

Pathways Toward Climate-Neutral Aviation: Sustainable Aviation Fuels, Policy Alignment, and the Emerging Role of Industrial Hemp

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ABSTRACT

The aviation sector remains one of the most challenging domains for decarbonization due to its dependence on high-energy-density liquid fuels and the limited short-term scalability of alternative propulsion systems. Recent international policy frameworks, industrial roadmaps, and sustainability strategies emphasize Sustainable Aviation Fuels (SAFs) as a central mitigation pathway for reducing lifecycle greenhouse gas emissions without compromising operational reliability. This article synthesizes contemporary academic and institutional perspectives on aviation emissions trajectories, SAF technological readiness, and policy-driven transformation, while introducing industrial hemp as an emerging and underexplored bio-based feedstock aligned with global sustainability frameworks. Drawing on reports from international energy agencies, aviation manufacturers, and multilateral governance bodies, the study integrates emissions modeling perspectives, feedstock sustainability criteria, and regulatory alignment considerations. Using a qualitative-analytical methodology, the paper evaluates how SAF deployment scenarios interact with policy instruments such as the European Green Deal and global climate commitments. Particular attention is given to the compatibility of hemp-based biomass with sustainability benchmarks, land-use constraints, and industrial scalability. The discussion highlights structural limitations, including feedstock availability, cost dynamics, and uneven policy harmonization across regions. The findings suggest that while SAFs alone are unlikely to deliver absolute climate neutrality, diversified feedstock strategies combined with coherent policy frameworks significantly enhance the sector's mitigation potential. The article contributes to the growing literature by positioning industrial hemp within aviation decarbonization discourse and by emphasizing systems-level integration rather than singular technological solutions.

Keywords: Sustainable aviation fuel, aviation emissions, industrial hemp, decarbonization policy, lifecycle assessment, energy transition.

INTRODUCTION

The global aviation industry occupies a paradoxical position within contemporary climate discourse. On one hand, it represents a relatively small proportion of total global greenhouse gas emissions when compared with sectors such as power generation or ground transportation. On the other hand, aviation emissions are projected to grow steadily due to increasing passenger demand, globalization of trade, and limited near-term substitutes for jet fuel in long-haul operations. According to international assessments, aviation contributes approximately 2–3% of global carbon dioxide emissions, yet its climate impact is magnified by high-altitude non-CO₂ effects and rapid traffic growth trajectories [1].

Policy-oriented analyses increasingly recognize that incremental efficiency improvements alone are insufficient to

align aviation with long-term climate targets. Aircraft design optimization, air traffic management improvements, and operational measures have delivered consistent but diminishing returns over recent decades. Consequently, attention has shifted toward systemic fuel transitions, with Sustainable Aviation Fuels (SAFs) emerging as a central pillar of decarbonization strategies articulated by industry stakeholders, governments, and multilateral organizations [2]. SAFs are defined broadly as non-fossil-derived aviation fuels that meet stringent technical certification standards while offering reduced lifecycle greenhouse gas emissions relative to conventional jet fuel.

Parallel to technological considerations, aviation decarbonization is deeply shaped by policy frameworks. The European Green Deal, global carbon offset mechanisms, and national blending mandates collectively

influence the pace and direction of SAF adoption [4]. These frameworks do not operate in isolation; instead, they interact with agricultural systems, land-use governance, and sustainability certification schemes. Within this complex landscape, feedstock selection has become a critical determinant of both environmental integrity and socio-economic feasibility.

Industrial hemp has recently gained attention within broader bioeconomy discussions due to its high biomass yield, low input requirements, and versatility across industrial sectors. While hemp has been explored extensively in textiles, construction, and bioplastics, its potential role as a feedstock for advanced biofuels remains comparatively underrepresented in aviation-focused literature. Importantly, hemp cultivation aligns with sustainability criteria articulated by international bodies, including soil regeneration potential and compatibility with existing agricultural systems [5]. These attributes raise the question of whether hemp-based SAF pathways could complement existing feedstock portfolios without exacerbating land-use conflicts.

This article aims to provide an integrated academic examination of aviation decarbonization through the lens of SAF deployment, policy alignment, and emerging bio-based feedstocks. Rather than advancing a singular technological solution, the study adopts a systems perspective that situates hemp-based fuels within broader energy transition dynamics. The core objective is to assess how SAF strategies, informed by policy frameworks and sustainability principles, contribute to emissions mitigation while acknowledging structural limitations. By synthesizing insights from authoritative institutional sources and recent academic discourse, the paper seeks to address a notable gap in the literature concerning diversified feedstock strategies for aviation decarbonization.

METHODS

Research Design

This study employs a qualitative-analytical research design grounded in secondary data analysis and integrative literature synthesis. The approach is appropriate given the policy-oriented and systems-level nature of aviation decarbonization, where empirical experimentation is constrained by scale, cost, and regulatory complexity. Rather than generating new quantitative emissions models, the analysis interprets and contextualizes existing institutional assessments, technology roadmaps, and sustainability frameworks.

Data Sources

Primary sources include reports and policy documents published by international energy agencies, aviation

manufacturers, and multilateral institutions. These documents provide authoritative insights into emissions trajectories, SAF technology readiness, and policy mechanisms shaping aviation's climate response [1-4]. Complementary academic literature on bioenergy sustainability and industrial hemp cultivation informs the feedstock analysis, particularly with respect to lifecycle considerations and land-use implications [5].

Analytical Framework

The analytical framework integrates three interrelated dimensions:

Emissions and Technology Dimension – Examination of aviation emissions profiles and the mitigation potential attributed to SAFs across different deployment scenarios.

Policy and Governance Dimension – Analysis of regulatory instruments, incentives, and sustainability criteria influencing SAF adoption, with emphasis on regional policy coherence.

Feedstock Sustainability Dimension – Evaluation of industrial hemp as a potential SAF feedstock based on agronomic characteristics, lifecycle emissions, and alignment with sustainability frameworks.

These dimensions are analyzed iteratively rather than sequentially, reflecting the interconnected nature of technological feasibility, policy support, and environmental integrity.

Limitations

The study does not include original lifecycle assessment modeling or cost-benefit analysis, relying instead on synthesized findings from existing literature. As such, conclusions should be interpreted as indicative rather than predictive. Additionally, the rapidly evolving policy landscape means that some regulatory details may change, although the structural insights remain relevant.

RESULTS

Aviation Emissions Trajectories

Institutional analyses consistently indicate that without substantial intervention, aviation emissions are expected to increase over the coming decades, driven primarily by passenger demand growth in emerging economies [1]. Efficiency gains from next-generation aircraft and improved operations are projected to offset only a fraction of this growth. Consequently, net emissions trajectories remain misaligned with long-term climate stabilization pathways.

Role of Sustainable Aviation Fuels

SAFs are widely recognized as the most viable near- to medium-term mitigation option compatible with existing aircraft fleets and fueling infrastructure [3]. Lifecycle emissions reductions vary significantly depending on feedstock type, conversion pathway, and energy inputs. Advanced biofuels derived from waste residues and non-food crops demonstrate higher mitigation potential than first-generation biofuels, particularly when indirect land-use change is minimized.

Policy Alignment and Market Signals

Policy instruments such as blending mandates, carbon pricing mechanisms, and research subsidies have demonstrably influenced SAF market development in certain regions, particularly within the European Union [4]. However, uneven policy adoption across jurisdictions contributes to fragmented markets and investment uncertainty. Global coordination remains limited, constraining economies of scale.

Industrial Hemp as a Feedstock

Industrial hemp exhibits several attributes relevant to SAF feedstock considerations, including rapid growth cycles, adaptability to diverse climates, and relatively low fertilizer and pesticide requirements [5]. While large-scale conversion pathways specific to aviation fuels are still emerging, hemp's biomass characteristics suggest compatibility with advanced biofuel technologies. Importantly, hemp cultivation aligns with sustainability frameworks emphasizing soil health and multifunctional land use.

DISCUSSION

Integrating SAFs Within a Systems Perspective

The findings underscore that SAFs function most effectively as part of a broader systems approach rather than as a standalone solution. While SAF deployment contributes to emissions intensity reduction, absolute emissions mitigation depends on complementary measures, including demand management and long-term propulsion innovation. This perspective aligns with international assessments cautioning against overreliance on singular mitigation pathways [1].

4.2 Policy Coherence and Sustainability Governance

Effective SAF integration requires policy coherence across energy, agriculture, and transport sectors. Sustainability certification schemes play a crucial role in ensuring that emissions reductions are not offset by adverse land-use impacts. Industrial hemp's alignment with established sustainability principles suggests potential synergies, although governance mechanisms must adapt to incorporate novel feedstocks without diluting standards [5].

Limitations and Future Research Directions

Despite promising attributes, hemp-based SAF pathways face uncertainties related to conversion efficiency, supply chain logistics, and economic competitiveness. Future research should prioritize comparative lifecycle assessments and region-specific feasibility studies. Additionally, interdisciplinary collaboration between agronomy, energy systems, and aviation policy research would enhance evidence-based decision-making.

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