PERSPECTIVE

Feedstock Quality and Conversion Efficiency as Key Determinants of Sustainable Aviation Fuel Production: Pathways, Reactions, and Challenges

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Abstract

Sustainable Aviation Fuel is the most viable near-term strategy for decarbonizing commercial aviation. Its performance depends fundamentally on the quality of the feedstock and conversion efficiency. This paper examines the four principal ASTM-certified pathways: Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK), Alcohol-to-Jet (ATJ), and Power-to-Liquid (PtL/eSAF). Additionally, it highlights how feedstock chemical composition, contaminants, moisture content, and carbon intensity affect conversion outcomes, including fuel yield, catalyst performance, minimum fuel selling price, and lifecycle greenhouse gas reduction. Feedstock cost accounts for 60-80% of the minimum fuel selling price across bio-based pathways. Fatty acid chain-length profiles directly determine hydrocarbon yield and jet-fraction selectivity in HEFA. Lignocellulosic heterogeneity is the principal technical bottleneck in gasification-FT routes. PtL pathways decouple production from biological feedstock constraints by substituting renewable electricity cost and CO_2 source quality as the governing variables.

Keywords: sustainable aviation fuel, reactions, HEFA, Fischer-Tropsch, Alcohol-to-Jet, Power-to-Liquid.

1 Introduction

Aviation accounts for roughly 2% of global CO_2 emissions and approximately 12% of transport-sector CO_2. Long-haul routes cannot rely on electrification or hydrogen fuel cells in the foreseeable future. Sustainable Aviation Fuel, aviation turbine fuel containing synthesized hydrocarbons from non-petroleum feedstocks (under ASTM D7566 for blended use and ASTM D1655 for co-processing), offers a drop-in replacement for conventional Jet A/A-1 without requiring aircraft or fueling infrastructure modifications [1, 2]. Currently, the International Civil Aviation Organization has established a net-zero target for 2050. The ReFuelEU Aviation mandate requires 2% SAF blending from 2025, rising to 70% by 2050. Global SAF production reached approximately one million tonnes in 2024, while U.S. jet fuel consumption

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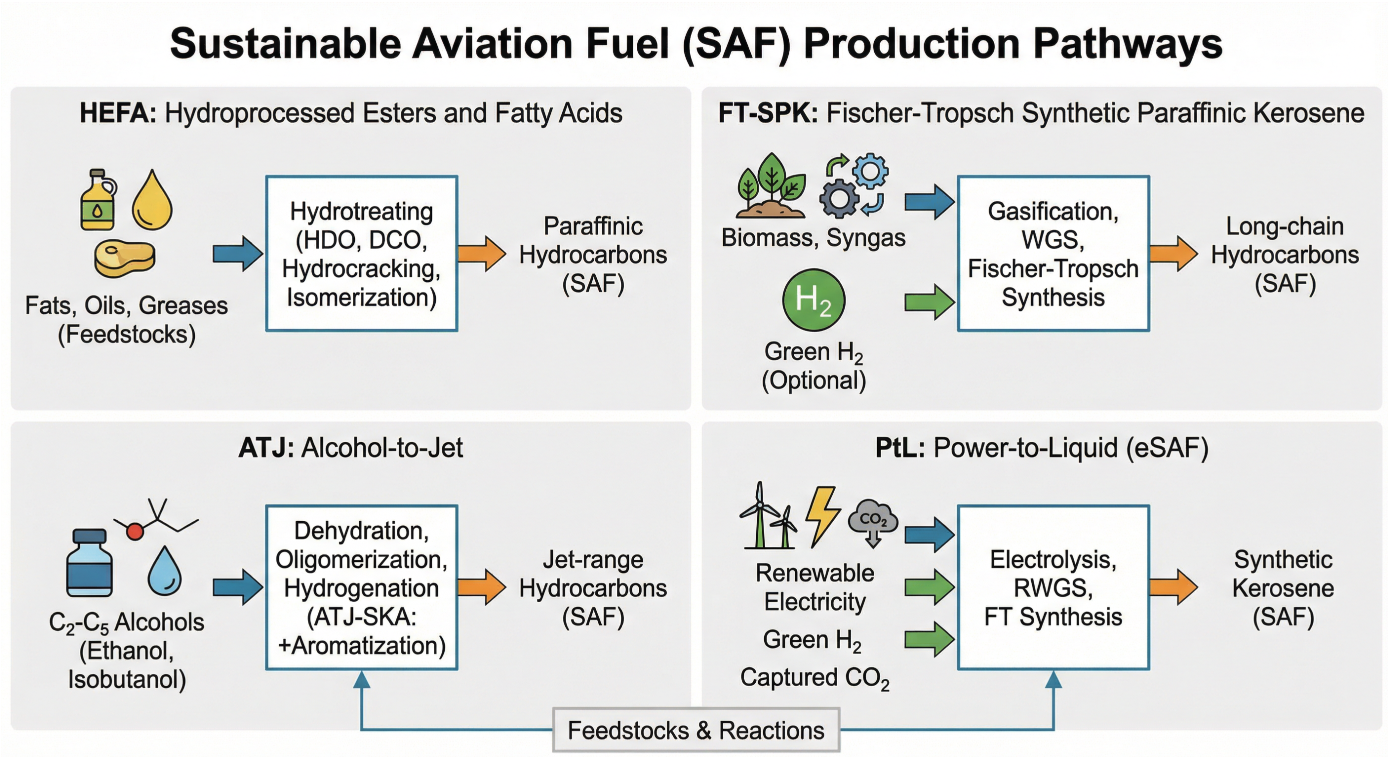

Figure 1. General SAF production pathways.

approaches 25 billion gallons annually, a 25-fold gap. Meeting the U.S. SAF Grand Challenge target of 35 billion gallons per year by 2050 requires scaling production by roughly twelve times from 2030 milestones [3–5].

This work argues that feedstock quality and conversion efficiency are tightly coupled determinants of SAF viability. Current analysis frameworks that treat them as independent variables often underestimate the real-world complexity of optimization. The study examines how specific feedstock attributes, e.g., lipid composition, lignocellulosic heterogeneity, alcohol carbon intensity, and CO_2 source purity, interact with conversion chemistry across each certified pathway. It reviews the central reactions involved, identifies critical impurity interactions and process constraints, and proposes priority research directions for cost-competitive, low-carbon SAF production.

2 Overview of SAF Production Pathways

Four principal pathways have achieved commercial relevance for SAF production (Figure 1). HEFA (Hydroprocessed Esters and Fatty Acids) is the dominant route, converting fats, oils, and greases into paraffinic hydrocarbons through hydrotreating and isomerization and accounting for over 99% of global SAF supply and approved for blending up to 50% with conventional Jet A [6–11]. Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) reactions transform biomass-derived syngas via gasification and catalytic synthesis into long-chain hydrocarbons, approaching commercial readiness at a pioneer scale [12–14]. Alcohol-to-Jet (ATJ) converts ethanol, isobutanol, or mixed C_2-C_5 alcohols to jet-range hydrocarbons through dehydration, oligomerization, and hydrogenation. The recently approved ATJ-SKA variant can synthesize aromatics, producing fuel chemically equivalent to fossil kerosene [10, 15–17]. Power-to-Liquid (PtL/eSAF) synthesizes jet-range hydrocarbons from renewable electricity, electrolytically produced green hydrogen, and captured CO_2. The ReFuelEU regulation establishes a dedicated PtL sub-target of 1.2% from 2030, rising to 35% by 2050 [7, 18, 19].

3 Feedstock Quality: Chemical Composition, Contaminants, and Their Process Implications

Lipids, triglycerides, and free fatty acids (FFA) are ideal for HEFA because their high CH_2 content and low heteroatom concentration produce high hydrocarbon yields with minimal deoxygenation demands. Fatty acid chain-length profiles determine product distribution. Soybean and canola oils are dominated by C_{16} and C_{18} fatty acids, which produce diesel-range hydrocarbons (C_{15}-C_{18}). Maximizing jet fraction (C_8-C_{16}) requires additional hydrocracking. Coconut oil, rich in shorter-chain (C_8-C_{14}) fatty acids, favors renewable gasoline. Polyunsaturated feedstocks, such as soybean oil, require substantially more hydrogen for saturation than saturated feedstocks like animal tallow, which increases operating costs and carbon intensity unless green hydrogen is used [4, 20, 23]. Contamination in waste streams (spent cooking oil, yellow and brown grease, animal fats) is the dominant operational challenge. Phosphorus is the critical contaminant. Without rigorous pretreatment (degumming, bleaching, drying), feedstocks with elevated phosphorus (50-500 ppm in crude oils) reduce catalyst life by 40-60% and increase hydrogen consumption by 15-25%. The composition of free fatty acids exceeding 2% promotes undesirable decarboxylation and decarbonylation, resulting in carbon loss to CO_2 and CO rather than liquid fuel [1, 16].

Agricultural residues (such as wheat straw, corn stover, and rice husks), forestry waste, and municipal solid waste offer enormous potential, estimated at several billion tonnes annually, but present qualitatively different challenges. These materials vary widely: moisture content ranges from 10-50% in fresh residues, ash content from 5-15% by weight (silica, calcium, alkali metals), and lignocellulosic ratios (cellulose 40-50%, hemicellulose 20-30%, lignin 15-25%). An elevated oxygen content (40-45% by weight) necessitates intensive energy for deoxygenation. Moisture content has an inverse relationship with gasification cold gas efficiency [8, 22]. Syngas quality determines FT conversion efficiency. Biomass gasification produces hydrogen sulfide, hydrogen chloride, ammonia, heavy metals, alkali vapors, and tar, all requiring reduction to sub-ppm levels before FT synthesis. High ash content catalyzes secondary tar-forming reactions, potentially halving liquid yields. Municipal solid waste feedstocks contain chlorinated organic contaminants from plastics, necessitating their specific removal. Despite decade-long investments, no commercial-scale standalone biomass-to-liquid FT facility for SAF has achieved sustained profitable operation [16].

ATJ is uniquely positioned as a bridge between feedstock diversity and aviation-grade production of fuel. Any fermentable carbon source can serve as the upstream precursor, provided alcohol quality is sufficient for catalytic upgrading. ATJ-SAF lifecycle carbon intensity depends primarily on upstream alcohol production, not the catalytic step itself. Corn-grain-derived ethanol achieves only about 15% lower carbon intensity than conventional jet fuel, unless carbon capture and sustainable farming practices are integrated. Cellulosic ethanol from agricultural residues achieves a 60-90% reduction of greenhouse gas relative to fossil jet fuel, making feedstock origin the decisive sustainability parameter. Isobutanol (C_4) offers 34% lower ATJ conversion cost than ethanol (C_2) due to more favorable dehydration and oligomerization thermodynamics, which is often offset by higher fermentation costs. Industrial waste-gas-derived ethanol, from steel mill flue gas fermentation, combines low cost, potentially very low carbon intensity (subject to counterfactual accounting), and avoidance of agricultural land use competition [15, 21].

PtL pathways replace biological feedstocks with CO_2 (from direct air capture or industrial point sources) and green hydrogen (from water electrolysis), decoupling production from land, water, and agricultural constraints. Key quality parameters shift to: (i) electricity carbon intensity; (ii) CO_2 supply purity and concentration; (iii) electrolyser efficiency. Grid electricity with significant fossil fuel content yields negligible or negative lifecycle greenhouse gas reductions. Analysis estimates that at least 84.6% of electricity input must derive from renewable sources to achieve emissions comparable to those of conventional jet fuel. Using renewable electricity with direct air capture yields theoretical lifecycle greenhouse gas reductions approaching 100%. Current process requirements are approximately 0.8 kg H_2 and 3.1 kg CO_2 per kilogram of SAF [18, 21].

4 Central Reactions Across SAF Production Pathways

HEFA converts lipid triglycerides to jet-range paraffin hydrocarbons through three sequential stages. Hydrodeoxygenation (HDO) removes oxygen via

$$C_nH_{2n}O_2 + 2H_2 \Rightarrow C_nH_{2n+2} + 2H_2O$$

The competing pathway, decarboxylation/decarbonylation (DCO), removes oxygen as CO_2 or CO via

$$C_nH_{2n}O_2 \Rightarrow C_{n-1}H_{2n} + CO_2$$

resulting in a one-carbon shorter chain and gas-phase carbon loss. HDO is preferred economically because it retains more carbon in the liquid product, but demands more hydrogen. The balance depends on catalyst formulation, temperature, and feedstock FFA content. Hydrocracking and hydroisomerization crack longer-chain ($C_{17} - C_{22}$) normal paraffins from C_{18} fatty acids into jet-range ($C_8 - C_{16}$) products and simultaneously isomerize linear paraffins to branched isoparaffins, improving cold-flow properties and meeting the $-47\,°C$ freeze point specification for Jet A-1. Maximizing jet yield requires additional reactor capacity and hydrogen consumption compared to renewable-diesel configurations, with estimated trade-offs of several hundred thousand tonnes of greenhouse gas reduction when the jet pathway is prioritized [4, 8, 20].

FT-SPK proceeds through gasification of carbonaceous feedstock at 800–1200 °C in steam and/or oxygen. Primary gasification reactions are

$$\mathrm{C + H_2O \Rightarrow CO + H_2} \quad \text{(steam reforming)}$$

$$\mathrm{C + O_2 \Rightarrow CO_2} \quad \text{(partial oxidation)}$$

producing raw syngas of CO, H_2, CO_2, CH_4, and impurities. The water-gas shift (WGS) reaction,

$$\mathrm{CO + H_2O \Rightarrow CO_2 + H_2}$$

adjusts the H_2/CO molar ratio to approximately 2.0 required for optimal FT synthesis. Fischer-Tropsch synthesis polymerizes syngas to produce straight-chain hydrocarbons following the Anderson-Schulz-Flory (ASF) statistical distribution:

$$\mathrm{nCO + (2n+1)H_2 \Leftrightarrow C_nH_{2n+2} + nH_2O}$$

The ASF chain-growth parameter (alpha) governs product distribution but limits straight-run jet fractions to about 40% of liquids. Supplementing biomass-derived syngas with electrolytic green hydrogen raises the H_2/CO ratio without water-gas shift losses, increasing carbon efficiency from 32.6% to 94.5% and overall energy efficiency from 33.1% to 50.9% [7, 9].

ATJ converts C_2-C_5 alcohols to jet-range hydrocarbons through three catalytic steps. Dehydration converts ethanol to ethylene

$$\mathrm{C_2H_5OH \Rightarrow C_2H_4 + H_2O}$$

or isobutanol to isobutylene

$$\mathrm{C_4H_9OH \Rightarrow C_4H_8 + H_2O}$$

Oligomerization couples light alkenes, producing C_8-C_{16} branched olefins. Final hydrogenation saturates olefins to isoparaffins:

$$\mathrm{C_nH_{2n} + H_2 \Rightarrow C_nH_{2n+2}}$$

ATJ-SKA adds dehydrogenation and aromatization steps, generating aviation-range aromatics, addressing the seal-swelling compatibility limitation of other paraffinic SAF pathways. Overall carbon efficiency from fermentable sugars to jet fuel is about 25–35% on a mass basis. Upstream fermentation quality directly affects carbon and energy efficiency by reducing fermentation yield and potentially fouling downstream catalysts [8, 15].

PtL production begins with water electrolysis:

$$\mathrm{H_2O \Rightarrow H_2 + 1/2\,O_2},$$

performed over alkaline, proton exchange membrane (PEM), or solid oxide electrolysis cells (SOEC), with current efficiencies of 65–75% for alkaline/PEM and potentially 80–90% for SOEC when integrated with high-temperature process heat. Captured CO_2 converts to CO via Reverse Water-Gas Shift (RWGS), achieving about 90% conversion at design conditions. The resulting CO/H_2 syngas undergoes FT synthesis. Overall, electricity-to-liquid conversion efficiency is typically 40–55% on an energy basis, requiring approximately 2.0–2.5 MJ of renewable electricity per MJ of SAF [7, 19].

5 Conversion Efficiency, Comparative Performance, and Future Directions

Conversion efficiency in SAF production involves several key metrics (Table 1): energy efficiency, carbon efficiency, yield, and cost. HEFA demonstrate the highest energy efficiency (70-85%) due to effective deoxygenation, requiring only 19.6 kWh/tonne of feedstock, significantly less than lignocellulosic pathways like Virent Bioforming. FT-SPK exhibit lower efficiencies (30-50% for energy and 25-45% for carbon) due to multi-stage conversion processes that introduce thermodynamic losses. Combining green hydrogen with FT synthesis can increase SAF yields by 70% while lowering production costs by 18%. ATJ technology yields approximately 1.6 times more SAF than FT-SPK with efficiencies of 55-65%. PtL shows the lowest overall efficiency (40-55%) but achieves excellent carbon utilization from CO_2. Notably, feedstock costs account for 60-80% of minimum fuel selling price (MFSP), emphasizing the need to enhance feedstock supply chain costs alongside conversion efficiencies.

Pretreatment processes are crucial for removing feedstock contaminants before conversion, with advanced technologies, such as hydrothermal cleanup, achieving minimal yield loss. Operational data

Table 1. Comparative Efficiency Metrics for Sustainable Aviation Fuel Production Pathways.

Pathway	Primary Feedstocks	SAF Yield (%)	MFSP ($/L)	Energy Efficiency (%)	Carbon Efficiency(%)
HEFA	Vegetable oils (soybean, canola, corn, palm, jatropha, camelina, carinata, tung), animal fats (tallow, chicken fat), spent cooking oil, yellow grease, algae oil, fats, oils, and greases	15–83	0.8–1.8	70–85	70–80
PtL	Captured CO_2 (Direct Air Capture, point source), Renewable/Green Hydrogen (electrolysis), water, renewable electricity	24–75	3.5–5.0	40–55	~100 (from CO_2)
ATJ	Ethanol, isobutanol, corn (grain, stover, kernel fiber), sugarcane, wheat (grain, straw), sugar beet, lignocellulosic biomass, waste gases, industrial flue gas, starches	30–90	1.2–2.8	55–65	55–65
FT-SPK	Lignocellulosic biomass (agricultural and forestry residues), municipal solid waste, woody biomass, energy crops, herbaceous crops, coal, natural gas	18–57	1.3–3.0	30–50	25–45

indicate that facilities without proper pretreatment face economic challenges due to catalyst fouling.

Five critical research areas require further investigation: standardization of analytical protocols for novel feedstocks, long-duration catalyst performance data under waste conditions, lifecycle carbon intensity assessment methods, techno-economic studies on retrofitting existing plants for SAF production, and real-world data on PtL conversion efficiencies at commercial scales. Addressing these gaps is essential for optimizing SAF production pathways.

6 Conclusion

Feedstock quality and conversion efficiency are inseparably intertwined determinants of SAF technical performance, economic viability, and environmental outcomes. The central reactions of each pathway (HEFA, FT-SPK, ATJ, and PtL) all exhibit strong sensitivity to feedstock composition and impurity profiles. These coupled constraints cannot be resolved through single-parameter optimization. *Pretreatment* is a prerequisite rather than an optional enhancement for waste-derived feedstocks. The high efficiency and commercial maturity of HEFA are offset by a fundamental lipid availability, necessitating pathway diversification. ATJ-SAF greenhouse gas performance is determined upstream by alcohol carbon intensity, not the conversion step. PtL offers the highest theoretical sustainability ceiling but demands very low renewable electricity costs that are only beginning to emerge in optimal geographic regions.

No single feedstock-conversion pathway combination will satisfy global SAF demand by 2050. A portfolio approach offers the most robust trajectory: HEFA in the near term, supplemented by FT-SPK and ATJ from diverse low-carbon-intensity feedstocks in the medium term, transitioning progressively toward PtL as renewable electricity costs decline. Achieving this requires simultaneous advances in feedstock characterization standards, catalyst resilience to waste-stream contaminants, harmonized lifecycle carbon methodology, and integrated process design that treats feedstock quality and conversion chemistry as coupled rather than independent variables.

Data Availability Statement

Not applicable.

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Conflicts of Interest

The author declares no conflicts of interest.

AI Use Statement

The author declares that AI tools were used in the preparation of this manuscript. Grammarly was employed to improve language readability and writing quality, and Gemini was used to assist in the creation of Figure 1. The author takes full responsibility for the content, accuracy, and integrity of the manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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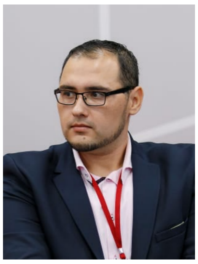

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