

Biodiesel blending strategies for aviation fuel: Feasibility, challenges and future outlook

Papareddy N^{1,*}, Amar C² and Pandu T C¹

¹ Department of Automobile Engineering, Government Polytechnic, Chinthamani-563125, Karnataka, India.

² Department of Automobile Engineering, Government C P C Polytechnic, Mysore-570007, Karnataka, India.

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Abstract

This paper examines the current landscape of biodiesel blending for aviation applications, with a focus on technical feasibility, performance characteristics, regulatory frameworks, and environmental implications. Through analysis of existing biodiesel feedstocks, production methodologies, and blending ratios, we evaluate the viability of various strategies for integrating biodiesel into conventional jet fuel. Our findings indicate that while medium-term blending targets of 10-30% are achievable with current technology, significant challenges remain in feedstock sustainability, cold-flow properties, and energy density optimization. The research concludes with recommendations for policy frameworks and technological developments needed to accelerate commercial-scale implementation of biodiesel blends in aviation.

Keywords: Sustainable Aviation Fuel (SAF); Biodiesel Blending FAME (Fatty Acid Methyl Esters); Cold-Flow Properties; Energy Density

1. Introduction

The aviation industry contributes approximately 2.5% of global carbon dioxide emissions, with projections suggesting this figure could triple by 2050 given current growth trajectories (ICAO, 2023). As the sector faces increasing pressure to reduce its environmental footprint, sustainable aviation fuels (SAFs) have emerged as a critical pathway toward decarbonization. Biodiesel, derived from renewable biological resources, represents a promising component of the SAF portfolio due to its reduced lifecycle greenhouse gas emissions compared to conventional petroleum-based jet fuel.

The integration of biodiesel into aviation fuel systems, however, presents unique challenges distinct from those encountered in ground transportation applications. Aviation fuel must meet exceptionally stringent specifications regarding energy content, cold-flow properties, and thermal stability to ensure safety and performance across diverse operating conditions. This paper examines the technical feasibility of various biodiesel blending strategies for aviation fuel, addressing both opportunities and limitations while considering the regulatory landscape and future research directions [1].

2. Biodiesel Fundamentals and Aviation Requirements

2.1. Biodiesel Characteristics

Biodiesel consists of mono-alkyl esters of long-chain fatty acids derived from renewable lipid feedstocks. The production process primarily involves transesterification, where vegetable oils or animal fats react with an alcohol

* Corresponding author: Papareddy N.

(typically methanol) in the presence of a catalyst. The resulting fatty acid methyl esters (FAME) or fatty acid ethyl esters (FAEE) constitute the primary components of biodiesel.

The physical and chemical properties of biodiesel vary significantly based on feedstock composition. Table 1 compares key properties of biodiesel derived from common feedstocks against conventional Jet A-1 fuel requirements.

Table 1 Comparison of Key Fuel Properties Between Biodiesel Feedstocks and Jet A-1

Property	Jet A-1 Requirement	Soybean Biodiesel	Palm Biodiesel	Jatropha Biodiesel	Camelina Biodiesel
Energy Density (MJ/kg)	42.8 (min)	37.2	36.5	38.5	39.7
Freezing Point (°C)	-47 (max)	-2	13	-6	-8
Viscosity at -20°C (mm ² /s)	8.0 (max)	12.7	19.4	11.8	10.3
Oxidative Stability (h)	-	3.5	10.2	4.8	2.5
Carbon Emissions (%) reduction) *	-	40-60%	30-55%	45-70%	50-75%

2.2. Aviation fuel requirements

Aviation turbine fuels must comply with stringent standards, most notably ASTM D1655 (for conventional jet fuel) and ASTM D7566 (for synthetic blending components). Key requirements include:

- Energy Content: High energy density is critical for maximizing aircraft range and payload capacity.
- Cold-Flow Properties: Fuels must maintain fluidity at high altitudes where temperatures can reach -40°C to -60°C.
- Thermal Stability: The fuel must resist degradation when used as a heat sink for aircraft systems.
- Material Compatibility: No adverse effects on elastomers, metals, and other components of fuel systems.
- Safety Parameters: Specific flash point, electrical conductivity, and lubricity requirements.

The disparities between biodiesel properties and aviation requirements necessitate either modification of the biodiesel components or limitation of blending ratios to ensure operational safety and performance.

3. Current biodiesel blending strategies

3.1. Approved Blending Pathways

As of 2025, several pathways for incorporating bio-derived components into jet fuel have received regulatory approval under ASTM D7566. Table 2 summarizes these pathways, highlighting the maximum allowable blending ratios and key characteristics.

Table 2 ASTM-Approved Pathways for Bio-derived Components in Jet Fuel

Conversion Process	Feedstock	Max. Blend Ratio	Key Characteristics	Approval Date
Fischer-Tropsch (FT)	Biomass	50%	Excellent cold-flow properties	2009
Hydroprocessed Esters and Fatty Acids (HEFA)	Oils and fats	50%	Similar to petroleum jet fuel	2011
Synthesized Iso-Paraffins (SIP)	Sugar	10%	Limited availability	2014
Alcohol-to-Jet (ATJ)	Alcohols	50%	Multiple feedstock options	2018

Catalytic Hydrothermolysis (CH)	Oils and fats	50%	High thermal stability	2020
Hydroprocessed Hydrocarbons (HC-HEFA)	Algal oils	10%	Emerging technology	2022
HEFA+	Enhanced oil processing	60%	Higher blend allowance	2023

Pure FAME biodiesel is notably absent from these approved pathways due to concerns regarding its cold-flow properties and oxidative stability. Instead, the hydroprocessing of esters and fatty acids (HEFA) represents the primary approved method for incorporating lipid-derived components, as this process removes oxygen and produces hydrocarbons more similar to conventional jet fuel.

3.2. Experimental Blending Approaches

Despite regulatory limitations, research continues on direct biodiesel blending strategies. Table 3 presents data from recent experimental studies investigating various biodiesel blends and their performance characteristics.

Table 3 Experimental Biodiesel Blending Strategies and Performance Metrics

Study	Biodiesel Type	Blend Ratio	Cold-Flow Performance	Energy Density	Emissions Reduction	Key Findings
Zhang et al. (2023)	Camelina	5-20%	Acceptable to 10%	-3.1% at 10% blend	7.2% CO ₂ , 18.5% PM	Minimal impact on engine parameters up to 10%
Ramírez-Verduzco (2024)	Jatropha	2-15%	Acceptable to 8%	-2.7% at 8% blend	6.5% CO ₂ , 24.1% PM	Enhanced lubricity, reduced particulate matter
Karatzos et al. (2023)	Palm + additives	5-12%	Acceptable to 7% with additives	-1.9% at 7% blend	5.8% CO ₂ , 15.2% PM	Cold-flow improvers extended blending potential
Vasu et al. (2024)	Algal	5-25%	Acceptable to 15%	-2.4% at 15% blend	11.6% CO ₂ , 26.8% PM	Superior cold-flow properties compared to crop-based biodiesel
Rodriguez et al. (2024)	Multi-feedstock	5-30%	Acceptable to 20% with processing	-3.6% at 20% blend	14.3% CO ₂ , 22.5% PM	Feedstock blending mitigated individual limitations

These experimental approaches demonstrate that limited blending (typically below 20%) may be feasible with appropriate feedstock selection, additive packages, and processing techniques. However, challenges remain in meeting all aviation requirements simultaneously, particularly regarding energy density and cold-flow properties [2].

4. Technical Challenges and Mitigation Strategies

4.1. Cold-Flow Properties

The poor low-temperature performance of biodiesel represents the most significant technical barrier to aviation applications. Table 4 summarizes various strategies for improving cold-flow properties and their relative effectiveness.

Table 4 Cold-Flow Improvement Strategies for Biodiesel Aviation Blends

Strategy	Effectiveness	Implementation Complexity	Cost Impact	Technology Readiness
Cold-flow improver additives	Moderate	Low	Low-Moderate	High

Winterization (fractionation)	High	Moderate	Moderate	Moderate-High
Feedstock selection (low saturation)	High	Low	Variable	High
Branched-chain esterification	Very High	High	High	Low-Moderate
Hydroisomerization	Very High	High	High	Moderate
Co-processing with petroleum	Moderate	Moderate	Moderate	Moderate-High
Partial catalytic dewaxing	High	High	High	Low

Among these strategies, feedstock selection combined with cold-flow improver additives represents the most immediately applicable approach for low-percentage blends. More advanced techniques such as branched-chain esterification offer greater potential for higher blending ratios but require further technological development.

4.2. Energy Density Considerations

The lower energy density of biodiesel compared to conventional jet fuel impacts aircraft range and payload capacity. For every 1% reduction in volumetric energy content, an aircraft's range decreases by approximately 0.5-0.7% (Yao et al., 2023). This relationship necessitates careful optimization of blending ratios to balance environmental benefits against operational impacts [3].

Table 5 illustrates the relationship between biodiesel blend percentage and key operational parameters based on modeling studies.

Table 5 Impact of Biodiesel Blend Ratio on Aircraft Operational Parameters

Blend Percentage	Energy Density Reduction	Range Impact	Max Payload Reduction	Additional Fuel Cost	CO ₂ Reduction (lifecycle)
5%	0.8-1.2%	0.4-0.7%	0.3-0.5%	1.2-1.8%	2.0-3.5%
10%	1.7-2.4%	0.9-1.5%	0.7-1.1%	2.5-3.6%	4.0-7.0%
20%	3.5-4.8%	1.9-3.1%	1.5-2.3%	5.0-7.2%	8.0-14.0%
30%	5.3-7.2%	2.8-4.6%	2.2-3.4%	7.5-10.8%	12.0-21.0%
50%	8.8-12.0%	4.7-7.7%	3.7-5.7%	12.5-18.0%	20.0-35.0%

Source: Compiled from modeling studies by Johnson et al. (2023), Rodriguez et al. (2024), and Vasu et al. (2024)

These data suggest that blends up to 10% may be operationally acceptable with minimal adjustments to flight planning and fuel logistics, while higher percentages would require more significant operational accommodations.

4.3. Oxidative Stability and Storage

Biodiesel's susceptibility to oxidative degradation presents challenges for the aviation industry's fuel storage and handling infrastructure. Table 6 compares the effectiveness of various stabilization approaches.

Table 6 Oxidative Stability Enhancement Methods for Biodiesel Aviation Blends

Method	Stability Improvement	Implementation Ease	Durability	Cost Factor
Synthetic antioxidants (BHT, TBHQ)	+150-300%	High	6-12 months	Low
Natural antioxidants (tocopherols)	+100-200%	Moderate	4-8 months	Moderate
Nitrogen blanketing	+200-400%	Low	Duration of storage	High

Reduced storage temperature	+50-100% per 10°C reduction	Moderate	Duration of storage	Moderate-High
Metal chelating agents	+50-150%	High	8-12 months	Low
Nanoparticle additives	+200-500%	Low	12-24 months	Very High

The aviation industry's requirement for extended fuel storage stability (typically 1-2 years) necessitates a combined approach, utilizing both antioxidant additives and improved handling practices. The cost implications of these measures must be factored into the overall economic assessment of biodiesel blending strategies [4].

5. Economic and Policy Considerations

5.1. Production Economics

The economic viability of biodiesel blending for aviation depends on production costs, scaling factors, and policy incentives. Table 7 presents comparative cost data for various production pathways.

Table 7 Production Cost Comparison for Aviation Biodiesel Pathways

Production Pathway	Feedstock Cost Share	Processing Cost Share	Current Cost Premium*	Projected Cost Premium (2030)*	Carbon Abatement Cost (\$/tCO ₂)
HEFA (vegetable oils)	70-80%	20-30%	+80-120%	+40-60%	150-230
HEFA (waste oils)	50-65%	35-50%	+50-90%	+30-50%	100-180
Direct biodiesel blending	65-75%	25-35%	+70-100%	+35-55%	120-200
Co-processing	60-70%	30-40%	+40-80%	+25-45%	90-170
Advanced fermentation	40-55%	45-60%	+120-200%	+60-90%	200-320

The data demonstrate that while all biodiesel pathways currently carry significant cost premiums, waste-derived feedstocks and co-processing approaches offer more favorable economics. Projected cost reductions by 2030 suggest improving competitiveness, though policy support remains necessary to bridge the cost gap with conventional jet fuel.

5.2. Regulatory Frameworks

Diverse policy instruments influence the adoption of biodiesel blending in aviation. Table 8 summarizes key global regulatory frameworks and their implications.

Table 8 Global Policy Frameworks for Aviation Biofuels

Region/Program	Type	Target/Mandate	Implementation Timeline	Key Features	Impact on Biodiesel Adoption
EU ReFuelEU Aviation	Blending Mandate	6% SAF by 2030, 70% by 2050	2025-2050	Sub-target for advanced biofuels	Strong positive
US SAF Grand Challenge	Volumetric Target	3 billion gallons annually	By 2030	Federal funding support	Moderate positive
ICAO CORSIA	Carbon Offsetting	Carbon-neutral growth	From 2021	Market-based mechanism	Moderate positive

UK Jet Zero Strategy	Blending Mandate	10% SAF by 2030	2025-2050	Competition funding available	Strong positive
China Civil Aviation Administration	Research Program	50,000 tons annually	By 2025	Focus on non-food feedstocks	Limited positive
Brazil ProBioQAV	Tax Incentives	1% by 2027, 10% by 2040	2027-2040	Integration with existing biodiesel program	Moderate positive

These frameworks demonstrate an accelerating global commitment to sustainable aviation fuels, though approaches vary significantly in ambition and implementation mechanisms. The fragmented regulatory landscape creates challenges for international aviation but also opportunities for regional leadership in biodiesel integration [4].

6. Environmental implications

6.1. Lifecycle Emissions Analysis

The environmental benefits of biodiesel blending depend critically on feedstock choice and production methods. Table 9 presents lifecycle greenhouse gas emission reductions for various biodiesel pathways compared to conventional jet fuel.

Table 9 Lifecycle GHG Emissions Analysis of Aviation Biodiesel Pathways

Biodiesel Pathway	Feedstock	GHG Reduction (%)	Land Use Change Impact	Water Usage (L/L fuel)	Co-product Credits	Overall Sustainability Rating
First-generation FAME	Soybean	40-60%	High negative	5,000-7,000	Moderate	Low-Moderate
First-generation FAME	Palm	30-70%*	Very high negative	2,000-3,000	Moderate	Low
Second-generation FAME	Used cooking oil	80-90%	Neutral	500-1,000	Low	High
Second-generation FAME	Animal fats	70-85%	Low negative	1,000-2,000	Moderate	Moderate-High
Advanced biodiesel	Algae	60-80%	Very low negative	3,000-10,000	High	Moderate
Advanced biodiesel	Jatropha	55-75%	Low negative	2,000-4,000	Low	Moderate
HEFA	Camelina	65-80%	Low negative	2,500-4,500	Moderate	Moderate-High

The data highlight the superior environmental performance of waste-derived feedstocks, while crop-based pathways demonstrate significant variability depending on cultivation practices and land use change considerations. This variability underscores the importance of robust sustainability certification systems for aviation biofuels.

6.2. Non-GHG Environmental Impacts

Beyond carbon emissions, biodiesel blending affects other environmental parameters relevant to aviation. Table 10 summarizes key findings on non-GHG environmental impacts.

Table 10 Non-GHG Environmental Impacts of Aviation Biodiesel Blends

Environmental Parameter	Impact Direction	Magnitude	Key Contributing Factors	Research Confidence
Particulate matter emissions	Reduction	15-40%	Oxygen content, reduced aromatic content	High
NOx emissions	Mixed	-5% to +8%	Combustion temperature, fuel nitrogen content	Moderate
Contrail formation potential	Reduction	5-20%	Reduced particulate emissions, fuel sulfur content	Low-Moderate
SOx emissions	Reduction	50-90%	Lower sulfur content	High
Unburned hydrocarbons	Reduction	20-50%	Oxygen content, combustion characteristics	Moderate-High
Local air quality impact	Improvement	Moderate	Combined effect of emission reductions	Moderate

These findings suggest that biodiesel blending offers co-benefits beyond greenhouse gas reduction, particularly regarding particulate matter and sulfur emissions that affect both local air quality and the formation of aviation-induced cloudiness [4].

7. Future Research Directions and Industry Outlook

7.1. Emerging Technologies

Several innovative approaches show promise for addressing current limitations in aviation biodiesel applications. Table 11 evaluates these emerging technologies.

Table 11 Emerging Technologies for Aviation Biodiesel Applications

Technology	Development Stage	Potential Impact	Timeframe to Commercial Viability	Key Technical Challenges	Key Research Institutions
Engineered microalgae	Research/Early Pilot	Very High	5-10 years	Scaling, productivity, harvesting costs	NASA, NREL, SINTEF
Genetic modification of oil crops	Advanced Research	High	3-7 years	Regulatory approval, yield optimization	CSIRO, Syngenta, Nuseed
Direct sugar-to-hydrocarbons	Pilot/Demonstration	Moderate-High	3-5 years	Catalyst longevity, selectivity	LanzaTech, Gevo, Amyris
Electrofuels (power-to-liquid)	Pilot/Demonstration	High	3-8 years	Energy efficiency, renewable electricity availability	Climeworks, Sunfire, Nordic Electrofuel
Advanced hydroprocessing	Demonstration/Early Commercial	Moderate	1-4 years	Hydrogen source, catalyst performance	UOP Honeywell, Haldor Topsoe, Axens

Low-temperature catalytic cracking	Research	Moderate-High	7-12 years	Selectivity, conversion efficiency	MIT, University of Delaware, KAUST
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Source: Compiled from university and industry research publications

These technologies collectively hold potential to address current limitations in feedstock availability, cold-flow properties, and energy density that constrain higher biodiesel blending percentages in aviation fuel.

7.2. Industry Adoption Forecast

Based on current trends, regulatory developments, and technological trajectories, Table 12 presents a forecast for biodiesel blending adoption in commercial aviation.

Table 12 Aviation Biodiesel Blending Adoption Forecast

Timeframe	Global Average Blend Ratio	Leading Markets	Trailing Markets	Key Drivers	Key Barriers
2025-2027	0.5-2%	EU, UK, US	Africa, South Asia	Early regulations, corporate commitments	Cost premium, limited infrastructure
2028-2030	2-5%	EU, UK, US, Japan	Middle East, Russia	Expanded support, policy cost reduction	Feedstock limitations, aircraft efficiency trade-offs
2031-2035	5-10%	EU, US, East Asia	Africa, South America	Technology improvements, mainstream acceptance	Infrastructure transition costs
2036-2040	10-20%	EU, US, East Asia, Oceania	Africa, South Asia	Advanced technologies, normalized cost structure	Remaining technical challenges
2041-2050	20-40%	Global convergence with regional variation	-	Climate targets, fully mature technology	Competition from other technologies (e.g., hydrogen, electric)

This forecast suggests a gradual but accelerating adoption curve, with regional disparities gradually diminishing as technologies mature and global climate imperatives intensify. The forecast assumes continued policy support and technological advancement without disruptive innovations in competing decarbonization pathways [5].

8. Conclusions and Recommendations

This research demonstrates that biodiesel blending represents a viable component of aviation's decarbonization strategy, with current technical limitations restricting blending percentages but not precluding meaningful adoption in the near term. Several key conclusions emerge:

- **Technical Feasibility:** Biodiesel blends of 5-10% are technically feasible with current technology, while blends of 20-30% appear achievable with targeted improvements in cold-flow properties and energy density.
- **Feedstock Priority:** Waste-derived and advanced feedstocks offer superior environmental performance and reduced competition with food production compared to first-generation crop-based options.
- **Economic Viability:** While current cost premiums are substantial, projected learning curves and scaled production suggest improving competitiveness, particularly with supportive policy frameworks.
- **Environmental Benefits:** Properly sourced biodiesel offers significant lifecycle GHG reductions and co-benefits for local air quality and non-CO₂ climate impacts.

Based on these findings, we recommend

- Policy Development: Establish clear, long-term policy frameworks that provide certainty for industry investment while incorporating robust sustainability criteria.
- Research Focus: Prioritize research on cold-flow improvement strategies, energy density optimization, and advanced feedstock development.
- Infrastructure Planning: Develop fuel handling infrastructure capable of supporting increasing biodiesel blend percentages to avoid bottlenecks in future deployment.
- Industry Collaboration: Foster pre-competitive collaboration on technical standards, sustainability certification, and supply chain development to accelerate industry-wide adoption.
- Integrated Strategy: Position biodiesel blending within a comprehensive aviation decarbonization strategy that includes aircraft efficiency, operational improvements, and longer-term breakthrough technologies.

Implementation of these recommendations would facilitate the responsible integration of biodiesel blending into aviation fuel systems, contributing meaningfully to the sector's climate objectives while maintaining operational safety and performance.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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