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Progress and Prospects of Sustainable Aviation Fuel Implementation: A Critical Analysis, Challenges and Conclusions

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Abstract: Modern aviation is one of the main consumers of petroleum-based fuels, consuming nearly 100 million gallons of fuel per year, and this consumption continues to grow. On the other hand, airlines have committed to achieving net-zero carbon dioxide (CO_2) emissions in the industry by 2050. Fulfilling this commitment necessitates the investigation of new and the optimization of existing processes for the production of alternative, renewable, and environmentally safe feedstocks. This article was prepared as part of the research project "Development of Technological Solutions for Obtaining Composite Motor Fuels from Secondary Raw Materials to Enhance Energy Security".

Keywords: sustainable aviation fuel (SAF); hydroprocessed esters and fatty acids (HEFA); alternative aviation fuels; animal fat hydrocracking; carbon dioxide emissions reduction; renewable feedstocks; energy efficiency in aviation

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1. Introduction

Air transportation is a key component of the modern economy, providing rapid and reliable transportation of passengers and cargo. Each year, billions of people use airline services, while the volume of goods and mail transported continues to grow, stimulating the development of international trade and enhancing economic integration [1]. However, despite its strategic importance, the aviation sector remains one of the largest consumers of fossil fuels, thereby exerting a significant impact on the environment.

The use of conventional jet fuel, which is mainly derived from petroleum, poses serious environmental and economic challenges. Greenhouse gas emissions associated with the production, transportation, and combustion of aviation fuel contribute to global warming, while the dependence on finite fossil fuel resources makes the industry vulnerable to price fluctuations, energy shortages, and global geopolitical instability. In response to these challenges, the international community is actively seeking solutions to reduce the environmental impact of aviation and ensuring its energy resilience.

The development of new types of jet fuel derived from renewable resources, known as Sustainable Aviation Fuel (SAF), has become an urgent necessity. SAF has the potential not only to reduce dependence on fossil fuels but also to significantly lower CO_2 emissions while maintaining compatibility with existing aviation engines and infrastructure. Furthermore, the advancement of such technologies offers opportunities to enhance energy security and stimulate economic growth through innovation and the attraction of new investments into the sector.

According to the report by the International Air Transportation Association (IATA) [2], the share of SAF in the leading strategies aimed at achieving net-zero CO_2 emissions in aviation by 2050 ranges from 24% to 70%, with the share of biofuel varying between 10% and 35% as illustrated in Figure 1. And according to IEA forecasts, the global share of renewable energy is expected to grow significantly through 2028, positioning SAF as a strategic contributor to decarbonization efforts in aviation [3].

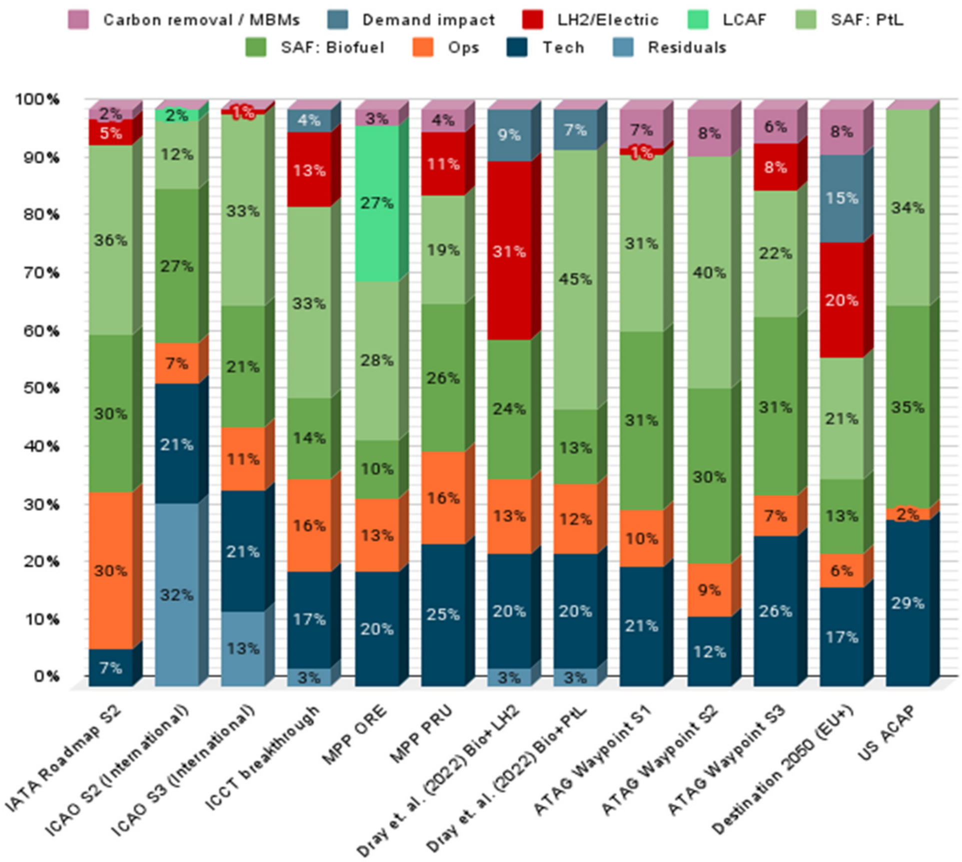

Figure 1. Emission reduction potential by transition measures in 2050, comparing across different roadmaps [2,4].

Recent years have seen growing momentum in both technological progress and international policy regarding SAF deployment. The European Union's "Fit for 55" package mandates an increasing SAF blending obligation starting from 2% in 2025 and reaching 70% by 2050, while the United States aims to produce 3 billion gallons of SAF annually be 2030 under the SAF Grand Challenge Roadmap. ICAO's CORSIA framework and IATA's net-zero roadmap further institutionalize global commitment toward SAF expansion. Technologically, recent advances include high-selectivity isomerization routes for HEFA fuels, hybrid catalytic systems, and novel waste-to-fuel pathways such as catalytic hydrothermolysis and plastic-derived SAF. As of 2024, over 450,000 commercial flights worldwide have used SAF blends, signaling a move from experimentation to scaling.

While certain sources, such as the IATA (2024) roadmap [2] and IEA (2023) projections [3], include forward-looking assessments, they are grounded in the current strategic planning frameworks of major international aviation and energy bodies. These projections are referenced not as predictive certainties but as indicative benchmarks that inform ongoing policymaking, investment, and regulatory alignment efforts within the SAF domain.

This article analyzes current trends in the aviation industry, recent advancements in the field of Sustainable Aviation Fuel (SAF), and provides a detailed comparison of technologies, feedstock bases, and physicochemical properties with the aim of identifying optimal parameters for the hydrocracking process of animal fats to produce ecologically safe components of jet aviation fuel. Our study contributes to the current discourse by examining technical bottlenecks, evaluating environmental and economic feasibility, and aligning hydroprocessing outcomes with international certification standards such as ASTM D7566-24d [5].

The hypothesis of this study is that the research findings will establish the necessary and sufficient conditions for the production of ecologically safe aviation fuels from domestic recycled raw materials, meeting the requirements of ASTM D7566-24d "Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons" [5]. This will enable an estimated 25% savings in petroleum feedstock while simultaneously reducing the anthropogenic impact on the environment by decreasing the share of petroleum-derived hydrocarbons through the substitution with synthetic, ecologically safe components in the composition of new blended fuels, as well as through recycling of waste from the animal industry sector.

The aim of this study is to conduct a comparative and casual analysis of the production processes and future prospects for the utilization of Sustainable Aviation Fuel (SAF).

The subject of the study encompasses the classification, physicochemical characteristics, and performance properties of SAF.

The object of the study comprises the feedstocks and chemical-technological processes involved in the production of advanced SAF.

2. Materials and Methods

This study employed a qualitative and comparative methodology to analyze the potential, limitations, and implementation strategies of Sustainable Aviation Fuel (SAF). The research combined a structured literature review with systematic comparative evaluations using SNW (Strengths–Neutrals–Weaknesses) and GAP analysis frameworks.

The selection of SNW and GAP analyses as primary methodological frameworks was driven by their complementary strengths in evaluating both current performance and future development potential of technologies. SNW analysis allows for a structured yet flexible evaluation of a technology's strengths, neutral aspects, and weaknesses, which is particularly useful in assessing emerging technologies like SAF that operate under evolving regulatory and market conditions. It facilitates a multidimensional overview without requiring quantitative data that may be limited for novel feedstocks such as animal fats. Meanwhile, GAP analysis is widely used in policy and technology assessment for identifying discrepancies between current capabilities and desired objectives, making it highly relevant for mapping barriers to SAF implementation and outlining actionable recommendations. These frameworks were selected over more traditional quantitative techniques (e.g., LCA, MCA) due to the limited availability of region-specific production data, and the exploratory nature of this study, which focuses on feasibility assessment rather than precise techno-economic modeling.

2.1. Literature Sources

Primary data were obtained from peer-reviewed scientific publications, international energy and aviation agency reports (e.g., IATA, ICAO, IEA), and relevant fuel standards

(ASTM D1655 [6], ASTM D7566 [5], DEF STAN 91-091 [7], and DEF STAN 91-91 [8]). The literature included both foundational studies on SAF production pathways and recent advancements in feedstock utilization, particularly animal fats and waste-derived oils.

2.2. SNW Analysis

The SNW framework was applied to evaluate key technical, environmental, and economic attributes of SAF types derived from various production pathways, such as HEFA-SPK, FT-SPK, and ATJ-SPK. The analysis compared SAF against conventional Jet A and Jet A-1 fuels using standard fuel parameters (e.g., viscosity, freezing point, sulfur content, oxidative stability) and implementation factors (e.g., infrastructure compatibility, government incentives, emissions).

The SNW analysis in this study followed a multi-criteria assessment approach. The procedure included the following steps:

1. Criteria Selection

Twelve technical, economic, environmental, safety and regulatory criteria were selected based on relevance to SAF implementation. These include: CO_2, NO_x, and SO_x emissions

2. Rationale for Criteria Selection

The selection of CO_2, NO_x, and SO_x emissions as core environmental criteria was based on their regulatory relevance, climate impact, and availability in comparative fuel data:

- CO_2 (carbon dioxide): A key greenhouse gas (GHG) directly linked to climate change. CO_2 emissions are central to net-zero strategies in aviation and from the basis of international reporting and offset mechanisms (e.g., CORSIA).
- NO_x (nitrogen oxides): Contribute to ozone formation at high altitudes and impact local air quality around airports. Reducing NO_x is a secondary but important sustainability target for next-gen fuels.
- SO_x (sulfur oxides): Regulated due to their role in acid rain formation and particulate matter pollution. Although conventional jet fuels already have sulfur limits, SAF typically achieves near-zero sulfur content, making it competitive advantage.

These emission parameters were selected as they capture both global (CO_2) climate goals and local/regional (NO_x and SO_x), aligning with ICAO and IATA sustainability frameworks.

3. Scoring Mechanism

For each SAF production pathway, every criterion was evaluated and classified using a three-tier qualitative scale, defined as follows:

- S (Strength)—Clear and consistent advantage over conventional Jet A/Jet A-1 fuel (e.g., $\geq$20% reduction in CO_2 emissions, fully compliant with ASTM D7566 without modification).
- N (Neutral)—Comparable to conventional fuels (e.g., differences within $\pm$10% range or performance without significant operational impact).
- W (Weakness)—Noticeable disadvantage or failure to meet industry thresholds (e.g., blending limit <30%, excessive production cost, lack of certification).

Each classification was based on benchmark values drawn from international standards, technical reports, and peer-reviewed data.

4. Interpretation

Aggregated patterns of "S", "N", and "W" designations across criteria helped identify robust SAF candidates and highlight bottlenecks for further research or policy intervention.

2.3. GAP Analysis

The GAP analysis was conducted with a specific focus on hydrocracking of animal fats and involved a structured five-step procedure to enhance methodological transparency and reproducibility:

1. Definition of Current State

Baseline performance indicators were identified using literature data and industry sources. These included production cost per liter, feedstock availability, process energy intensity, emissions from processing, and existing technical limitations in catalyst performance.

2. Target State Definition

Desired benchmarks were defined based on the best international practices, regulatory goals (e.g., ASTM D7566 compliance, net-zero emissions), and techno-economic viability (e.g., breakeven production cost, full engine compatibility).

3. Gap Identification

Deviations between the current and target states were mapped across key domains—economic (e.g., high cost), environmental (e.g., process emissions), technological (e.g., limited advancement in catalyst formulation and optimization), and regulatory (e.g., blending limitations).

4. Root Cause Mapping

For each identified gap, underlying causes were analyzed, such as insufficient research on feedstock impurities, limitation in hydrogen availability, or absence of pilot-scale validation.

5. Recommendations Development

Each gap was linked to a corresponding improvement pathway. For example, optimizing isomerization conditions to enhance cold-flow properties, or designing hybrid catalyst systems to improve selectivity and conversion efficiency.

This approach ensured that the GAP analysis not only identified shortcomings but also provided targeted, actionable strategies for advancing the hydrocracking of animal fats into SAF. It also supported the formulation of policy-relevant recommendations that align with global decarbonization frameworks.

2.4. Technological Classification

The SAF technologies considered in this study were categorized according to ICAO's approved conversion pathways, including but not limited to HEFA, FT, ATJ, SIP, CHJ, and co-processing methods. Technical data such as blending limits, feedstock sources, and certification status were used for comparative analysis.

2.5. Standards and Certification Review

A normative comparison was conducted using international aviation fuel standards to determine the compliance of SAF properties with existing engine and infrastructure requirements. This included evaluation of SAF's conformity with ASTM D1655 and ASTM D7566 specifications, as well as ICAO and IATA guidance documents.

3. Results

3.1. Conventional Aviation Fuel

The primary global standards for conventional aviation fuels are Jet A and Jet A-1 [6–11]. These types of aviation turbine fuels have been used in civil aviation since the mid-20th century. Jet A began to be widely utilized in the United States in the 1950s, when airlines required standardized fuel for commercial flights. Jet A-1, developed later, became the global standard due to its versatile properties that meet the operational requirements of various regions, including cold climate zones.

The standards describing the technical specifications of these fuels are ASTM D1655 "Standard Specification for Aviation Turbine Fuels" and DEF STAN 91-091. Key parameters of Jet A and Jet A-1 aviation fuels include physical properties—density, viscosity, and surface tension, freezing and flash points, heat of combustion; chemical properties—chemical composition, elemental composition, sulfur and water content, oxidative stability. Other important properties include, for example, antistatic properties, which ensure safety during refueling operations by reducing the risk of static electricity accumulation. The key physicochemical characteristics of Jet A and Jet A-1 are summarized in Table 1 according to ASTM D1655 and DEF STAN 91-091 standards.

Table 1. Reference values of key physicochemical characteristics of conventional aviation fuel according to ASTM D1655 and DEF STAN 91-091 standards.

Characteristic	Jet A	Jet A-1
Freezing point	minus 40 °C	minus 47 °C
Flash point	38 °C or higher	
Density at 15 °C	0.775–0.840 g/cm^3	
Viscosity at minus 20 °C	≤8.0 mm^2/s	
Heat of combustion	42.8 MJ/kg	
Sulfur content	≤0.3% mass	
Water content	≤70 mg/kg	
Antistatic additives	may be added	mandatory

3.2. Alternative Aviation Fuel

Currently, there is no standard for 100% SAF. Only the use of SAF blended with conventional Jet A or Jet A-1 fuels up to a certain percentage—typically not exceeding 50% by volume—is permitted [5,8,12]. The use of SAF in the military sector remains extremely limited due to higher standards, the absence of a fully developed technological process, and an insufficient number of traits. However, the potential application of SAF in military aviation is actively being considered by several European countries. In early 2025, the Norwegian Ministry of Defense announced the initiation of operations using F-35 fighter jets fueled with a blend containing 40% SAF [13].

ICAO Global Framework for Aviation Alternative Fuels defines 11 approved technological pathways for converting feedstocks into aviation fuel [12]. They are Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene (FT); Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids (HEFA); Synthesized iso-paraffins from hydroprocessed fermented sugars (SIP); Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources (FT-SKA); Alcohol to jet synthetic paraffinic kerosene (ATJ-SPK); Catalytic hydrothermolysis jet fuel (CHJ); Synthesized paraffinic kerosene from hydrocarbon—hydroprocessed esters and fatty acids (HC-HEFA-SPK); Synthetic Paraffinic Kerosene with Aromatics (ATJ-SKA); Co-hydroprocessing of esters and fatty acids in a conventional petroleum refinery; co-hydroprocessing of Fischer-Tropsch hydrocarbons in a conventional petroleum refinery; Co-Processing of HEFA.

Comparative analyses of SAF properties demonstrate substantial variability depending on both feedstock and production technology [14,15], as summarized in Table 2.

Table 2. Comparison of the main physicochemical characteristics of SAF types by production technology.

Characteristics	HEFA-SPK	FT-SPK	SIP	ATJ-SPK	PTL	RCF	HFS-SIP
Max blend %	50	50	10	50	-	-	-
Feedstock	Vegetable oils, animal fats, used cooking oil, waste-derived fats	Lignocellulosic biomass (wood, agricultural residues); wet organic waste (animal manure, household organic waste, sewage sludge); micro and macroalgae	Sugar-containing materials (sugarcane, sugar beet, corn)	Ethanol, butanol, other alcohols (agricultural crops, lignocellulosic materials, industrial waste)	Carbon dioxide and hydrogen derived from renewable sources	Plastic waste, industrial gas emissions, solid and liquid carbon-containing waste	Sugar-containing biomass and waste
Freezing point	−47 °C	−50 °C	−30 °C	−80 °C	−47 °C	−47 °C	−30 °C
Flash point	≥38 °C	49 °C	100 °C	45–50 °C	≥38 °C	≥38 °C	≥38 °C
Density at 15 °C	0.760 g/cm^3	0.750 g/cm^3	0.805 g/cm^3	0.757 g/cm^3	0.775–0.840 g/cm^3	0.775–0.840 g/cm^3	~0.78 g/cm^3
Viscosity at −20 °C	2.997 mm^2/s	3.177 mm^2/s	2.997 mm^2/s	3.177 mm^2/s	3.0–4.0 mm^2/s	3.0–4.0 mm^2/s	3.0–4.0 mm^2/s
Heat combustion	42.8 MJ/kg	44.0 MJ/kg	43.0 MJ/kg	42.8 MJ/kg	43.5 MJ/kg	43.2 MJ/kg	44.0 MJ/kg
Sulfur content	0.0003–0.0007% mass	0.0015% mass	≤0.001% mass	≤0.001% mass	~0% mass	~0% mass	~0% mass
Water content	≤50 mg/kg	≤50 mg/kg	≤50 mg/kg	≤50 mg/kg	≤50 mg/kg	≤50 mg/kg	≤50 mg/kg
Antistatic additives	Added as needed to achieve electrical conductivity of 50–600 pS/m.						

3.3. Analysis

For the purpose of comprehensive analysis, SNW and GAP analysis methods were applied. The study involved a comparative assessment of conventional aviation fuels and alternative fuels, with a particular focus on various alternative fuel types categorized by their production technologies. This approach enabled the identification of key strengths, needs, and potential gaps in the adoption and scalability of each fuel type within the aviation industry.

An SNW analysis was conducted to assess the strengths, neutral factors, and weaknesses of SAF, providing a comprehensive evaluation of its advantages as well as identifying the challenges and limitations compared to conventional aviation fuels (Table 3).

Table 3. SNW analysis of SAF based on key technical, economic, and environmental characteristics.

Characteristics	SAF vs. Conv.	FT	HEFA	SIP	FT-SKA	ATJ-SPK	CHJ	HC-HEFA-SPK	ATJ-SKA	Co-HP of EFA [1]	Co-HP of FT Hydrocarbons [1]	HEFA from Biomass
Availability and Production												
Availability in Ukraine	N	N	N	W	N	W	W	N	W	W	W	N
Global availability	S	S	S	W	S	N	N	S	N	N	N	S
Dependance on Imports	S/N [2]	N	N	N	N	W	W	N	W	W	W	N
Implementation costs	W	W	W	W	W	W	W	W	W	W	W	W
Environmental Impact [2,9]												
CO_2 emission	S	S	S	S	S	S	S	S	S	S	S	S
NO_x emission	N	N	N	N	N	N	N	N	N	N	N	N
SO_x emission	S	S	S	S	S	S	S	S	S	S	S	S
Safe disposal	S	S	S	S	S	S	S	S	S	S	S	S
Energy Efficiency [16]												
Combustion efficiency	S	S	S	N	S	N	N	S	N	N	N	S
Energy content per unit	N	N	N	N	N	N	N	N	N	N	N	N
Fuel weight-to-energy ratio	N	N	N	N	N	N	N	N	N	N	N	N
Fuel consumption per km of flight	N	N	N	N	N	N	N	N	N	N	N	N
Cost												
Production cost [9,17,18]	W	W	W	W	W	W	W	W	W	W	W	W
Logistics cost [18]	N	N	N	N	N	N	N	N	N	N	N	N
Availability of Government subsidies and incentives	S	S	S	S	S	S	S	S	S	S	S	S
Safety and Reliability												
Low temperature resistance	S	S	S	N	S	N	N	S	N	N	N	S
High temperature resistance	S	S	S	N	S	N	N	S	N	N	N	S
Risk of ignition or explosion	N	N	N	N	N	N	N	N	N	N	N	N

Table 3. *Cont.*

Characteristics	SAF vs. Conv.	FT	HEFA	SIP	FT-SKA	ATJ-SPK	CHJ	HC-HEFA-SPK	ATJ-SKA	Co-HP of EFA [1]	Co-HP of FT Hydrocarbons [1]	HEFA from Biomass
Shelf life (without degradation)	S	S	S	S	S	S	S	S	S	S	S	S
Special transportation and/or storage requirements	N	N	N	N	N	N	N	N	N	N	N	N
Infrastructure [2,16]												
Compatibility with existing infrastructure	S	S	S	N	S	N	N	S	N	N	N	S
Compatibility with existing engines	S	S	S	N	S	N	N	S	N	N	N	S
Certification												
ICAO [12]	S	S	S	S	S	S	S	S	S	S	S	S
ASTM	S	S	S	S	S	S	S	S	S	S	S	S
IATA	S	S	S	S	S	S	S	S	S	S	S	S
Support through long-term decarbonization programs [2]	S	S	S	S	S	S	S	S	S	S	S	S

[1] In a conventional petroleum refinery. [2] S, if domestic feedstocks are available. Otherwise N.

Research in the field of SAF indicates the necessity of improving existing processes, particularly the hydrocracking of animal fats, which is considered one of the promising pathways for SAF production.

The analysis of barriers and opportunities for technological development is critically important for enhancing product yield, reducing production costs, and minimizing environmental impact. Table 4 presents a GAP analysis of SAF production technologies, with an emphasis on identifying critical technological, economic, and regulatory gaps.

Table 4. GAP analysis of SAF Technologies with a focus on the hydrocracking of animal fats.

Criterion	Current State	Target State	Gap	Recommendations
Economic efficiency	High production cost compared to conventional jet fuel	Cost reduction through process optimization and energy consumption reduction	High production costs	Development of methods to reduce production costs and improve energy efficiency
Environmental impact	SAF significantly reduces CO_2 emissions, but production still generates unwanted emissions	Minimize additional emissions at the production phase	Emissions at the production phase	Optimizing technologies to minimize the carbon dioxide footprint

Table 4. *Cont.*

Criterion	Current State	Target State	Gap	Recommendations
Feedstock base	Animal fats are available as waste from the animal industry sector, but their use in the SAF production is limited	Expanding the use of animal fats as feedstock for SAF	Limited utilization of animal fats due to an insufficient research foundation	Initiating comprehensive studies on the feasibility, efficiency and optimization of animal fats as a feedstock for SAF production
Technological limitations	Optimization of the hydrocracking process for animal fats is necessary to improve processing efficiency and yield	Advancing catalyst development and optimizing hydrocracking process conditions to maximize SAF yield	Optimization of technological parameters for the hydrocracking of animal fats remains incomplete	Catalyst development and technological enhancement of the hydrocracking process for animal fats [1]
Market availability	Limited market share of SAF resulting from high production costs and restricted manufacturing capacity	Expansion of the SAF market share driven by cost reductions through technological optimization	Absence of large-scale SAF production facilities	Expansion of production capacity, attraction of investments, and initiation of additional research activities [2]
Regulatory requirements	Limitation on the maximum allowable percentage of SAF in blends with conventional aviation fuel	Certification up to 100% of SAF blending ratios.	Utilization of SAF as a standalone fuel without the need for blending	The need for adaptation and international certification to enable 100% SAF integration. Amendments to international standards to facilitate broader adoption of SAF

[1] recent studies suggest that isomerization strategies can significantly improve fuel cold-flow properties while maintaining HEFA compliance [19]. [2] multi-criteria supplier evaluation frameworks may support effective SAF sourcing and decision-making under uncertainty [20].

4. Results and Discussion

Alternative aviation fuels are a key area of development in the aviation industry, aimed at reducing environmental impact and lowering CO_2 emissions toward net-zero targets. Research in this field demonstrates significant progress in the development and implementation of environmentally sustainable fuel technologies. SAF produced from biological feedstocks and various types of waste—such as through hydrothermal liquefaction of wet organic materials—shows substantial potential for reducing CO_2 emissions, improving energy efficiency, and enhancing the energy independence of the aviation sector [21].

SWOT, SNW, and GAP analyses conducted within the scope of this article demonstrate that the Physicochemical properties of SAF, particularly viscosity, heat of combustion, and oxidative stability, largely meet the standards of conventional jet fuel, allowing their use in modern aviation engines without the need for substantial modifications or significant reductions in engine lifespan. The analysis of existing technologies indicates that the most promising processes are the hydroprocessed esters and fatty acids (HEFA) method, the Fischer-Tropsch synthesis of paraffins (FT-SPK), and the alcohol-to-jet conversion (ATJ-SPK), with FT-SPK standing out for its scalability and synthesis pathway efficiency [22]. Animal fats have a high content of saturated fatty acids, making them an ideal substrate, ensuring a stable yield of fuel with high energy density and high selectivity under optimized hydroconversion conditions [23]. These methods ensure high product quality and compliance with international aviation fuel standards.

The use of animal fats for SAF production appears to be one of the most promising solutions due to the availability, sustainability, and technological suitability of this feedstock. Animal fats offer several advantages compared to other sources, such as vegetable oils or synthetic gases. They are a by-product of the meat and fish industries, ensuring a continuous supply without the need for dedicated cultivation of feedstock. Unlike vegetable oils, which require large areas of agricultural land, animal fats do not compete with food production and do not contribute to land-use change. The cultivation of oil crops such as palm oil has been associated with deforestation and sustainability challenges in developing countries, as evidenced by policy implementation difficulties in regions like Liberia [24]. Therefore, animal fats represent a more environmentally acceptable and socially responsible source for SAF production. Previous research has identified both the promise and processing challenges of using animal fats as SAF feedstock, especially related to hydrogenation and impurity control [25].

The hydroprocessed esters and fatty acids (HEFA) process is the most mature and certified technology for producing alternative jet fuel. Animal fats have a high content of saturated fatty acids, making them an ideal substrate, ensuring a stable yield of fuel with high energy density and compliance with international aviation standards (ASTM D7566).

Utilizing animal fats for SAF production reduces the amount of organic waste, which would otherwise pose environmental risks as soil and water pollution. Additionally, the conversion of meat industry by-products into biofuel supports the creation of closed production cycles, aligning with the principles of the circular economy.

Due to the low cost of animal fats as a feedstock, SAF production via the HEFA process has the potential to become competitive on the market. Stable supply and relatively low price fluctuations of animal fats compared to vegetable oils provide an economic advantage for the long-term development of the biofuel sector, a conclusion supported by techno-economic assessments of SAF feedstocks in other regional contexts [26].

Thus, the working hypothesis regarding the relevance of using animal fats and the technological process of their conversion for further research has been validated. This aligns with recent overviews highlighting SAF as a cornerstone of aviation decarbonization strategies.

The data presented in the SNW and GAP analyses underscore several critical implications for SAF implementation.

From an operational standpoint, the compatibility of HEFA-based SAF, especially from animal fats, with existing engines and infrastructure suggests minimal disruption during the transition phase. As shown in Table 3, most SAF pathways, including hydrocracked animal fats, achieve key performance benchmarks such as freezing point and combustion efficiency, ensuring safe operation even in high altitude, low temperature conditions.

In terms of economic implications, the consistently rated weakness for production cost across SAF types highlights the pressing need for scale-up and process optimization. However, the use of low-cost waste feedstocks like animal fats could provide regional cost advantages, especially in agricultural economies. Reducing hydrogen consumption and improving catalyst selectivity in hydrocracking can directly reduce operational expenses and improve cost party with conventional jet fuels.

Environmentally, the findings confirm that SAF pathways significantly reduce CO_2 and SO_x emissions, but the upstream emissions from feedstock processing remain a challenge. The hydrocracking of animal fats offers a notable advantage here due to its ability to valorize waste without inducing land-use change or biodiversity loss—issues that often affect crop-based feedstocks like palm or soybean oil.

These interpretations suggest that policy interventions (e.g., subsidies for waste based SAF, certification fast tracks, carbon credit incentives) should prioritize feedstock pathways like animal fats that offer cumulative operational, economic, and ecological benefits.

Recent analysis from the IEA indicates a continued acceleration of SAF deployment driven by emerging mandates, especially in the EU and U.S., alongside expanded capacity projections extending through 2029 [27].

In this context, the United States' Inflation Reduction Act (IRA) of 2022 introduces a substantial financial incentive for SAF production via §40B tax credits, offering up to 1.75 USD per gallon depending on lifecycle emissions reductions. This incentive is expected to accelerate commercialization, particularly for feedstocks such as animal fats, which perform favorably in LCA frameworks. However, successful scale-up also depends on addressing feedstock supply chain risks, including regional availability constraints, price volatility, and competition from sectors such as biodiesel and pet food. Strategies such as long-term procurement contracts, diversified sourcing, and enhanced rendering infrastructure should be considered to mitigate these challenges in both domestic and international SAF markets.

5. Conclusions

In this study, a comparative and causal analysis of SAF production pathways was carried out, with special emphasis on hydrocracking animal fats as an underutilized but promising route. SNW and GAP analyses demonstrated that hydroprocessed esters and fatty acids (HEFA) derived from animal fats produce high quality jet fuel components that meet ASTM D7566-24d certification requirements, reduce reliance on crop-based oils, and leverage waste streams from the animal industry.

Overall, the SNW analysis revealed that HEFA derived from animal fats exhibits a clear set of advantages and a few notable drawbacks when compared to conventional Jet A/Jet A-1 fuels. In terms of strengths, animal fat HEFA-SPK meets critical physicochemical requirements, such as a freezing point below −47 °C, near zero sulfur content, and combustion efficiency within 5% of conventional jet fuel, thereby ensuring full compatibility with existing engines and infrastructure under ASTM D7566-24d guidelines. Additionally, because animal fats are waste byproducts of the meat and rendering industries, this feedstock does not compete with food crops or contribute to indirect land-use change, which underscores its strong environmental credentials. Neutral aspects include density, energy content< and engine performance characteristics that closely match those of Jet A, implying minimal operational adjustments. However, weaknesses were evident in production cost, currently estimated at 25–30% above fossil kerosene due to high hydrogen consumption and expensive catalysts, and in limited local processing capacity, which poses a barrier to large-scale implementation, particularly in the Ukrainian context.

The GAP analysis further clarified which barriers must be overcome to make animal fat HEFA economically and technically viable. Economically, current production cost (approximately 1.2–1.4 USD per liter at pilot scale) exceed the target breakeven threshold (≤1.0 USD per liter), largely because hydrogen use exceeds 2 kg per kilogram of fat and catalyst lifetime remain below 500 h.

In addition to cost considerations, recent studies indicate that SAF produced from waste lipids such as animal fats can achieve well-to-wing GHG emission reductions of approximately 60–85% compared to conventional Jet A-1, depending on the hydrogen source and processing efficiency [27]. These environmental benefits enhance the viability of animal fat-based SAF under global decarbonization frameworks such as CORSIA and ReFuelEU. While this study does not perform a full techno-economic assessment (TEA) or lifecycle assessment (LCA), the inclusion of benchmark values provides additional context for evaluating both cost competitiveness and sustainability performance.

Technologically, pilot unit conversion average only 75% at 350–380 °C and 150 bar, falling short of the ≥90% conversion target needed for cost-effective cold-flow performance. Feedstock variability, specifically free-fatty acid content ranging from 8% to 15%, leads to inconsistent hydrogen demand and occasional catalyst fouling, highlighting a need for improved pretreatment.

Reported practices for hydrocracking lipid-based feedstocks typically involve the use of bifunctional catalysts such as NiMo or CoMo supported on γ-Al_2O_3, operated at 340–400 °C and 70–120 bar hydrogen pressure. These systems enable simultaneous hydrodeoxygenation and cracking but are vulnerable to feedstock impurities, including phosphorus, sulfur, and trace metals commonly present in animal fats. Elevated free fatty acid (FFA) content contributes to increased hydrogen consumption—often exceeding 2 kg of H_2 per kg of feedstock—and accelerates catalyst deactivation. To mitigate these challenges, pretreatment techniques such as degumming, bleaching, and hydrotreating are widely applied to improve feed quality and extend catalyst life. The optimization of catalyst formulations and process conditions specifically for animal fat conversion remains an important direction for future research.

Finally, the current regulatory framework restricts the blending of all certified SAF types, including HEFA-SPK, to a maximum of 50% by volume, thereby preventing their use as standalone jet fuels. Although test campaigns have demonstrated the technical feasibility of operating aircraft on 100% SAF, full certification under ASTM D7566 [5] remains limited. Taken together, these gaps highlight the need for catalyst optimization, pilot-scale demonstrations to validate continuous operation yields, detailed feedstock characterization, and regulatory developments to enable full blend approval across SAF pathways.

Future research should explore the scalability of animal fat-based SAF in greater depth, particularly considering regional differences in meat industry waste availability and competition with other uses such as biodiesel and pet food. Additionally, a comprehensive lifecycle assessment (LCA) is recommended to quantify the net environmental benefits, land-use implications, and cross-sectoral trade-offs of using animal fats as a SAF feedstock. This would provide a more holistic evaluation of their sustainability and inform long-term policy and investment decisions.

These research directions will be critical to positioning animal fat-based SAF within a long-term strategy for decarbonizing aviation. To contribute meaningfully to the 2050 net-zero target, SAF deployment must follow a phased roadmap that integrates technical feasibility, cost reduction, and regulatory alignment. In the near term, waste-derived feedstocks such as animal fats offer a viable entry point with low infrastructure barriers. In the medium term, improving catalyst stability and hydrogen efficiency will be essential to reducing operational costs. Ultimately, long-term success will rely on lifecycle-based certification, regulatory reform, and public–private investment coordination. This study supports a structured, regionally adaptive pathway to SAF commercialization that aligns with global decarbonization goals.

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Abbreviations

The following abbreviations are used in this manuscript:

ASTM	American Society for Testing and Materials
ATJ-SKA	Alcohol-to-Jet Synthetic Kerosene with Aromatics
ATJ-SPK	Alcohol-to-Jet Synthetic Paraffinic Kerosene
CHJ	Catalytic Hydrothermolysis Jet fuel
CO2	Carbon Dioxide
DEF STAN	Defense Standard
FT-SKA	Fischer-Tropsch Synthesized Kerosene with Aromatics
FT-SPK	Fischer-Tropsch Synthesized Paraffinic Kerosene
GAP	Gap Analysis
GHG	Greenhouse gas
HC-HEFA-SPK	Hydrocarbon-Hydroprocessed Esters and Fatty Acids-SPK
HEFA	Hydroprocessed Esters and Fatty Acids
HEFA-SPK	Hydroprocessed Esters and Fatty Acids-Synthetic Paraffinic Kerosene
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
JIG	Joint Inspection Group
NOx	Nitrogen Oxides
SAF	Sustainable Aviation Fuel
SIP	Synthesized Iso-Paraffins
SNW	Strengths, Neutrals, Weaknesses
SOx	Sulfur Oxides

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