A Review on Green Propulsion Technologies using Aerospace Biofuels

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Abstract

The integration of biofuels in aviation propulsion systems is a promising solution to mitigate the environmental impact of air travel, particularly by reducing greenhouse gas emissions and reliance on fossil fuels. This review explores the potential of second- and third-generation biofuels, derived from algae, agricultural waste, and municipal waste, which are highly sustainable and offer emissions reductions of up to 50% compared to conventional jet fuel. The production costs, however, remain a challenge, with advanced biofuels such as HEFA-SPK costing 2-3 times more than traditional jet fuels. The adoption of hybrid propulsion systems combining biofuels with electric and hydrogen technologies is emerging as a pathway to further improve fuel efficiency by up to 20% and reduce emissions by 50% or more.Technological advancements in fuel conversion processes and the development of new feedstocks are essential for scaling biofuel production to meet the growing demand for aviation fuels. Furthermore, the integration of biofuels with hydrogen can potentially reduce the carbon footprint of aviation, achieving a 50%+ reduction in GHG emissions and enhancing overall aircraft performance. Policy frameworks, including subsidies, regulatory support, and fuel certification standards, are critical to fostering the development of sustainable aviation fuels (SAFs). The future of aviation lies in the continued innovation of biofuel production technologies, the integration of hybrid propulsion systems, and the collaboration between industry and government to ensure a low-carbon aviation future.

***Key words**: Biofuels, Hybrid Propulsion Systems, Greenhouse Gas Emissions Reduction, Sustainable Aviation Fuels (SAFs), Fuel Conversion Technologies.*

1. Introduction

The aviation industry plays a crucial role in global transportation and economic development but is also a significant contributor to greenhouse gas (GHG) emissions. According to the International Air Transport Association (IATA), aviation accounts for approximately 2-3% of global CO_2 emissions, with projections indicating a rise due to increasing air travel demand [1]. To address this issue, the sector has been exploring sustainable aviation fuels (SAFs) as a viable alternative to conventional fossil-based jet fuels. SAFs, particularly biofuels derived from renewable feedstocks, offer a promising pathway to reducing aviation-related emissions while ensuring fuel performance and reliability.

Biofuels are liquid fuels produced from biological sources, such as plant oils, agricultural residues, algae, and waste biomass. Compared to conventional Jet A-1 fuel, SAFs can reduce lifecycle CO_2 emissions by up to 80% [2]. This reduction is achieved by replacing petroleum-based fuels with bio-derived alternatives that recycle carbon from the atmosphere. Moreover, sustainable biofuels are drop-in fuels, meaning they can be used in existing aircraft engines without modifications [3]. The adoption of aerospace biofuels aligns with international climate targets, including the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and the European Union's Fit for 55 initiative, which aims to decarbonize aviation by increasing SAF adoption [4].

1.1. Biofuels in Reducing Environmental Impact

The environmental impact of aviation extends beyond CO_2 emissions to include nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), and contrail formation. These pollutants contribute to climate change and degrade air quality. Biofuels have been shown to significantly reduce these emissions, making them an effective solution for mitigating aviation's environmental footprint [5].

One of the key benefits of aerospace biofuels is their potential to reduce non-CO_2 climate effects. Unlike fossil-based fuels, many biofuels have a lower aromatic content, which leads to reduced soot formation and fewer contrails, a major contributor to radiative forcing in aviation [6]. Additionally, the use of biofuels can decrease sulfur emissions, which helps improve air quality near airports and reduces acid rain formation [7].

Beyond emissions, biofuel production also promotes circular economy principles, as it utilizes waste materials such as used cooking oils, agricultural residues, and algae. These feedstocks not only provide an alternative to petroleum-based fuels but also reduce waste disposal issues. Algae-based biofuels, for instance, can be cultivated on non-arable land using wastewater, minimizing land-use conflicts with food production [8].

By synthesizing recent research and industry developments, this review will highlight the current state, benefits, and future potential of biofuels in aerospace propulsion. The findings will provide insights for policymakers, researchers, and industry stakeholders working towards greener aviation.

1.2. Overview of Aerospace Biofuels

Biofuels are renewable fuels derived from biological sources such as plants, algae, and waste materials. They serve as an alternative to fossil fuels, offering significant reductions in carbon emissions and environmental impact. Based on feedstock type and production method, aerospace biofuels are classified into:

First-generation biofuels are derived from food-based crops like corn, sugarcane, and vegetable oils, producing biodiesel and bioethanol. While they offer moderate GHG emission reductions, their sustainability is limited due to competition with food production, land-use concerns, and deforestation.

Second-generation biofuels, such as Hydroprocessed Esters and Fatty Acids (HEFA) and Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK), use non-food biomass like waste oils and forestry residues. These fuels provide higher carbon reduction and better sustainability, making them viable for aviation. However, challenges such as feedstock availability and high production costs remain. HEFA and FT-SPK have received ASTM certification, supporting their commercial adoption.

Third-generation biofuels, derived from microalgae and Hydrothermal Liquefaction (HTL), offer higher yield potential of 20,000 to 60,000 liters per hectare, minimal land-use impact, and growth in non-arable conditions. Despite their potential, high costs and scalability issues require further research to achieve widespread adoption in aviation.

1.3.Biofuel Feedstocks for Aviation

Feedstock selection is critical for sustainable fuel production. Table 1 compares the most

Table 1: Comparative Analysis of Biofuel Feedstocks for Aviation

Feedstock	Yield (L/ha)	CO_2 Emission Reduction (%)	Land Use Impact	Scalability	Reference
Algae	20,000 – 60,000	70 – 85%	Low	High	[9]
Jatropha	1,500 – 2,500	60 – 75%	Medium	Medium	[10]
Camelina	1,000 – 1,500	65 – 78%	Low	Medium	[2]
Waste Cooking Oil	3,000 – 6,000	80 – 90%	Negligible	High	[11]

Forestry Residues	2,500 – 5,000	65 – 80%	Medium	Medium	[12]
Biomass (Wood, Corn Stover)	2,000 – 4,500	50 – 70%	Medium	Medium	[13]

The comparative analysis of biofuel feedstocks highlights the varying sustainability and performance of different sources. Algae-based biofuels emerge as the most promising option due to their high yield potential and minimal land use impact, but their widespread adoption is currently hindered by technological challenges and high production costs. Waste cooking oil and forestry residues are the most environmentally friendly options, offering high CO_2 reduction and efficient conversion while requiring no additional agricultural land. Jatropha and camelina-based biofuels, on the other hand, present moderate yields and sustainability benefits, making them more scalable in the short term. Overall, while each feedstock has unique advantages and challenges, the transition to a sustainable aviation biofuel economy will require a multi-feedstock approach that balances efficiency, cost, and environmental benefits.

2. Production Processes and Fuel Certification

Aerospace biofuels must meet stringent certification standards to ensure safety, efficiency, and compatibility with existing aviation infrastructure.

2.1. Biofuel Production Pathways

There are multiple production methods for converting biomass into aviation fuel. Table 2 summarizes the major processes.

Table 2: Comparison of Biofuel Production Methods

Production Process	Feedstock Type	Efficiency (%)	CO_2 Reduction (%)	Certification Status	Reference
Hydroprocessed Esters and Fatty Acids (HEFA)	Waste oils, vegetable oils	85 – 90%	70 – 80%	ASTM D7566 Approved	[14]
Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	Biomass, forestry waste	60 – 75%	65 – 80%	ASTM D7566 Approved	[15]
Alcohol-to-Jet Fuel (ATJ-SPK)	Ethanol, butanol	55 – 70%	60 – 75%	ASTM D7566 Approved	[16]
Hydrothermal Liquefaction (HTL)	Algae, wet biomass	65 – 80%	68 – 85%	Under Testing	[13]
Power-to-Liquid (PtL) Synthetic Fuels	CO_2 + Hydrogen	50 – 70%	80 – 95%	Under Testing	[17]

A detailed comparison of biofuel production pathways reveals critical differences in efficiency, certification status, and CO_2 reduction potential. Hydroprocessed Esters and Fatty Acids (HEFA) and Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) have proven to be the most commercially viable, given their high efficiency (85–90%) and ASTM certification. On the other hand, Alcohol-to-Jet (ATJ-SPK) and Hydrothermal Liquefaction (HTL) biofuels, while promising, require further technological advancements to enhance efficiency and cost-effectiveness. Additionally, Power-to-Liquid (PtL) synthetic fuels, which utilize CO_2 and hydrogen to create aviation fuels, present a potentially game-changing innovation, offering up to 95% CO_2 reduction.

However, infrastructure development and energy input requirements remain major hurdles to their commercial deployment. The future of sustainable aviation fuel will depend on continued R&D efforts, supportive government policies, and investment in production scaling to make these advanced biofuel pathways cost-competitive with fossil-derived jet fuels.

2.2.ASTM Certification Standards

To ensure safety, performance, and environmental compliance, aerospace biofuels must meet rigorous ASTM certification standards before being integrated into commercial aviation. The ASTM D7566 standard regulates the blending of synthetic and bio-based hydrocarbons with conventional Jet A-1 fuel. Currently, several biofuel production pathways, including HEFA-SPK, FT-SPK, and ATJ-SPK, have received ASTM certification, allowing them to be blended up to 50% with conventional jet fuel. This certification ensures that biofuels meet strict performance metrics, including energy density, viscosity, freezing point, and thermal stability. Future advancements aim to increase biofuel blending ratios and ultimately develop 100% drop-in sustainable aviation fuels (SAF) that can fully replace fossil-based Jet A-1 without any modifications to existing aircraft engines or fuel systems. Continued research and regulatory development will be essential to expanding biofuel adoption and achieving net-zero emissions in the aviation sector. Aerospace biofuels are a viable alternative to fossil-based Jet A-1, offering significant CO_2 reduction and diverse production options.

- HEFA and FT-SPK are commercially viable and ASTM-certified.
- Algae-based biofuels and HTL pathways offer high sustainability potential but require further technological advancements.
- Future aviation sustainability depends on increasing production efficiency, scaling biofuel adoption, and regulatory advancements.

2.3.Comparative Technical Outputs of Aerospace Biofuels

The following table 3 compares various biofuels based on key technical parameters, including energy density, CO_2 emission reduction, viscosity, flash point, freezing point, cetane number, sulfur content, and blending ratio. These parameters are crucial for assessing fuel performance, safety, and compatibility with existing jet engines.

Aerospace biofuels offer significant potential for reducing aviation's environmental impact while maintaining high energy efficiency. Among the various biofuels analyzed, HEFA, FT-SPK, and ATJ-SPK are currently the most viable alternatives, meeting ASTM certification for use in commercial aviation. However, next-generation fuels such as HTL and algae-based biofuels are expected to increase adoption due to higher sustainability and improved scalability. Future advancements in production efficiency, cost reduction, and government policies will play a crucial role in determining the widespread commercialization of biofuels in aviation.

Table 3: Technical Outputs of Aerospace Biofuels

Fuel Type	**Energy Density (MJ/kg)**	**CO_2 Emission Reduction (%)**	**Viscosity (cSt at 40°C)**	**Flash Point (°C)**	**Freezing Point (°C)**	**Cetane Number**	**Sulfur Content (ppm)**	**Specific Gravity**	**Blending Ratio (%)**	**Reference**
Jet A-1 (Conventional Fuel)	43.0	0%	1.2 – 1.5	38 – 50	-47	45 – 55	400 – 800	0.80	100% (Base Fuel)	[14]
Algae-Based Biofuel	41.0	70%	2.1 – 2.6	45 – 55	-42	50 – 60	<10	0.78	Up to 50%	[9]
Waste Oil Biofuel	42.5	80%	3.0 – 3.5	50 – 60	-40	50 – 65	<5	0.79	Up to 50%	[11]

Biomass-Derived Biofuel	41.5	65%	1.8 – 2.3	42 – 55	-43	48 – 58	<15	0.79	Up to 50%	[12]
Hydroprocessed Esters and Fatty Acids (HEFA)	42.8	75%	2.5 – 3.0	47 – 58	-45	55 – 65	<10	0.78	Up to 50%	[14]
Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	43.5	80%	1.3 – 1.7	48 – 55	-50	60 – 70	<5	0.79	Up to 50%	[15]
Alcohol-to-Jet Fuel (ATJ-SPK)	42.0	65%	1.9 – 2.4	43 – 55	-45	50 – 58	<15	0.79	Up to 50%	[16]
Hydrothermal Liquefaction (HTL) Biofuel	41.3	68%	2.2 – 2.8	46 – 55	-44	48 – 57	<20	0.78	Up to 50%	[13]
Carinata-Based Biofuel	42.2	72%	2.6 – 3.1	50 – 58	-43	50 – 60	<12	0.78	Up to 50%	[17]
Camelina-Based Biofuel	42.4	70%	2.4 – 2.9	49 – 57	-42	52 – 62	<10	0.78	Up to 50%	[10]

3.Green Propulsion Technologies in Aerospace

Aviation contributes significantly to global carbon emissions, prompting the industry to explore green propulsion technologies. Biofuels, derived from renewable feedstocks such as waste oils, algae, and biomass, offer a viable alternative to conventional Jet A-1 fuel by reducing lifecycle CO_2 emissions by 50–90% [17]. Unlike hydrogen and electric propulsion, which require entirely new infrastructure, biofuels can be used as drop-in replacements, meaning they can be blended with conventional fuels and used in existing gas turbine engines without modification. This feature gives biofuels a significant advantage over hydrogen and battery-electric propulsion, which demand new fuel storage, distribution, and aircraft design changes. However, biofuels face challenges related to feedstock availability, conversion efficiency, and economic scalability. The two most commercially viable biofuels—Hydroprocessed Esters and Fatty Acids (HEFA) and Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)—have already received ASTM D7566 certification, making them suitable for commercial aviation. However, the industry is still working on improving cost-effectiveness and increasing production capacity to meet growing global demand.

3.1.Comparative Analysis of Biofuels for Green Propulsion

A comparison of biofuels and conventional as shown in table 4 Jet A-1 highlights key differences in energy content, CO_2 reduction, and operational feasibility. While biofuels offer significant emission reductions, their production requires high initial costs and extensive refining infrastructure.

Conventional Jet A-1 fuel provides an energy density of approximately 42-43 MJ/kg, making it the industry benchmark for commercial aviation fuel. However, its carbon footprint remains high, contributing 2-3% of global CO_2 emissions [16]. In contrast, HEFA-based biofuels maintain a similar energy density of 42–44 MJ/kg, ensuring engine compatibility and high combustion efficiency, while achieving a 70-85% reduction in CO_2 emissions. Among advanced biofuels, Fischer-Tropsch (FT-SPK) fuels derived from biomass gasification offer slightly lower energy content (40-42 MJ/kg) but deliver significant sustainability benefits, including 65-80% CO_2 reduction. Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK), derived from ethanol conversion, has slightly lower efficiency (39-41 MJ/kg) but remains a viable alternative fuel under ASTM standards. Hydrothermal Liquefaction (HTL) biofuels, particularly those sourced from algae, exhibit energy densities similar to fossil fuels (38-42 MJ/kg) with 68-85% carbon reduction. However, high production costs and technological constraints limit large-scale deployment. Power-to-Liquid (PtL) synthetic fuels, leveraging carbon capture and hydrogen electrolysis, offer the highest CO_2 reduction potential (80-95%), but their viability depends on the availability of low-cost renewable energy.

Table 4: Biofuels vs. Conventional Jet Fuel in Green Propulsion

Fuel Type	Energy Density (MJ/kg)	CO_2 Reduction (%)	Certification Status	Operational Challenges	Reference
Jet A-1 (Fossil Fuel)	42 – 43	0%	Fully Certified	High emissions, non-renewable	[14]
HEFA-SPK (Waste Oils)	42 – 44	70 – 85%	ASTM D7566 Approved	Feedstock supply chain issues	[17]
FT-SPK (Biomass)	40 – 42	65 – 80%	ASTM D7566 Approved	High production cost	[15]
ATJ-SPK (Ethanol-based)	39 – 41	60 – 75%	ASTM D7566 Approved	Energy-intensive conversion	[16]
HTL Biofuel (Algae)	38 – 42	68 – 85%	Under Testing	High scalability potential but costly	[13]
Power-to-Liquid (PtL)	38 – 41	80 – 95%	Under Testing	Hydrogen supply dependency	[17]

3.2.Hybrid and Electric Propulsion Integration with Biofuels

To further enhance sustainability in aviation, researchers are integrating biofuels with hybrid and electric propulsion systems. Hybrid propulsion combines a combustion engine (running on biofuel) with an electric motor, reducing fuel consumption and emissions. Electric propulsion systems aim for a zero-emission future, though challenges such as battery weight and energy density limit their application in large commercial aircraft [16]. Several hybrid-electric aircraft prototypes have demonstrated fuel efficiency improvements when integrating biofuels. The E-Fan X, developed by Airbus, Rolls-Royce, and Siemens, was an experimental hybrid-electric aircraft that showed up to 30% lower fuel consumption [18]. The system used a turbofan engine running on biofuel, supplemented by an electric motor for added propulsion efficiency.

3.3.Comparative Analysis of Propulsion Technologies

From the table 5 Hybrid-electric propulsion integrates biofuel-powered engines with electric motors, reducing fuel consumption and emissions while maintaining long-range capabilities. Fully electric propulsion, on the other hand, offers zero-emission operation but is constrained by battery energy density and aircraft weight limitations. While conventional jet engines rely solely on Jet A-1, emitting high levels of CO_2 and NOx pollutants, hybrid-electric systems offer a 20-30% improvement in fuel efficiency and up to 85% CO_2 reduction when combined with biofuels [19]. However, battery weight and energy limitations remain a challenge, with current lithium-ion batteries providing an energy density of only 0.25 MJ/kg, significantly lower than biofuel (40+ MJ/kg). Fully electric aircraft like the NASA X-57 Maxwell demonstrate potential for regional flights but require advancements in solid-state or lithium-air battery technologies to extend range and increase energy output. Thus, in the short term, hybrid-electric biofuel systems provide the most practical pathway toward sustainable aviation, while fully electric propulsion remains a long-term goal.

Table 5: Hybrid and Electric Propulsion vs. Conventional Systems

Propulsion Type	Energy Source	Efficiency Improvement (%)	CO_2 Reduction (%)	Challenges	Reference
Conventional Jet Engine	Jet A-1 (Fossil Fuel)	0%	0%	High emissions, non-renewable fuel	[16]
Biofuel-Powered Jet Engine	HEFA, FT-SPK	10 – 15%	50 – 80%	Limited biofuel availability	[17]

Hybrid-Electric Propulsion	Biofuel + Battery	20 – 30%	70 – 85%	Battery weight, energy storage	[19]
Fully Electric Propulsion	Lithium-Ion Batteries	40 – 60%	100%	Battery limitations, short range	[20]

3.4. Case Studies of Biofuel-Powered Flights

KLM Boeing 777 (2019): Commercial Biofuel Integration In 2019, KLM operated a Boeing 777 flight from Amsterdam to Madrid, using a 50% blend of HEFA biofuel. The aircraft's twin GE90 engines showed no performance degradation, and the flight achieved a 60% net CO_2 reduction [21]. However, the cost of biofuel remained three times higher than conventional Jet A-1, indicating the need for government subsidies and increased production scaling.

Qatar Airways Airbus A350 (2021): 100% Biofuel Test Qatar Airways tested a 100% HEFA biofuel-powered Airbus A350 in 2021, achieving an 80% net CO_2 reduction while maintaining full engine efficiency. Detailed emissions analysis showed a 75% decrease in particulate matter (PM2.5) and NOx emissions, reducing the aircraft's impact on local air quality [22].

NASA X-57 Maxwell (2023): Advancing Electric Propulsion NASA's X-57 Maxwell is a fully electric aircraft designed to demonstrate zero-emission flight. Though it does not use biofuels, it provides critical insights into the performance and energy storage limitations of electric propulsion. The aircraft's 14-motor distributed propulsion system enables energy efficiency improvements of up to 60%, but current battery technology limits its range to 160 km [23].

4.Renewable Energy Sources for Sustainable Aviation Fuels (SAFs)

4.1.Biomass and Waste-Derived Fuels

Biomass-based sustainable aviation fuels (SAFs) are derived from organic materials such as crop residues, algae, forestry waste, and municipal solid waste (MSW). These fuels are considered carbon-neutral, as the CO_2 emitted during combustion is offset by the CO_2 absorbed during biomass growth [2].

Table 6: Key Feedstocks for Biomass SAFs

Feedstock	**Processing Method**	**Fuel Type**	**CO_2 Reduction (%)**	**Energy Density (MJ/kg)**	**Reference**
Algae	Hydrothermal Liquefaction (HTL)	Bio-SPK	60-80%	38-42	[1]
Waste Oils	HEFA (Hydroprocessed Esters)	HEFA-SPK	70-90%	42-44	[2]
Forest Residue	Fischer-Tropsch (FT)	FT-SPK	65-85%	40-42	[24]
Municipal Waste	Gasification + FT	FT-SPK	60-75%	39-41	[19]
Agricultural Waste	Pyrolysis + Upgrading	Bio-SPK	50-80%	37-41	[25]

The table 6 highlights the variation in energy density and CO_2 reduction across different biofuel feedstocks. HEFA-SPK, derived from waste oils, offers the highest CO_2 reduction (70-90%) and a comparable energy density (42-44 MJ/kg) to conventional Jet A-1 (43 MJ/kg). In contrast, pyrolysis-derived biofuels from agricultural waste have a lower energy density (37-41 MJ/kg) and require additional processing to meet aviation fuel standards. Algae-based HTL biofuels show promise (60-80% CO_2 reduction) but are currently not cost-effective for large-scale production.

4.2.Hydrogen and Synthetic Fuels

Hydrogen is considered a zero-emission aviation fuel, producing only water vapor upon combustion. However, storage and distribution challenges limit its immediate adoption. Liquid hydrogen (LH_2) requires cryogenic tanks at -253°C, adding weight to the aircraft, affecting efficiency.

Table 7: Energy density vs. CO_2 reduction for different fuel

Fuel Type	Energy Density (MJ/kg)	CO_2 Reduction (%)	Challenges	Reference
Jet A-1	43	0%	High emissions	[2]
HEFA-SPK	42-44	70-90%	Feedstock cost	[1]
FT-SPK	40-42	65-85%	Complex conversion	[24]
Hydrogen (LH_2)	120	100%	Storage & infrastructure	[26]
Power-to-Liquid (PtL)	42-45	80-95%	High energy input	[19]

The table 7 highlights Energy density vs. CO_2 reduction for different fuel in that Hydrogen-based aviation fuels offer the highest energy density (120 MJ/kg) and zero CO_2 emissions, making them an ideal long-term solution. However, the logistical challenges of cryogenic storage and high infrastructure costs make it difficult to implement hydrogen at scale in commercial aviation. Power-to-Liquid (PtL) fuels, derived from renewable energy and CO_2 capture, provide an 80-95% CO_2 reduction while maintaining a similar energy density (42-45 MJ/kg) to Jet A-1, but their production remains energy-intensive (40-60 kWh per liter of fuel). In contrast, HEFA and FT-SPK fuels offer moderate CO_2 reduction but are currently the most commercially viable SAF alternatives.

4.3. Technological Advancements in Fuel Conversion

Innovations in fuel processing aim to improve yield, efficiency, and cost-effectiveness. The comparison of various biofuel conversion pathways based on process efficiency, advantages, and limitations. Hydroprocessed Esters and Fatty Acids (HEFA) offers the highest efficiency (80-90%) and is commercially certified but depends on limited waste oil feedstocks [1]. Fischer-Tropsch (60-80%) is highly versatile in feedstock usage but suffers from high processing costs [25]. Pyrolysis (50-70%) enables fast processing, yet requires additional upgrading to meet aviation fuel standards [24]. Hydrothermal Liquefaction (55-75%) is effective for wet biomass, though high reactor costs remain a challenge [26]. Power-to-Liquid (PtL) (40-60%) stands out for near-zero emissions, but its high energy input makes it costly [19]. These pathways highlight the trade-offs between efficiency, sustainability, and economic feasibility in the development of sustainable aviation fuels.

Renewable energy sources, including biomass, waste-derived fuels, hydrogen, and synthetic fuels, provide viable pathways for sustainable aviation. HEFA and FT-SPK fuels are commercially viable today, while hydrogen and PtL require further technological and infrastructure advancements. Future research must focus on improving energy efficiency, scaling production, and reducing costs to enable full aviation decarbonisation.

5.Environmental and Performance Impact of Biofuels

5.1. Emissions Reduction Compared to Fossil Fuels

A key advantage of biofuels in aviation is their ability to reduce greenhouse gas (GHG) emissions, primarily CO_2, NO_x, SO_x, and particulate matter (PM), compared to fossil-based jet fuels [2]. Sustainable aviation fuels (SAFs) derived from HEFA (Hydroprocessed Esters and Fatty Acids), Fischer-Tropsch (FT), and Hydrothermal Liquefaction (HTL) have demonstrated GHG reductions of up to 90% when using waste-based feedstocks [1]. Table 8 explores the comparison of Sustainable Aviation Fuels and Conventional Jet Fuel Biofuels, especially HEFA and PtL, offer significant reductions in CO_2 emissions (70-95%), making them crucial for achieving net-zero aviation emissions. HEFA-SPK also reduces sulfur emissions by over 90%, addressing the formation of contrail-induced climate effects. FT-SPK fuels, though highly effective, require additional blending with fossil fuels due to lower aromatic content, which can impact engine material compatibility.

Table 8: Comparison of Sustainable Aviation Fuels and Conventional Jet Fuel

Fuel Type	CO_2 Reduction (%)	NO_x Reduction (%)	SO_x Reduction (%)	PM Reduction (%)	Energy Density (MJ/kg)	Thermal Stability	Engine Efficiency Change (%)	GHG Emissions (gCO_2e/MJ)	Land Use Impact	Water Use (L/MJ)	Reference
Jet A-1	0%	0%	0%	0%	43	High	Baseline (0%)	87-89	None	0.5	[2]
HEFA-SPK	70-90%	10-30%	90-99%	60-80%	42-44	High	+0.5 to +1.2%	15-20	Low	1.5	[1]
FT-SPK	65-85%	15-35%	85-95%	50-75%	40-42	Moderate-High	0% to -0.5%	20-30	Medium	2.0	[24]
Bio-SPK (HTL)	50-80%	10-25%	80-95%	55-70%	38-41	Moderate	-0.5 to -1.5%	25-35	High	3.5	[25]
PtL	80-95%	15-40%	95-99%	70-85%	42-45	High	+0.8 to +1.5%	5-10	None	0.8	[19]

5.2. Engine Performance and Efficiency Considerations

Biofuels must meet strict ASTM D7566 aviation fuel standards to ensure compatibility with existing jet engines. Various SAF types offer different combustion characteristics, energy content, and thermal stability, which influence engine efficiency and operational performance [26]. HEFA and PtL fuels closely match Jet A-1 in energy density, ensuring minimal impact on engine performance. PtL fuels have a slight efficiency gain (+1.5%), making them an ideal long-term alternative. FT and HTL biofuels may lead to minor efficiency losses (-0.5 to -1.5%), requiring engine modifications or blending with Jet A-1 to maintain performance.

5.3. Lifecycle Assessment of Aerospace Biofuels

Lifecycle assessment (LCA) evaluates the total environmental impact of biofuels, from feedstock cultivation, fuel production, transportation, combustion, and disposal. While biofuels significantly reduce in-flight emissions, the upstream processes (land use, fertilizer, and refining) must also be optimized to achieve full sustainability [26]. Among SAFs, PtL fuels offer the lowest lifecycle emissions (5-10 gCO_2e/MJ), making them the most promising long-term solution. HEFA fuels have low land-use impact and moderate emissions (15-20 gCO_2e/MJ), making them the most commercially feasible alternative today. However, HTL-based biofuels have higher emissions (25-35 gCO_2e/MJ) and water use, making them less sustainable unless process efficiencies improve.

6.Challenges and Research Gaps in Biofuels for Sustainable Aviation

6.1. Economic and Scalability Issues

The economic feasibility and scalability of biofuels in aviation remain significant challenges due to their high production costs compared to conventional Jet A-1 fuel. Jet A-1 is priced at approximately $2.5-$3.0 per gallon due to its reliance on fossil-based feedstocks and well-established refining infrastructure [2]. In contrast, HEFA-SPK costs range from $4.0 to $7.0 per gallon, primarily due to limited feedstock availability and processing costs associated with waste oils [1]. FT-SPK, with costs between $3.5 and $6.0 per gallon, also faces challenges related to high processing expenses and feedstock transportation costs [19]. Power-to-Liquid (PtL) fuels, while offering the highest emissions reduction potential, are the most expensive, costing between $5.5 and $9.0 per gallon due to their reliance on renewable electricity and high energy inputs [25]. The scalability of biofuels is further hindered by feedstock supply constraints and the high capital cost of infrastructure development. Without substantial technological advancements, feedstock diversification, and policy incentives, biofuels will continue to struggle to compete with conventional jet fuel on a cost basis.

6.2. Feedstock Availability and Land-Use Concerns

The availability of sustainable feedstocks is a critical factor in the development of biofuels for aviation. First-generation biofuels are derived from food crops (corn, soy), raising concerns about competition with food production and land-use change [25]. On the other hand, second- and third-generation biofuels, which utilize algae, agricultural waste, and municipal waste, face challenges related to cost-effective collection, transportation, and processing. While algae and waste-derived feedstocks present a higher renewable potential, they require further research on efficient harvesting, processing, and economic scalability. First-generation biofuels, derived from food crops, face land-use conflicts and may exacerbate food security issues, thus making them less desirable for large-scale adoption. Research must focus on optimizing second- and third-generation feedstocks that do not compete with food production.

6.3. Need for Policy and Regulatory Support

Another significant challenge in scaling biofuels in aviation is the lack of comprehensive policy frameworks to encourage investment in SAFs and ensure consistent fuel quality standards [26]. Currently, subsidies for fossil fuels, along with limited government incentives for biofuels, create an uneven playing field. Furthermore, policy efforts are needed to address feedstock certification, production facility standards, and cross-border fuel integration [2]. While regional policies exist to promote SAF development, there is a need for global harmonization to standardize fuel specifications and provide consistent economic incentives for producers. Governments must implement comprehensive strategies to encourage long-term investment in SAF infrastructure and address global regulatory inconsistencies.

7.Future Trends and Opportunities in Sustainable Aviation Fuels (SAFs)

7.1. Innovations in Biofuel Production and New Feedstocks

The future of biofuels for aviation lies in advancements in feedstock development and fuel production technologies. Next-generation biofuels, such as algae-based fuels and waste-derived fuels, have the potential to meet growing demand without compromising food security. Algae is particularly promising due to its high yield per acre and ability to be grown in non-arable land [26]. Synthetic biology and genetically engineered organisms are also being explored to enhance feedstock conversion efficiency. Algae and waste oils represent the highest potential for sustainable aviation fuels due to their high yield and carbon-neutral production. Innovations in feedstock engineering will enable these alternatives to become cost-competitive with fossil fuels. Agricultural waste, while abundant, still faces scalability challenges due to complex processing needs.

7.2. Integration with Hydrogen and Electrification

The integration of biofuels with hydrogen and electric propulsion technologies is seen as the next frontier in sustainable aviation. According to the research from the table 9 the Hybrid systems using both biofuels and hydrogen could achieve greater fuel efficiency, while electrification could be used for short-haul flights. Research into liquid hydrogen and fuel cells for aviation is progressing rapidly, and there is significant potential for biofuels to complement these technologies in reducing aviation emissions.

Table 9: Efficiency and emission reduction potential of biofuel hybrid technologies

Technology Integration	Efficiency Improvement	GHG Emission Reduction	Challenges	Reference
Biofuel + Hydrogen (Hybrid)	+15% to +20%	50%+	Infrastructure & storage	[26]

Biofuel + Electric Propulsion	+10% to +25%	30%+	Battery weight & energy density	[19]

Hybrid biofuel-hydrogen systems offer significant efficiency improvements with 50%+ GHG reductions, but hydrogen storage and distribution remain significant challenges. Biofuel-electric systems can achieve up to 25% greater efficiency on shorter flights, though battery weight and energy density issues need to be resolved for long-haul flights.

7.3. Policy Directions for Sustainable Aviation Fuel Adoption

To ensure widespread adoption of SAFs, governments and international bodies must focus on policies that promote long-term investment in both biofuel production and supportive infrastructure. This includes subsidies for SAF production, global fuel certification standards, and incentives for aircraft modifications to run on SAFs. Furthermore, carbon taxation and mandates for SAF use in aviation will be key drivers of sustainable aviation.

Global policy frameworks must promote investment in SAF infrastructure, with a focus on harmonizing fuel standards and providing incentives for fuel production. Increased SAF usage mandates will drive market demand, ensuring a sustainable aviation transition. The adoption of biofuels in aviation faces several economic, scalability, and regulatory challenges. However, innovations in feedstock development, hybrid and electric propulsion systems, and policy support are paving the way for widespread SAF adoption. Continued research into cost reduction, efficient feedstock use, and advanced fuel technologies will play a crucial role in meeting global aviation decarbonization goals.

Conclusion

The transition to biofuels in aviation presents a significant opportunity to reduce the sector's environmental impact. Biofuels, particularly those derived from second- and third-generation feedstocks like algae, agricultural waste, and municipal waste, offer a sustainable solution without competing with food production. These biofuels have demonstrated a high potential for emissions reduction and can lower aviation's carbon footprint by up to 50% when integrated with advanced propulsion technologies. Technological advancements, such as hybrid propulsion systems that combine biofuels with electric and hydrogen-based technologies, hold promise for achieving up to 20% greater fuel efficiency and enhanced emissions reductions. These innovations could transform the industry, especially as biofuels continue to be optimized and integrated with other alternative energy systems. For biofuels to be adopted at a global scale, strong policy support is essential. Governments need to implement financial incentives, develop regulatory frameworks, and standardize fuel certification to ensure consistency across international aviation networks. The availability of sustainable feedstocks and the development of cost-effective biofuel production methods are key to making biofuels economically viable. As research into new feedstocks and advanced production technologies progresses, the cost of biofuels is expected to decrease, making them more competitive with fossil fuels. In conclusion, biofuels offer a crucial pathway to achieving a low-carbon aviation future, with substantial environmental and economic benefits. With continued innovation, investment in infrastructure, and supportive policies, biofuels can play a central role in transforming the aviation industry toward sustainability.

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