reduce transport and handling costs [32]. Multi-feedstock strategies combining WCO, forestry residues, and agricultural waste can stabilize price exposure and enhance flexibility.

Advancements in catalysis-especially for lignocellulosic and waste-based routes can drive significant efficiency gains. Mansy et al. highlight several multi-functional catalytic systems that simultaneously reduce hydrogen consumption and increase selectivity to jet-range hydrocarbons. For example, bifunctional catalysts based on Pt/SAPO-11 and Ni-ZSM-5 can reduce H₂ demand by up to 25%, contributing directly to OPEX (Operational Expenditure) reductions in FT-SPK and AtJ-SPK processes [31]. Furthermore, simplified reaction schemes and single-reactor architectures reduce both capital costs and energy intensity, helping improve process economics and lifecycle GHG metrics.

Regulatory mechanisms remain indispensable to bridge the cost gap with fossil JF. Under the ReFuelEU Aviation Regulation, EU airlines must blend 2% SAF by 2025, scaling to 6% by 2030 and 70% by 2050 [33]. These mandates are supported by the EU Emissions Trading System (ETS), where carbon prices exceeded €90 per ton of CO₂ in early 2025, equivalent to a €285-350/tonne uplift in fossil JF costs [34].

5. Conclusion

SAF represents the aviation sector's most viable pathway to decarbonization, yet its scalability faces critical interdependencies across feedstock sustainability, technological maturity, geopolitical dynamics, and cost structures. While first-generation lipid-based feedstocks (e.g., WCO, tallow) dominate current production (more than 90%), their inherent scarcity and land-use constraints necessitate a transition toward lignocellulosic biomass, which have a theoretical potential of more than 100 EJ/year, and synthetic pathways like PtL. Catalytic processing applied to HEFA production gives advantage such as the use of ambient-temperature performance of electrochemical FT with a 60% jet-yield catalysts, though production remains concentrated in policy-driven regions; indeed Europe North America and Asia have different approaches and views on the handling of SAF, with the consequence that SAF supplied just 0.2% of global jet demand in 2023, with projections indicating only 0.7% by 2025, that is far below the 65% contribution needed by 2050 to meet climate targets. The cost gap between SAF and conventional JF (2-5 times) is still large, due to feedstock dominance in OPEX, energy-intensive processes and nascent scale. In order to overcome the 23 Mt annual deficit by 2035 a combined approach is needed: feedstock diversification (beyond HEFA-limited supply chains), industrial symbiosis (e.g., refinery co-processing, renewable energy integration), catalytic innovations reducing hydrogen consumption and boosting yields and, most important, globally aligned policy frameworks (blending mandates, carbon pricing, sustainability certification).

Achieving net-zero in aviation demands urgent, coordinated action: advancing R&D, accelerating infrastructure modernization, and fostering global partnerships to overcome critical barriers.

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