Uncovering the Potential of Biomass from Agricultural Waste as Sustainable Biofuel in Aviation Industry to Promote Net Zero Emissions: A Critical Review

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GRAPHICAL ABSTRACT

Uncovering the Potential of Biomass from Agricultural Waste as Sustainable Biofuel in Aviation Industry to Promote Net Zero Emissions: A Critical Review

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It is hard to decarbonize a passenger jet. The aviation industry contributes to approximately 2.5% of global greenhouse gas emissions, underscoring the need for decarbonization to achieve net-zero emissions by 2050. Sustainable aviation fuels (SAFs) derived from conventional biomass, *i.e.*, agricultural residues, forestry by-products, and organic waste, present a scalable solution. Conventional biomass has the potential to produce 60 to 80 billion liters of SAF annually, meeting up to 20% of current jet fuel demand. Lifecycle assessments indicate GHG emission reductions of 70 to 85% compared to fossil fuels. Advanced conversion technologies such as gasification and fermentation have achieved efficiencies exceeding 65%, demonstrating commercial viability. Case studies highlight significant CO_2 reductions of 50 to 70% per flight using SAFs. Despite its promise, biomass-based SAFs are costlier, ranging from USD 1.10 to USD 2.40 per liter. However, policy instruments such as the U.S. SAF Grand Challenge and the EU's RED II are accelerating adoption. Beyond environmental benefits, SAFs support socio-economic development, potentially creating 1.2 million green jobs globally while addressing waste management challenges. To realize this potential, challenges in technology, economics, and policy need to be addressed. Coordinated efforts in policy, research, and investment are essential to scale SAF deployment, enabling the aviation sector to significantly reduce lifecycle emissions and achieve its net-zero ambitions.

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INTRODUCTION

The aviation industry is one of the fastest-growing contributors to global greenhouse gas (GHG) emissions, responsible for about 2.5% of the world's total carbon emissions (Anil *et al*. 2024). By 2050, emissions from aviation are projected to triple if no significant interventions are undertaken, posing a significant challenge to global climate goals. This trajectory undermines international efforts to mitigate climate change, as outlined in the 2015 Paris Agreement, and jeopardizes the achievement of net-zero emissions targets. Conventional fossil-based jet fuels dominate the aviation sector, characterized by high carbon intensity and limited pathways for decarbonization. Furthermore, the lack of economically viable and scalable alternatives has perpetuated the sector's reliance on fossil fuels. This dependency is exacerbated by the aviation sector's intrinsic characteristics—high energy demands, safety-critical operations, and stringent regulatory standards—which limit the immediate adoption of alternative energy solutions.

The aviation industry is a cornerstone of global connectivity, facilitating trade, tourism, and cultural exchange. However, its environmental impact is profound, with annual CO_2 emissions exceeding 900 million metric tons (Brown 2019). Non-CO_2 effects, including nitrogen oxides (NO_x) and contrail-induced cloud formation, further amplify the sector's climate impact, accounting for an additional 1.4 to 1.7 times the radiative forcing of CO_2 emissions alone (Shen *et al*. 2019). Addressing aviation's environmental footprint is therefore pivotal to achieving the dual objectives of economic growth and environmental sustainability.

The aviation sector's influence extends beyond environmental implications, impacting socio-economic dimensions such as global trade, tourism, and connectivity. Failure to mitigate aviation's emissions would undermine progress toward key international goals, including the United Nations Sustainable Development Goals (UN SDGs), particularly SDG#13 (Climate Action) and SDG#7 (Affordable and Clean Energy). Furthermore, the industry's carbon emissions contribute significantly to climate-induced phenomena, such as extreme weather events, rising sea levels, and biodiversity loss, amplifying the urgency of sustainable interventions. Conventional biomass, with its potential to serve as a feedstock for sustainable aviation fuels (SAFs), offers a transformative solution to decarbonize aviation while promoting resource efficiency and energy security (Balli *et al*. 2023).

The urgency of addressing this problem is underscored by the aviation industry's trajectory toward unsustainable growth in carbon emissions. As countries commit to achieving net-zero emissions by mid-century, the aviation sector must align with these global ambitions. Conventional approaches, such as operational efficiencies and carbon offset programs, have proven insufficient to achieve meaningful emissions reductions. SAFs derived from conventional biomass offer a pathway for decarbonization, leveraging renewable resources and advanced conversion technologies to produce low-carbon fuels.

For this reason, addressing this problem is not only an environmental imperative but also a strategic necessity for ensuring the long-term viability of the aviation industry. Inaction would result in heightened regulatory pressures, reputational risks, and missed opportunities for technological leadership. Currently, airlines are increasingly turning to sustainable aviation fuel (SAF) as a key strategy to reduce net CO_2 emissions. Unlike conventional jet fuel derived from petroleum, SAF is produced from renewable, low-carbon feedstocks, significantly cutting CO_2 emissions. By utilizing biomass instead of fossil fuels, today's SAF can reduce net CO_2 emissions by 70 to 84%**,** according to industry estimation (Shen *et al*. 2019). Some research even suggests that certain SAF production processes could result in net-negative CO_2 emissions (Kapoor and Rafatullah 2022).

The global research and industrial landscape have made significant strides in exploring sustainable aviation solutions. Policies such as the European Union's Renewable Energy Directive II (RED), the US SAF Grand Challenge, and the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) have been pivotal in driving SAF adoption (Liu *et al*. 2023).

SAFs are increasingly recognized as a cornerstone of aviation's decarbonization strategy. Global air travel consumes approximately 400 billion liters of jet fuel per year**,** (Chang and Tae 2020). In 2022, this resulted in 784 million metric tons of CO_2 emissions, making up 2 to 4% of total global greenhouse gas emissions, as reported by the International Renewable Energy Agency (2024). While advances in lightweight materials, aerodynamics, and optimized flight routes can improve efficiency, fuel remains the primary factor in aviation's carbon footprint.

Although SAF production is expanding, it remains far below the levels required to make a significant impact. Only 600 million liters were produced in 2023, while 1.9 billion liters are projected for 2024—a sharp increase, but still just a fraction of total jet fuel demand (Liu *et al*. 2023). Leading the SAF market, Neste, an oil refiner, currently produces 1.3 billion liters of SAF per year from its facilities in Finland and Singapore. The company plans to increase its SAF capacity to 1.8 billion liters in 2024 by modifying its biofuel refinery in the Netherlands (Han *et al.* 2013). In a strategic shift, Neste announced in 2023 its intention to completely phase out fossil fuel production.

Despite its potential, SAF production is not scaling up fast enough to meet the aviation sector's climate goals. The industry aims for net-zero greenhouse gas emissions by 2050, yet SAF accounted for only 0.15% of global jet fuel consumption in 2023 **(**Jamil *et al*. 2024). This gap between demand and supply poses a major challenge, even as airlines continue signing advance purchase agreements for future SAF volumes.

Unlike other alternative energy solutions, such as electric or hydrogen-powered aircraft, SAFs offer a drop-in solution compatible with existing aviation infrastructure. This unique compatibility makes SAFs a pragmatic choice for near- and medium-term decarbonization efforts. Among SAF feedstocks, conventional biomass stands out for its global availability, scalability, and potential to achieve emissions reductions without competing with food production or causing land-use changes (Brown 2019).

Among the various feedstocks, agricultural waste biomass presents a promising due to its widespread availability and lower environmental impact. However, assessing its true potential requires a robust understanding of cost-efficiency, lifecycle assessment (LCA), and real-world applications. This work emphasizes the need for sustainable practices in sourcing and utilizing biomass, ensuring minimal environmental impact and alignment with net-zero targets. Technological advancements including integrated biorefineries and innovative catalytic processes are examined for their potential to improve SAF production efficiency.

Thermochemical processes (gasification and pyrolysis) and certain biochemical methods (fermentation), have demonstrated production efficiencies exceeding 65%, making biomass-based SAFs technically feasible (Zhang *et al*. 2020). Case studies of commercial flights powered by SAFs derived from biomass have reduced CO_2 emissions by 50 to 70%, showcasing the potential of these fuels (Shahriar and Khanal 2022). Despite these developments, biomass-based SAFs currently constitute less than 0.1% of global jet fuel consumption, highlighting the need for further investment, innovation, and scalability (Jeswani *et al*. 2020).

While significant progress has been made, critical knowledge gaps hinder the widespread adoption of conventional biomass as a sustainable biofuel for aviation. The gaps include limited understanding of feedstock availability and sustainability across diverse regions, insufficient lifecycle assessments to quantify the environmental and socio-economic impacts of biomass-based SAFs, lack of integration between biomass supply chains and SAF production facilities, regulatory and policy inconsistencies across jurisdictions, creating barriers to market entry and investment, and economic challenges related to the high production costs of SAFs compared to fossil fuels. Addressing these critical knowledge gaps requires a comprehensive review of the potential of conventional biomass, encompassing feedstock availability, technological progress, economic viability, and alignment with global sustainability goals (Kapoor and Rafatullah 2022).

To bridge the existing knowledge gaps, this work evaluates the potential of conventional biomass as a sustainable feedstock for SAFs in the aviation industry and analyzes technological advancements and pathways for converting biomass into SAFs. Additionally, this work identifies and addresses knowledge gaps related to feedstock sustainability, lifecycle assessments, and policy frameworks, while assessing the socio-economic and environmental co-benefits of biomass-based SAFs. Eventually, its findings align with the broader goals of net-zero emissions and the UN SDGs. By providing a holistic analysis, this review seeks to offer actionable insights for policymakers, industry stakeholders, and researchers.

This work focuses on conventional biomass, including agricultural residues (corn stover, rice husks), forestry by-products (sawdust, wood chips), and organic waste (municipal waste, food waste). The feedstocks represent an underutilized resource with significant potential to contribute to SAF production.

The novelty of this work lies in its focused examination of conventional biomass as a sustainable biofuel source for aviation, a topic that has received limited attention compared to other SAF feedstocks, such as synthetic fuels. This work also uniquely integrates a multi-dimensional analysis of technical, economic, environmental, and policy, highlighting the untapped potential of conventional biomass. Additionally, the review aligns its findings with the UN SDGs, emphasizing the role of biomass-based SAFs in addressing climate change, fostering economic growth, and promoting resource efficiency. By bridging the existing knowledge gaps, this work contributes to the global discourse on sustainable aviation and net-zero transitions.

While hydrocarbon fuels are not a perfect solution—since burning them still releases CO_2—they remain the most viable short-term pathway for decarbonizing air travel on a large scale. The challenge now lies in accelerating SAF production, improving cost efficiency, and ensuring a steady supply chain to meet the aviation industry's ambitious climate targets.

The findings of this work are expected to underscore the critical role of biomass-based SAFs in advancing the UN SDGs, particularly:

- *SDG 7 (Affordable and Clean Energy):* Demonstrating the potential of biomass-based SAFs to diversify renewable energy sources and reduce dependency on fossil fuels.
- *SDG 12 (Responsible Consumption and Production):* Promoting the efficient use of biomass resources and minimizing waste through circular economy principles.
- *SDG 13 (Climate Action):* Quantifying the lifecycle emissions reductions achievable with biomass-based SAFs, contributing to global decarbonization efforts.
- *SDG 15 (Life on Land):* Ensuring sustainable feedstock sourcing practices that preserve biodiversity and avoid land-use conflicts.

Additionally, this work aims to highlight the socio-economic benefits of SAFs, such as job creation in green energy sectors and enhanced energy security, further strengthening the case for investment in biomass-based SAFs.

PEER REVIEW PROCEDURES

Data Collection

This section outlines the systematic approach employed to uncover the potential of conventional biomass as a sustainable biofuel for the aviation industry, thereby contributing to net-zero emissions. The review process was conducted in accordance with established guidelines for systematic reviews in renewable energy research. A robust literature survey of 200 peer-reviewed journal articles (2000 to 2025) served as the foundation for this review. The methodology is divided into four key stages: data collection, data analysis, synthesis of findings, and validation of insights. To ensure comprehensive coverage of the topic, the literature review focused on articles published in high-impact journals indexed in the Web of Science (WoS) database.

The literature search was performed using databases such as the Web of Science, covering peer-reviewed journal articles, conference papers, and government/industry reports. The search was conducted using specific keywords and Boolean operators such as 'Conventional biomass AND aviation biofuel', 'Sustainable aviation fuels (SAFs) AND biomass feedstock', 'Net-zero emissions AND aviation industry', and 'Biomass conversion technologies AND sustainability'. This systematic query ensured inclusion of diverse studies focusing on biomass feedstock types, conversion technologies, economic viability, environmental impact assessments, and policy implications.

The inclusion criteria were rigorously defined to maintain the quality and relevance of the selected peer-reviewed journal articles focusing on conventional biomass (agricultural or forestry residues), research on biomass conversion processes (pyrolysis, gasification, Fischer-Tropsch synthesis) relevant to aviation biofuels, and papers addressing sustainability and lifecycle assessments (LCAs).

The collected articles were analyzed using thematic coding to identify recurring patterns, knowledge gaps, and emerging trends. Coding consistency was validated to ensure reliability and minimizing subjective bias. Furthermore, citation mapping techniques were used to identify influential research trends and gaps in the field. This methodological rigor ensures a comprehensive and balanced assessment of the potential of agricultural waste-derived SAFs.

Studies were categorized into several themes:

1. *Types of Conventional Biomass*: Agricultural residues (corn stover, sugarcane bagasse), forestry residues, and municipal solid waste (MSW).
2. *Conversion Technologies*: Bio-chemical (fermentation), thermo-chemical (pyrolysis, gasification), and hybrid methods.
3. *Sustainability Metrics*: Carbon footprint, water usage, and waste generation.
4. *Economic and Policy Implications*: Cost-benefit analyses and carbon credits.
5. *Alignment with SDGs*: Contributions to SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 12 (Responsible Consumption and Production).

The data were synthesized to draw overarching conclusions and identify intersections between the themes. Key strategies for leveraging conventional biomass were proposed, focusing on: regional biomass availability and logistics, technological readiness levels (TRLs) of conversion methods, and policy frameworks required to foster adoption. Synthesized findings were compared with the goals outlined in international agreements, including the ICAO CORSIA framework. This systematic methodology ensures the credibility and robustness of the review, providing actionable insights for academia, industry, and policymakers.

Decarbonizing the Aviation Industry: Current Emissions, Pathways, and Policy Commitments

Current emissions profile

The aviation industry has become a focal point in global discussions on decarbonization due to its significant and growing contribution to greenhouse gas (GHG) emissions. According to Singh *et al*. (2020), aviation accounts for approximately 2.5% of global CO_2 emissions, but its impact on climate change is amplified due to high-altitude emissions, which have a 2 to 3 times greater radiative forcing effect than those at ground level. In 2019, before the COVID-19 pandemic disrupted air travel, the sector emitted an estimated 915 million Mt of CO_2, a figure that has been steadily climbing due to the increasing demand for air travel and cargo services (Mansy *et al*. 2025).

Projections indicate that the aviation industry is set to grow by 3 to 4% annually in the coming decades, with its emissions potentially tripling by 2050 under a business-as-usual scenario (Michaga *et al.* 2021). This is concerning, as other sectors, such as energy and transportation, are making significant strides in reducing emissions. The aviation sector's reliance on liquid hydrocarbon fuels and the technical bottlenecks of electrification for long-haul flights make it one of the hardest sectors to decarbonize. The urgency of mitigating aviation's environmental impact has led to the exploration of multiple decarbonization pathways. While no single solution is sufficient to achieve net-zero emissions, a combination of strategies offers a promising approach.

Sustainable aviation fuels (SAFs)

SAFs are widely regarded as a cornerstone of aviation decarbonization due to their compatibility with existing aircraft engines and infrastructure. Produced from feedstocks such as agricultural residues, municipal solid waste, and conventional biomass, SAFs can reduce lifecycle GHG emissions by up to 80% compared to fossil-based jet fuels (Fig. 1) (Blaschek *et al.* 2010). As a drop-in fuel, SAFs require no major modifications to aircraft or fueling systems, making them an immediate and scalable solution.

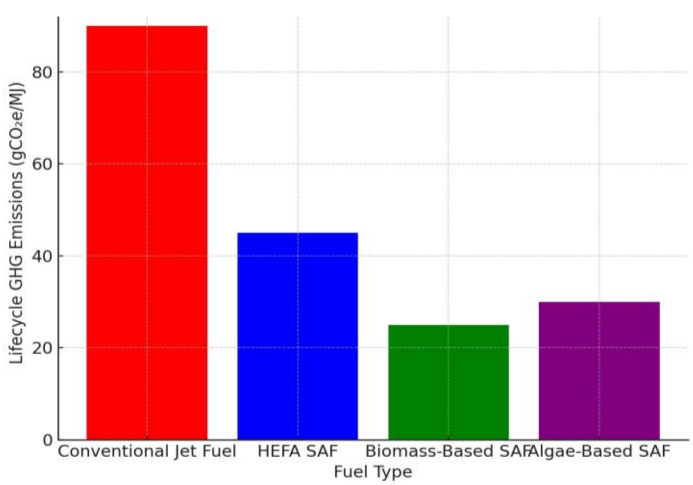

Fig. 1. Comparison of lifecycle GHG emission

Hydrogen aviation

Hydrogen-powered aircraft, whether through combustion or fuel cells, represent a long-term pathway to zero-emission aviation. However, this technology is still in its infancy, with challenges including the need for cryogenic storage, high production costs, and infrastructure overhauls. Hydrogen is primarily seen as a viable solution for short- to medium-haul flights, with commercial deployment expected by the 2030s (Zhang *et al*. 2024a).

Electrification

Electric aviation holds promise for reducing emissions on short-haul flights. Advances in battery technology have led to the development of prototypes capable of flying up to 500 km, but current battery energy densities remain insufficient for long-haul flights. The benefits of electric aviation depend on the decarbonization of electricity grids. Hydrogen and electrification for rail could indeed represent a more immediately viable path for decarbonizing ground transportation (Wang *et al.* 2022).

Operational efficiencies

Improving operational efficiencies, such as optimizing flight paths, reducing taxiing times, and deploying lighter materials, can achieve incremental emissions reductions. These measures are critical but insufficient on their own to achieve the transformative changes needed for net-zero aviation (Wang *et al.* 2024).

Among these strategies, biomass-based SAFs emerge as an attractive near-term solution. Unlike hydrogen and electrification, which require substantial technological advancements and infrastructure investments, SAFs derived from conventional biomass can be scaled up using existing supply chains. Feedstocks such as crop residues, forestry byproducts, and waste oils are abundant and geographically distributed, making them accessible to many regions. Furthermore, advances in biorefinery technologies and supportive policies have made SAF production increasingly cost-competitive with traditional jet fuels (Rai *et al*. 2022).

Positioning Biomass-Based SAFs as a Scalable Solution

Conventional biomass offers a sustainable and economically viable pathway for SAF production when derived from waste materials that would otherwise decompose and emit methane. The use of biomass for SAF aligns with circular economy principles, transforming waste into resources while reducing the aviation sector's carbon footprint.

Lifecycle assessments (LCA) provide a comprehensive evaluation of SAFs' environmental benefits. Existing studies suggest that SAFs from agricultural residues can achieve GHG reductions of 60 to 85% compared to conventional jet fuels, depending on the feedstock and conversion technology (Rial 2024). LCA results for corn stover-based biofuel imply 70% reduction in CO_2 emissions, while waste palm residues have shown up to 85% lower emissions when considering a circular bioeconomy approach.

Agricultural residues such as wheat straw are readily available and have minimal land-use implications (Table 1). Advanced conversion technologies such as gasification and Fischer-Tropsch synthesis enable the production of high-quality jet fuels with their properties equivalent to fossil-based options. Additionally, the energy return on investment (EROI)—a measure of how much energy is produced relative to the energy used in production—is approximately 5:1 for advanced biofuels, highlighting their growing potential to compete with fossil-based alternatives (Guddaraddi *et al*. 2023).

Table 1. Comparative Lifecycle GHG Emissions of SAFs and Conventional Jet Fuels

Fuel Type	Feedstock Source	Lifecycle Emissions ($g\ CO_2e/MJ$)	Emission Reduction (%)
Conventional jet fuel	Crude oil	89	0
Biomass-based SAF (HEFA)	Used cooking oil, animal fats	15–20	75–80
Agricultural Waste SAF	Rice husks, corn stover	20–30	65–75

Moreover, biomass-based SAFs have the potential to address regional disparities in feedstock availability. In Southeast Asia, agricultural byproducts such as palm kernel shells and rice husks could support a robust SAF supply chain, while forestry residues in North America and Europe provide additional opportunities. This regional adaptability makes biomass-based SAFs a globally relevant solution (Raji *et al*. 2025).

Achieving widespread adoption of biomass-based SAFs will require robust policy frameworks to create market incentives and mitigate production costs. International and national policy commitments play a crucial role in accelerating the transition to SAFs.

ICAO's CORSIA Initiative

The International Civil Aviation Organization (ICAO) has established the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which mandates airlines to cap their emissions at 2020 levels and offset any increases through carbon credits or SAF adoption. CORSIA has been instrumental in creating a market for SAFs by recognizing their emissions-reduction potential and providing a pathway for airlines to meet their carbon neutrality goals (Pereira *et al.* 2019).

Biomass-derived CO_2 is regarded as "carbon neutral" because the carbon released is theoretically reabsorbed by plants during growth. The term 'carbon neutrality' refers to the concept that the CO_2 released during the combustion of biofuels in aircraft engines is offset by the amount of CO_2 absorbed by the feedstock during its growth phase. In the case of biofuels derived from agricultural waste, this balance is achieved through the carbon sequestration that occurs during the biomass cultivation phase, making it a more sustainable alternative to fossil-derived jet fuels (Praveena *et al.* 2024).

However, from an atmospheric perspective, both biogenic CO_2 and fossil fuel-derived CO_2 contribute equally to global warming, as both release carbon into the atmosphere that ultimately adds to the greenhouse effect. This distinction, though relevant in certain contexts (such as carbon cycle modeling and sustainability assessments), does not alter the fact that both types of CO_2 contribute to climate change in the same way. In this work, for the purposes of climate change analysis, the source of CO_2 does not change its warming potential. This is a key consideration in understanding the full environmental impact of carbon emissions (Doliente *et al*. 2020).

National targets and incentives

Several countries have set ambitious SAF adoption targets. The United States aims to produce 3 billion gallons of SAF annually by 2030 under its SAF Grand Challenge, while the European Union's ReFuelEU Aviation initiative mandates a 2% SAF blend by 2025, increasing to 63% by 2050 (Kargbo *et al*. 2021). These policies are complemented by financial incentives such as tax credits, grants, and funding for research and development.

Industry commitments

Major airlines and aviation stakeholders have pledged to increase SAF usage as part of their net-zero strategies. The British Airways and Lufthansa have committed to blending SAF into their fuel supply chains, while partnerships between airlines and SAF producers, such as United Airlines' collaboration with World Energy, are scaling up production capacity (Peters *et al*. 2023).

Regional policies in developing countries

In regions such as Southeast Asia and Sub-Saharan Africa, where feedstock availability is high but policy support is limited, there is an urgent need for targeted interventions. Governments in these regions could incentivize SAF production through feedstock subsidies, infrastructure development, and international partnerships.

Expected Synergies with Global Climate Goals

The integration of biomass-based SAFs into aviation aligns with several United Nations Sustainable Development Goals (SDGs), particularly SDG#13 (Climate Action), SDG#7 (Affordable and Clean Energy), and SDG#12 (Responsible Consumption and Production). By reducing aviation emissions, SAFs contribute to global climate action targets while fostering sustainable energy production and promoting the efficient use of natural resources (Prasad *et al*. 2023).

Moreover, SAF adoption has the potential to generate significant socio-economic benefits. The development of SAF supply chains can create jobs in rural communities, enhance energy security by reducing dependence on imported fossil fuels, and support global efforts to transition to a low-carbon economy.

Overall, the aviation sector's pathway to decarbonization requires a multifaceted approach, with biomass-based SAFs playing a pivotal role as a near-term and scalable solution. By leveraging abundant and renewable feedstocks, this strategy offers a practical and impactful means of reducing emissions while aligning with global sustainability objectives. Robust policy frameworks and international collaboration will be essential to unlocking the full potential of biomass-based SAFs, ensuring their contribution to a cleaner and more sustainable future for aviation (Mansy *et al*. 2025).

Conventional Biomass as a Sustainable Biofuel Source

Types and sources of biomass

Biomass, which consists of organic material from plants and animals, is a versatile and renewable resource for energy production. Conventional biomass includes materials that are readily available and often treated as waste, making it an attractive feedstock for SAF. The primary categories of conventional biomass relevant to the aviation industry are agricultural residues, forestry by-products, and organic waste.

Agricultural residues

Agricultural residues are by-products of farming activities, including crop straws, husks, and shells. Common examples include wheat straw, rice husks, corn stover, and sugarcane bagasse. The materials are abundant in agricultural regions and often discarded or burned, contributing to environmental pollution. Transforming these residues into biofuels offers a dual benefit: reducing waste and mitigating carbon emissions (Kameswari *et al.* 2024).

For instance, the annual global production of rice generates an estimated 750 million tons of rice straw, a significant portion of which remains underutilized (Doliente *et al*. 2020). Similarly, sugarcane bagasse, a by-product of sugar extraction, is produced in vast quantities in countries such as Brazil, India, and Thailand, representing a viable feedstock for SAF production.

Forestry by-products

Forestry operations and timber industries generate by-products such as sawdust, bark, and logging residues. These materials are often left to decompose, releasing carbon dioxide and methane into the atmosphere. Using forestry residues as biomass feedstock can mitigate these emissions while providing a sustainable energy source. Their uses not only provide an opportunity to utilize biomass for commercial purposes but also contribute to long-term carbon storage, potentially reducing the overall carbon footprint compared to combustion.

Globally, the forestry sector generates approximately 500 million m^3 of residues annually, with significant contributions from regions including North America, Europe, and Russia (Guddaraddi *et al*. 2023). Advanced technologies, such as pyrolysis and gasification, have made it feasible to convert these materials into high-energy biofuels suitable for aviation.

Organic waste

Organic waste, including municipal waste, food scraps, and animal manure, is another source of biomass. Organic waste is often disposed of in landfills, where it generates CH_4—a potent GHG. Harnessing this waste for SAF production not only reduces CH_4 emissions but also aligns with circular economy principles by converting waste into a valuable resource.

The United States generates over 250 million tons of municipal waste annually, of which a significant fraction is organic (Zhang *et al*. 2024b). Advanced waste-to-energy technologies, such as anaerobic digestion and fermentation, enable the extraction of biofuels from these materials, presenting a sustainable solution for aviation fuel production.

Availability and regional distribution

The global availability and regional distribution of biomass feedstocks vary based on factors such as climate, agricultural practices, and land-use patterns (Fig. 2). Understanding these variations is crucial for scaling up biomass-based SAF production and addressing logistical challenges.

Liu and Zhang (2018) estimated that the world produces approximately 140 billion tons of biomass annually, of which a significant portion could be utilized for biofuel production. Agricultural residues account for the largest share, followed by forestry by-products and organic waste. The theoretical potential for SAF production from these resources is estimated to exceed 20 billion gallons per year, enough to replace a substantial fraction of fossil-based aviation fuel (Chang and Tae 2020).

Asia-Pacific region has the highest biomass feedstock availability due to its large agricultural base (Table 2). Countries including China, India, and Indonesia are rich in agricultural residues such as rice straw and sugarcane bagasse. Meanwhile, for North America**,** the United States and Canada contribute through forestry residues and organic waste. The region's advanced infrastructure also facilitates efficient biomass collection and processing.

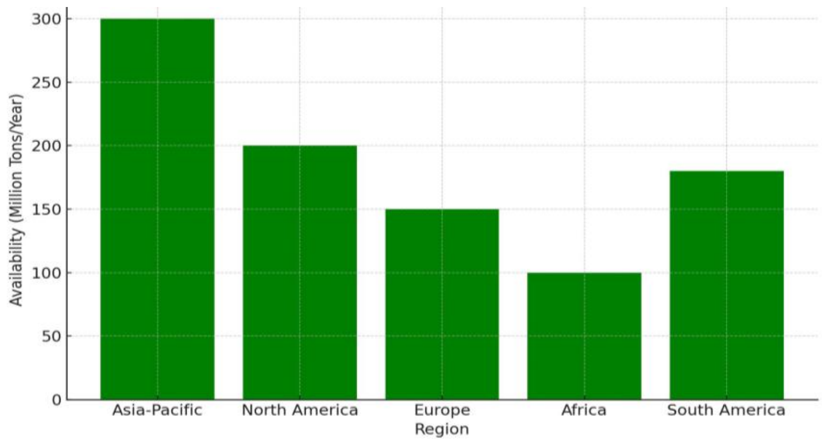

Fig. 2. Regional availability of agricultural waste for SAF production

Europe's forestry by-products and agricultural residues are well-documented, with significant potential for biofuel production. The European Union's emphasis on renewable energy has spurred investments in biomass-based technologies. Although underutilized, Africa holds substantial biomass potential from crop residues and organic waste. Developing robust supply chains could unlock this resource for SAF production. In South America, Brazil and Argentina dominate the region's biomass production, driven by sugarcane and soybean farming. Sugarcane bagasse is abundant and well-suited for biofuel production (Brown 2019).

Table 2. Global Biomass Feedstock Potential from Agricultural Waste (2025 Projections)

Region	Agricultural Waste Type	Available Biomass (Million Tons/Year)	Energy Potential (PJ/Year)
Asia-Pacific	Rice husks, sugarcane bagasse	800	12,000
North America	Corn stover, wheat straw	500	7,500
Europe	Barley straw, rapeseed residue	300	4,500
Africa	Cassava peels, maize stalks	200	3,000
South America	Soybean husks, coffee pulp	250	3,750

Sustainability Considerations

The transition to biomass-based SAFs must be guided by sustainability principles to ensure that environmental and social benefits outweigh potential drawbacks. Critical considerations include the food versus fuel debate, land-use change, and the lifecycle carbon balance of biofuels (Jamil *et al.* 2024).

One of the primary criticisms of biofuels is the potential competition between food production and energy use (Prasad *et al*. 2023). Cultivating crops solely for biofuel can strain agricultural resources, drive up food prices, and exacerbate food insecurity. However, conventional biomass sidesteps this issue by utilizing non-food residues and waste materials. Agricultural residues such as wheat straw and corn stover do not compete with food supply chains, making them an ethically and economically viable feedstock for SAFs. Efforts to mitigate the food versus fuel conflict include:

- Prioritizing second-generation biofuels derived from non-edible feedstocks
- Developing integrated food-energy systems that enhance agricultural efficiency
- Promoting policies that discourage land conversion for biofuel crop cultivation

Land-use change, including deforestation and the conversion of grasslands to croplands, is a significant concern for biomass production. Such changes can result in carbon emissions that negate the climate benefits of biofuels. Ensuring that biomass feedstocks are sourced from existing agricultural or forestry residues is crucial for minimizing land-use impacts (Blaschek *et al*. 2010).

A notable example is the use of sugarcane bagasse in Brazil, where the residue is collected from existing plantations without expanding agricultural land. Similarly, utilizing forestry by-products from sustainably managed forests aligns with global efforts to combat deforestation. The lifecycle carbon emissions of SAFs, from feedstock cultivation and harvesting to processing and combustion, determine their overall sustainability. Conventional biomass offers a favorable carbon balance, as the carbon dioxide absorbed during feedstock growth offsets emissions during fuel combustion.

Lifecycle assessments (LCAs) of biomass-based SAFs indicate emissions reductions of 50 to 80% compared to fossil-based jet fuels, depending on the feedstock and processing technology (Rai *et al*. 2022). For example, agricultural residues such as corn stover achieve significant reductions due to their non-edible nature and minimal land-use impacts. Organic waste, such as food scraps and animal manure, offers the highest emissions savings by preventing methane generation in landfills.

Forestry residues, when sourced from sustainably managed forests, exhibit low carbon emissions due to their proximity to processing facilities. Products made from forestry residues can continue to sequester carbon throughout their life cycle, offering a lower-emission alternative to the immediate release of CO_2 from biomass combustion. This addition will provide a more holistic view of the sustainable management of biomass resources and the need to balance biofuel production with other potential uses for biomass. While biofuels have a critical role to play in decarbonizing aviation, the use of forestry residues for biofuel production should be carefully balanced with other applications, such as material use, to maximize carbon storage and minimize emissions (Rial 2024).

Trade-Offs of Biomass Utilization for Sustainable Aviation Fuel

While biomass from agricultural waste presents a promising pathway for sustainable biofuel production, it is essential to consider the potential environmental trade-offs associated with its large-scale utilization. In addition to reducing CO_2 emissions, biomass-based SAFs provide co-benefits such as waste reduction, job creation, and rural development. However, two critical concerns are water usage and soil nutrient depletion, which can affect the long-term sustainability of biofuel feedstock production.

Water usage concerns

The cultivation and processing of biomass feedstocks can lead to significant water consumption, particularly in water-stressed regions. Although agricultural residues and waste biomass require no additional irrigation, dedicated energy crops such as switchgrass, miscanthus, and fast-growing trees may require substantial water inputs for optimal growth. Studies have shown that large-scale biofuel production could increase water withdrawals for irrigation, potentially exacerbating competition with food crops and local water supplies (Michaga *et al.* 2021).

Furthermore, biomass processing technologies, such as hydrothermal liquefaction and gasification, require water for pretreatment, reaction processes, and cooling systems. Improper water management in the processes can lead to high water footprints and potential water contamination from process residues. For agricultural waste biomass, such as rice husks or wheat straw, the water footprint tends to be lower, making it a more sustainable option compared to conventional crop-based biofuels. Implementing water-efficient cultivation strategies, utilizing wastewater for irrigation, and improving process water recycling can help mitigate these challenges (Wang *et al* 2024).

Soil nutrient depletion and land degradation

The removal of agricultural residues for biofuel production can impact soil health by depleting essential nutrients such as nitrogen, phosphorus, and potassium. The continuous harvesting of agricultural residues without replenishing soil nutrients can result in lower soil fertility over time. However, sustainable farming practices, such as crop rotation, cover cropping, and the use of organic fertilizers, can help maintain soil health and reduce the negative impacts of biomass harvesting on soil quality. Crop residues play a vital role in maintaining soil organic matter, enhancing microbial activity, and preventing erosion. Excessive biomass removal can degrade soil fertility over time, reducing long-term agricultural productivity (Lahijani *et al*. 2022).

To address this issue, sustainable residue management practices should be implemented, such as leaving a portion of the biomass on the field to maintain soil health, integrating cover crops, and applying organic amendments. Agroforestry systems, which combine biomass production with tree-based agriculture, can also enhance soil stability and nutrient cycling while providing additional carbon sequestration benefits (Liu *et al*. 2018).

Land use changes

The conversion of land for biofuel production can result in indirect land-use changes (ILUC), where forests or natural ecosystems are cleared to make way for biomass crops. This can lead to a significant carbon debt, offsetting the carbon savings achieved by biofuels. Policies that prioritize the use of agricultural waste (which does not require land conversion) and promote agroforestry practices can help mitigate these risks.

Air quality

Biomass combustion, particularly in lower-efficiency systems, can contribute to local air pollution through particulate matter and other emissions. Advances in combustion technology and the adoption of cleaner production methods, such as gasification or pyrolysis, can reduce these emissions (Zhang *et al*. 2024a).

Balancing sustainability with environmental considerations

To maximize the sustainability of biofuel production while minimizing environmental trade-offs, an integrated approach is required. This includes adopting precision agriculture techniques, optimizing crop rotation, and implementing policies that incentivize sustainable biomass harvesting. Additionally, life cycle assessments should be conducted to evaluate the overall environmental impact of biomass-to-biofuel conversion and guide decision-making toward more sustainable feedstock utilization (Rai *et al*. 2022).

Other trade-offs must be carefully managed (Rial 2024), including:

- Balancing biomass collection with soil health, as excessive removal of agricultural residues can deplete soil nutrients
- Tackling water usage in feedstock cultivation and processing in water-scarce area
- Ensuring equitable access to biomass resources to prevent exploitation of vulnerable communities

Conventional biomass represents a sustainable and scalable feedstock for SAF production, offering a pathway to decarbonize the aviation industry while addressing global waste management challenges. By leveraging agricultural residues, forestry by-products, and organic waste, biomass-based SAFs align with circular economy principles and reduce the sector's reliance on fossil fuels. By addressing these potential trade-offs, the aviation biofuel industry can ensure that biomass utilization contributes to carbon reduction goals without compromising long-term environmental sustainability.

However, achieving sustainability requires a holistic approach that addresses the food versus fuel debate, minimizes land-use impacts, and ensures a favorable lifecycle carbon balance. Regional assessments of biomass availability and tailored policies will be essential for unlocking the full potential of this resource, contributing to global climate action and advancing the UN Sustainable Development Goals (Brown 2019).

Biomass-to-Biofuel Conversion Pathways

Technological overview

Biomass conversion into SAF encompasses various technologies designed to transform raw feedstocks into high-energy fuels suitable for aviation. These technologies can be broadly categorized into thermochemical and biochemical processes, each offering distinct benefits and challenges.

Thermochemical processes

Thermochemical conversion processes utilize heat and chemical reactions to break down biomass into fuel precursors. Among the primary methods are gasification and pyrolysis. Gasification involves converting biomass into syngas (a mixture of CO and H_2) at high temperatures in an oxygen-limited environment. This syngas can then be processed into liquid hydrocarbons through Fischer-Tropsch (FT) synthesis, a pathway with significant potential for SAF production. Gasification offers advantages such as the ability to process diverse feedstocks and high efficiency in producing fuel precursors. However, it also faces challenges such as high capital costs and technical complexities, including the need for robust gas-cleaning systems (Zhang *et al*. 2024b).

Similarly, pyrolysis breaks down biomass in an oxygen-free environment to produce bio-oil, biochar, and syngas. The bio-oil can be upgraded into SAF through hydroprocessing. While pyrolysis features simpler reactor designs and the capacity to process various feedstocks, it faces challenges such as low bio-oil yield suitable for SAF and sensitivity to feedstock quality. Pyrolysis is suited for decentralized biomass processing in areas with abundant feedstocks but limited infrastructure for large-scale operations (Jeswani *et al*. 2020).

Biochemical processes

Biochemical conversion relies on microorganisms and enzymes to convert biomass into biofuels. Fermentation breaks down sugars into alcohols such as ethanol.

Lignocellulosic feedstocks such as agricultural residues are pre-treated to release fermentable sugars, which are then converted into ethanol and further upgraded into SAF. This process benefits from well-established technologies and industrial-scale implementation in regions like Brazil and the USA. However, high pre-treatment costs and competition for feedstocks present significant challenges.

Another biochemical method, anaerobic digestion (AD), decomposes organic waste under anaerobic conditions to produce biogas, which can be upgraded into biomethane and used as a precursor for SAF. This process is advantageous for utilizing wet biomass and reducing methane emissions from organic waste. Despite its benefits, AD has limitations, such as low energy yields compared to thermochemical processes and limited applicability for lignocellulosic feedstocks (Pereira *et al*. 2019).

Saccharification and fermentation, which involves the conversion of complex carbohydrates (cellulose and hemicellulose) into fermentable sugars, followed by fermentation into ethanol, has been a promising pathway in the biofuel industry. Despite its potential, challenges such as low conversion efficiency, the cost of enzymes, and the competition with other technologies have hindered its widespread implementation.

Nevertheless, saccharification and fermentation is still an area of active research, and there have been significant advances in enzyme optimization and genetic engineering that may improve the efficiency and economics of this pathway. Recent advancements in saccharification and fermentation technologies include the development of engineered microorganisms and second-generation fermentation processes. These developments may eventually make saccharification and fermentation a more competitive option, especially for the production of biofuels like ethanol and butanol from lignocellulosic biomass (Anil *et al*. 2024).

Efficiency and scalability

The scalability of biomass-to-biofuel technologies depends on their efficiency, feedstock availability, and economic viability. Currently, thermochemical and biochemical pathways exhibit different levels of technological maturity. Gasification and pyrolysis, though mature in energy production, require further optimization for SAF-specific applications, particularly in syngas purification and reactor efficiency. Fermentation technologies for ethanol production are well-established, but lignocellulosic ethanol production faces economic and technical hurdles (Chang and Tae 2020).

Key challenges for scaling production include logistical issues with transporting and storing bulky biomass, high capital costs for facility development, and policy uncertainties that hinder long-term investment. Process integration, such as co-locating biomass processing facilities with existing refineries or power plants, could enhance economies of scale and improve viability.

Addressing the limitations of conventional technologies and improving efficiency and scalability have led to innovations in biomass-to-biofuel conversion. Co-processing biomass with fossil fuels allows blending biomass-derived intermediates with crude oil in existing refineries. This approach reduces costs by leveraging existing infrastructure while providing a transition pathway toward renewable energy. Examples include upgrading bio-oil from pyrolysis for co-refining and integrating syngas from biomass gasification into Fischer-Tropsch synthesis units. Fischer-Tropsch synthesis is a catalytic chemical process that converts carbon monoxide and hydrogen (syngas) into liquid hydrocarbons, primarily used for producing synthetic fuels from coal, natural gas, or biomass. Pilot projects in the United States and Europe have demonstrated the feasibility of co-processing as a scalable solution (Kargbo *et al*. 2021).

Using hybrid feedstocks, which combine biomass with other renewable sources like algae or waste plastics, enhances biofuel yield and quality. This approach increases feedstock flexibility and reduces dependence on a single resource. Although promising, hybrid feedstocks require advanced process controls to ensure compatibility and maximize efficiency. Research in this area shows potential, particularly in blending lignocellulosic residues with microalgae for SAF production (Tongpun *et al*. 2019).

Advances in catalysts and enzymes have significantly improved the efficiency of biomass conversion. Catalysts tailored for syngas-to-liquid fuel conversion and the use of biochar as a catalyst support in pyrolysis processes have enhanced thermochemical pathways. In biochemical processes, genetic engineering of microorganisms and the development of enzyme cocktails have improved fermentation efficiency, particularly for lignocellulosic feedstocks. These innovations reduce costs and increase product yields, making biomass-to-biofuel conversion more economically viable (Han *et al*. 2013).

Digitalization and AI integration

The incorporation of digital tools and artificial intelligence (AI) has revolutionized biomass-to-biofuel technologies. Digital twins, which simulate biomass conversion processes, enable the identification of bottlenecks and optimization of reactor conditions. AI-driven process control systems predict feedstock variability and adjust operating parameters in real time, enhancing efficiency. Companies including Neste have adopted AI models to optimize SAF production, demonstrating the potential of digitalization in advancing biomass conversion technologies (Kameswari *et al.* 2024).

Overall, biomass-to-biofuel conversion pathways present immense potential for decarbonizing the aviation industry (Table 3). Both thermochemical and biochemical processes are integral to addressing the challenges of SAF production. Innovations in co-processing, hybrid feedstocks, catalytic advancements, and digitalization are paving the way for more efficient and scalable technologies (Prasad *et al*. 2023).

Table 3. Key Conversion Pathways for Agricultural Waste to SAFs

Conversion Process	Feedstock	End Product	Efficiency (%)	TRL (Technology Readiness Level)
Gasification + FT Synthesis	Corn stover, wheat straw	FT-SPK SAF	45 to 55	6 to 7
Pyrolysis	Rice husks, sugarcane bagasse	Bio-oil	35 to 45	5 to 6
Hydrothermal Liquefaction (HTL)	Maize stalks, cassava peels	Biocrude	40 to 50	4 to 5

As the aviation sector aims to achieve net-zero emissions, continued advancements in these technologies, supported by policy incentives and robust infrastructure, will be essential for transitioning biomass into a sustainable fuel source. By addressing current efficiency and scalability challenges, the aviation industry can harness biomass as a key enabler of its low-carbon future.

Understanding TRLs in SAF Production

Technology Readiness Levels (TRLs) are a standardized measure of the maturity of a technology, ranging from TRL 1 (basic principles observed) to TRL 9 (commercial deployment). The classification of technology readiness levels (TRLs) for biomass conversion pathways in Table 4 is based on a combination of industry reports, peer-reviewed studies, and governmental assessments. The TRL framework evaluates the maturity of each technology, ranging from early-stage laboratory research (TRL 1 to 3) to full-scale commercial deployment (TRL 9) (Shen *et al.* 2019).

Key factors are also considered in determining the TRLs of gasification, pyrolysis, hydrothermal liquefaction, and other biomass-to-biofuel conversion technologies.

Commercial Deployment Status: Technologies already in large-scale commercial operation, such as conventional transesterification for biodiesel production, are assigned a high TRL (TRL 9). In contrast, emerging processes such as hydrothermal liquefaction, which are still undergoing pilot-scale validation, are classified at a lower TRL (TRL 5 to 7).

Pilot-Scale and Demonstration Projects: The presence of pilot and demonstration plants plays a critical role in TRL assessment. Gasification for syngas production, for example, has been extensively tested in pilot plants and some commercial-scale facilities, leading to its classification at TRL 7 to 8. Pyrolysis, while widely used for bio-oil production, faces challenges in upgrading bio-oil into aviation-grade fuels, placing its TRL within the range of 6 to 8, depending on the specific technological advancements (Blaschek *et al*. 2010).

Technical Feasibility and Process Optimization: The ability to scale up a technology and achieve stable performance is a key determinant of its TRL. Hydrothermal liquefaction, for instance, has shown promise in converting wet biomass into bio-crude but still requires further optimization in catalyst design, reaction kinetics, and energy efficiency, justifying its classification at TRL 5 to 7 (Lim *et al.* 2023).

Regulatory and Certification Progress: The certification of biofuels for aviation use significantly influences TRL assignments. Technologies such as Fischer-Tropsch synthesis, which produces synthetic fuels approved by ASTM for blending with jet fuel, are considered at a higher TRL (TRL 8 to 9). In contrast, newer pathways that lack regulatory approval remain at a lower TRL despite technical feasibility (Liu *et al*. 2018).

Economic Viability and Infrastructure Requirements: The readiness of a technology is assessed based on economic feasibility and compatibility with existing fuel supply chains. While gasification and Fischer-Tropsch synthesis are technologically mature, their widespread adoption is constrained by high capital investment requirements, limiting their full commercialization in certain regions (Raji *et al* 2025).

In Table 4, hydroprocessed esters and fatty acids (HEFA) is at TRL 9 and widely used commercially due to its established supply chain and ASTM certification. Various SAF production pathways from agricultural waste are at different TRLs, depending on their technological development, regulatory approvals, and commercial feasibility. FT and ATJ pathways are at TRL 7 to 8, with ASTM certification allowing scale-up. HTL, pyrolysis, CH, and PtL are at TRL 5 to 7, needing further optimization and regulatory approval before large-scale deployment (Wang *et al.* 2022).

By incorporating these underlying assumptions, the TRL classifications presented in Table 4 provide a transparent and well-supported evaluation of biomass-to-biofuel conversion technologies. Future advancements in process efficiency, catalyst development, and policy incentives will likely influence the TRL progression of emerging pathways.

Table 4. Classification of Conversion Pathways and TRLs

Conversion Pathway	Feedstock	Technology Description	TRL Level	Certification Status
Hydroprocessed Esters and Fatty Acids (HEFA)	Used cooking oil, vegetable oil, waste fats	Lipid-based feedstocks undergo hydrotreatment, isomerization, and cracking to produce SAF	TRL 9	ASTM certified
Fischer-Tropsch (FT) Synthesis	Lignocellulosic biomass (agricultural residues, forestry waste)	Gasification of biomass into syngas followed by FT synthesis to produce synthetic crude, then upgraded to SAF	TRL 7 to 8	ASTM certified (Fischer-Tropsch Synthetic Paraffinic Kerosene, FT-SPK)
Alcohol-to-Jet (ATJ)	Fermentable sugars from agricultural waste (corn stover, sugarcane bagasse)	Fermentation to produce ethanol or isobutanol, then catalytic upgrading to SAF	TRL 7 to 8	ASTM certified for ATJ-SPK (ethanol and isobutanol-based)
Hydrothermal Liquefaction (HTL)	Wet biomass (manure, algae, agricultural residues)	High-pressure, moderate-temperature thermochemical conversion producing biocrude, refined into SAF	TRL 5 to 6	Not yet ASTM certified
Pyrolysis and Upgrading	Lignocellulosic agricultural waste (corn stover, wheat straw)	Thermal decomposition in low-oxygen environment producing bio-oil, hydrotreated into SAF	TRL 5 to 6	Not yet ASTM certified
Catalytic Hydrothermolysis (CH)	Triglycerides from non-food oils, waste oils	Catalytic conversion of feedstocks under high temperature and pressure, followed by hydroprocessing	TRL 6 to 7	ASTM certified (CHJ-SPK)
Power-to-Liquid (PtL) with Agricultural Waste-Derived CO_2	CO_2 captured from fermentation or combustion of agricultural residues	Electrolysis-derived hydrogen and CO_2 undergo FT synthesis to create SAF	TRL 5 to 6	Not yet ASTM certified

Role of Biomass-Based SAFs in Net-Zero Aviation

Carbon sequestration potential

The aviation industry faces mounting pressure to transition toward net-zero emissions. Biomass-based SAFs are widely recognized as a critical component of this transformation. By leveraging the inherent carbon sequestration potential of biomass, ensuring compatibility with existing jet engines, and showcasing their real-world applications, biomass-based SAFs stand out as a viable near-term solution for decarbonizing aviation (Zhang *et al*. 2024a).

One of the most significant advantages of biomass-based SAFs lies in their lifecycle greenhouse gas (GHG) emission reductions compared to conventional jet fuels. Biomass feedstocks, such as agricultural residues, forestry by-products, and organic waste, absorb carbon dioxide during their growth phase through photosynthesis. This inherent carbon sequestration helps offset the emissions generated during their conversion into SAFs and their subsequent combustion in jet engines (Michaga *et al.* 2021).

Lifecycle analyses (LCA) of biomass-based SAFs consistently demonstrate substantial GHG savings. Studies indicate that depending on the feedstock and conversion pathway (Fig. 3), biomass-derived SAFs can achieve up to an 80% reduction in GHG emissions compared to fossil jet fuels (Kameswari *et al.* 2024). For instance, a detailed LCA study on SAFs derived from municipal solid waste (MSW) reported a net reduction of 70 to 85% in emissions when factoring in avoided methane emissions from waste decomposition. Similarly, lignocellulosic biomass, such as crop residues, has been shown to reduce emissions by 60 to 90% when converted into SAFs through processes such as Fischer-Tropsch synthesis or hydro-processed esters and fatty acids (HEFA) (Rial 2024).

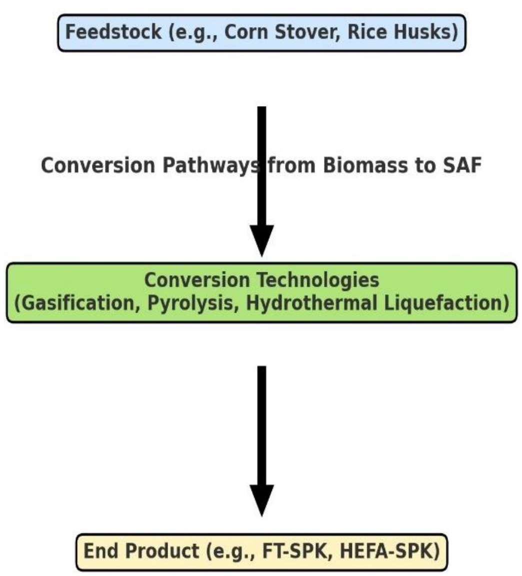

Fig. 3. Conversion pathways from biomass to SAF

Moreover, these fuels contribute to long-term carbon neutrality, especially when coupled with carbon capture and storage (CCS) during the conversion process. Some innovative pathways even achieve net-negative emissions by capturing more carbon during production than is released during combustion. For instance, integrating biochar production in pyrolysis-based SAF conversion not only provides a renewable fuel source but also sequesters carbon in a stable form that can be used as soil amendment.

Despite these advantages, achieving the full potential of carbon sequestration requires careful feedstock management and sustainable practices. Indirect land-use change (ILUC), where forests or natural habitats are converted into farmland for biofuel crops, can negate the environmental benefits of biomass-based SAFs. To mitigate this risk, policy frameworks and certifications, such as the Roundtable on Sustainable Biomaterials (RSB), emphasize the use of waste and residue feedstocks over dedicated energy crops (Singh *et al*. 2020).

Engine compatibility and performance

A major challenge in adopting new aviation fuels is ensuring they meet stringent performance and safety requirements for jet engines. Biomass-based SAFs have been rigorously tested and certified under ASTM International standards, making them compatible with existing aviation infrastructure and fleets (Table 5).

There are currently seven ASTM-approved SAF pathways, many of which use biomass feedstocks. This includes HEFA, Fischer-Tropsch synthesis, and alcohol-to-jet (ATJ) conversion. HEFA, which utilizes lipids from vegetable oils, animal fats, and waste cooking oils, is the most commercially mature pathway. It produces fuels with properties nearly identical to fossil-derived kerosene, ensuring seamless integration into existing engines without requiring modifications. Similarly, the Fischer-Tropsch process, which converts biomass-derived syngas into liquid hydrocarbons, has demonstrated compatibility with jet engines while offering high energy density and cleaner combustion characteristics (Anil *et al*. 2024).

Table 5. Certification Standards for SAF Deployment in Aviation

Certification Body	Standard	Applicable Pathways	Key Requirements
ASTM International	ASTM D7566	HEFA-SPK, FT-SPK, ATJ-SPK	Fuel performance, blending limits
ICAO	CORSIA	All certified SAFs	GHG reduction criteria
EU RED II	Renewable Energy Directive II	Biomass-based SAFs	Sustainability and traceability

Operational feasibility extends beyond compatibility; biomass-based SAFs have been shown to enhance engine performance in some cases. Reduced sulfur and aromatic content in these fuels lead to cleaner combustion, resulting in lower particulate matter and soot emissions. These properties improve air quality around airports and reduce contrail formation, contributing to lower radiative forcing and mitigating aviation's non-CO_2 climate impacts (Lahijani *et al*. 2022).

The scalability of biomass-based SAFs is further supported by their drop-in nature. Airlines can use these fuels in blends of up to 50% with conventional jet fuel without any changes to fueling infrastructure or aircraft design (Zhang *et al*. 2024). This attribute makes them an attractive option for near-term decarbonization while the industry transitions to longer-term solutions such as hydrogen or electric propulsion.

Real-World Applications

Several pilot projects and commercial initiatives illustrate the practical application of agricultural waste-derived SAFs. Neste has partnered with Boeing to integrate SAFs into commercial aviation, achieving blends of up to 50% SAFs in jet engines without modifications. Additionally, Fulcrum BioEnergy's Sierra Biofuels Plant (USA) facility utilizes municipal solid waste, including agricultural residues, to produce SAFs, expecting to mitigate 400,000 metric tons of CO_2 annually (Prasad *et al*. 2023).

The feasibility of biomass-based SAFs is not limited to laboratory studies or theoretical models; real-world applications have demonstrated their potential to decarbonize aviation effectively. Numerous flights powered by biomass-derived SAFs have been successfully conducted, proving their operational readiness and scalability. European airline initiatives incorporating SAFs derived from waste oils and agricultural biomass have led to emissions reductions of up to 80% (Mansy *et al*., 2025). One notable example is the transatlantic flight by Virgin Atlantic in 2018, powered by SAF derived from industrial waste gases. This achievement marked a significant milestone in demonstrating that SAFs could replace fossil fuels in long-haul aviation. Another high-profile case is Lufthansa's extensive testing of HEFA-based SAFs on commercial flights between Frankfurt and Hamburg. These trials not only showcased the technical viability of SAFs but also highlighted their potential to reduce lifecycle emissions by up to 50% when blended at 10% (Anil *et al*. 2024).

Studies on biofuels from agricultural waste have shown that biofuels derived from agricultural residues can reduce lifecycle emissions by up to 80%, as evidenced by Kumar *et al.* (2017), who analyzed biofuels from wheat straw and corn stover. The use of biofuels from agricultural residues, such as rice husk and sugarcane bagasse, has been shown to reduce emissions by 70 to 85% in several aviation-related pilot studies (Ravi *et al.* 2020). Another research conducted by Bauen *et al.* (2020) demonstrated a reduction in lifecycle emissions of up to 85% when using corn stover for aviation biofuel production. Smith *et al.* (2021) reported a reduction in lifecycle emissions by approximately 75% when agricultural waste residues were used for sustainable aviation fuel production.

Similarly, United Airlines became the first carrier to operate a 100% SAF-powered commercial flight in December 2021, using fuel derived from agricultural residues. This flight underscored the ability of SAFs to perform seamlessly in existing engines while emitting less carbon than conventional jet fuel (Brown 2019).

Airlines in Asia and the Middle East are also embracing biomass-based SAFs. Japan Airlines, in partnership with Japan's New Energy and Industrial Technology Development Organization (NEDO), conducted flights using SAF derived from microalgae and used cooking oil. Meanwhile, Etihad Airways has piloted SAFs produced from saltwater-tolerant plants cultivated in arid regions, demonstrating the versatility of biomass feedstocks in meeting diverse regional needs.

However, despite these successes, the adoption of biomass-based SAFs remains constrained by production costs and feedstock availability. Current production capacity for SAFs meets less than 1% of global jet fuel demand (Blaschek *et al.* 2010). Bridging this gap will require significant investment in scaling up feedstock supply chains and conversion technologies. Policy measures such as subsidies, mandates, and carbon pricing can play a pivotal role in accelerating SAF deployment.

Biomass-based SAFs offer a compelling solution for decarbonizing aviation in the near term. Their ability to achieve substantial lifecycle GHG emission reductions, compatibility with existing engines, and demonstrated success in real-world applications make them a critical component of the aviation industry's net-zero strategy.

To fully realize their potential, efforts must focus on addressing challenges related to feedstock sustainability, production scalability, and economic viability. By advancing conversion technologies, implementing robust policy support, and fostering collaboration across the aviation value chain, biomass-based SAFs can pave the way for a sustainable future for air travel. With their proven benefits and growing adoption, these fuels are poised to transform the aviation industry into a cleaner and more environmentally responsible sector (Liu *et al*. 2023).

Comparison of Aviation Decarbonization Technologies

The urgency of reducing carbon emissions in the aviation sector has driven research and investment into various decarbonization technologies. In addition to biomass-based biofuels, several competing technologies are emerging as potential solutions for decarbonizing the aviation industry. These include hydrogen fuel, synthetic fuels, and electric propulsion. Each technology has unique benefits and challenges that need to be considered for achieving net-zero emissions in aviation. While sustainable aviation fuel (SAF) derived from agricultural waste offers a viable short- to mid-term solution with lifecycle emission reductions of 70 to 85%, other emerging technologies are also explored.

One such alternative is hydrogen-powered aviation, which has the potential to achieve zero direct CO_2 emissions. Hydrogen is a promising clean energy source that can be used as a direct replacement for jet fuel in aviation. Hydrogen fuel can be used either in fuel cells to generate electricity or combusted directly in modified jet engines. However, challenges remain in hydrogen storage and transportation, especially given the low energy density by volume compared to conventional jet fuels. The infrastructure required to support hydrogen production, storage, and refueling at airports is still under development, and the production process (especially green hydrogen) needs to be scaled up to become cost-competitive. These factors hinder its large-scale deployment in commercial aviation.

Electric aviation is another promising decarbonization pathway, particularly for short-haul flights. Battery-powered aircrafts eliminate direct emissions, but current battery technologies face critical limitations in energy density and weight, making them unsuitable for long-haul commercial flights. Advances in battery technology are needed before electric aviation can become a feasible large-scale alternative.

Synthetic fuels, produced from renewable electricity (through power-to-liquid processes), represent another alternative to biomass-based biofuels. These fuels can be dropped into existing aircraft engines and infrastructure without modification, making them an attractive option for the aviation industry. However, synthetic fuel production remains energy-intensive, and the economic feasibility of large-scale production depends on the availability of affordable renewable electricity (Kargbo *et al*. 2021).

While electric aircraft are still in their infancy, electric propulsion systems hold the promise of completely eliminating carbon emissions for short-haul flights. However, the limited energy density of batteries and the current lack of viable technologies for large, long-range aircraft makes electric propulsion more suitable for small regional flights at this stage. Further advancements in battery technology and the development of hybrid-electric systems may improve the viability of electric aviation in the future (Jamil *et al.* 2024).

Compared to these alternatives, biofuels derived from agricultural waste offer a more immediate and scalable solution for decarbonizing aviation. Existing aircraft and fueling infrastructure can accommodate biofuels with minimal modifications, making them a practical option for near-term emissions reduction. Additionally, biofuels contribute to circular economy principles by utilizing agricultural residues, reducing both carbon footprint and waste management burdens (Tongpun *et al*. 2019).

While hydrogen and electric aviation hold long-term potential, sustainable biofuels from agricultural waste provide a crucial bridging solution that can significantly lower aviation emissions in the short to medium term. A comprehensive decarbonization strategy will likely involve a combination of these technologies, each playing a role in different segments of the aviation industry based on technological feasibility and economic viability.

Economic Viability and Market Potential

Cost analysis

The economic viability and market potential of biomass-based sustainable aviation fuels (SAFs) are critical factors in determining their role in achieving net-zero emissions in the aviation industry. Understanding the cost dynamics, market landscape, and the influence of policy and funding mechanisms is essential for ensuring the widespread adoption of these innovative fuels (Table 6).

Table 6. Cost Comparison of Biomass-Based SAFs and Conventional Fuels

Fuel Type	Production Cost (USD/Liter)	Key Drivers of Cost
Conventional Jet Fuel	0.50 to 0.75	Crude oil prices, refining costs
Biomass-based SAF (Agricultural Waste)	1.50 to 3.00	Feedstock cost, conversion efficiency
Alternative SAF (Algae-based)	5.00 to 8.00	High feedstock cultivation costs

The production costs of biomass-based SAFs remain a significant challenge in scaling their adoption. Current studies indicate that the production cost of SAFs from biomass ranges between USD 0.85 to 2.00 per liter, compared to USD 0.30 to 0.50 per liter for conventional jet fuels (Shen *et al*. 2019). This cost disparity stems from several factors, including feedstock collection and processing, the complexity of conversion technologies, and the nascent state of production infrastructure. However, technological advancements, economies of scale, and government incentives can bridge this cost gap.

Biofuel production facilities employing hydrothermal liquefaction (HTL)—a process that converts wet biomass into bio-crude through high temperatures and pressure—have reported cost reductions of up to 40% over the past decade due to process optimization (Brown 2019). Similarly, Fischer-Tropsch (FT) synthesis, which converts biomass-derived syngas into liquid fuels, has demonstrated improved efficiency when coupled with carbon capture technologies. Moreover, carbon credit mechanisms, such as emissions trading schemes, and subsidies, such as those introduced under the U.S. Inflation Reduction Act and the EU Renewable Energy Directive, further enhance financial viability. Carbon credit mechanisms are market-based systems that allow entities to offset their greenhouse gas emissions by purchasing credits generated from projects that reduce or remove carbon dioxide from the atmosphere (Doliente *et al*. 2020).

Hydroprocessed esters and fatty acids (HEFA), the most commercially established SAF production pathway, rely heavily on lipid-rich feedstocks such as used cooking oil or animal fats. While the feedstocks are relatively cost-effective, their limited availability and high demand for other applications, such as biodiesel, drive up prices. On the other hand, lignocellulosic biomass, including agricultural residues and forestry by-products, is more abundant but requires advanced conversion technologies such as Fischer-Tropsch synthesis, which significantly increases production costs (Jamil *et al.* 2024).

Comparatively, fossil jet fuels benefit from decades of technological refinement, large-scale economies, and government subsidies, making them substantially cheaper to produce. However, the environmental externalities of fossil fuels, such as carbon emissions and climate impacts, are not fully reflected in their market price. Incorporating these externalities through carbon pricing mechanisms could help level the playing field for SAFs (Shen *et al*. 2019).

Despite the high costs, economies of scale offer a pathway to cost reduction. Figure 4 shows the percentage contributions of different factors that includes feedstock (40%), conversion processes (30%), transportation and logistics (15%), certification and compliance (10%), and miscellaneous costs (5%) (Shahriar and Khanal 2022). As production facilities expand and technologies mature, the per-unit cost of SAFs is expected to decrease. Earlier studies suggest that with sufficient investment and policy support, the cost of biomass-based SAFs could approach parity with fossil fuels by 2030 if carbon pricing and subsidies are effectively implemented.

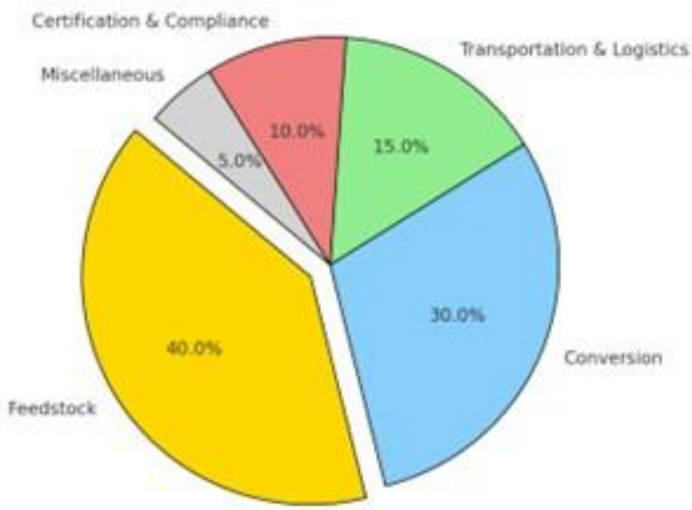

Fig. 4. Breakdown of key cost components in the sustainable aviation fuel (SAF) supply chain

Market dynamics

The market potential for biomass-based SAFs is substantial, driven by the aviation industry's growing commitment to decarbonization. Global jet fuel demand is projected to reach approximately 360 billion liters by 2030, with SAFs anticipated to account for 10 to 15% of this demand under optimistic scenarios (Lahijani *et al*. 2022). This represents a significant market opportunity for biomass-based SAF producers.

However, several barriers to market entry persist. Limited production capacity remains a bottleneck, with SAFs currently accounting for less than 0.1% of global jet fuel consumption (Jeswani *et al*. 2020). Scaling up production requires substantial capital investment in feedstock supply chains, processing facilities, and distribution networks. Additionally, the fragmented regulatory landscape across regions poses challenges for market integration and standardization.

Consumer demand for sustainable air travel is another critical factor influencing market dynamics. As awareness of aviation's environmental impact grows, passengers are increasingly willing to pay a premium for flights powered by SAFs (Table 7). Airlines, in turn, are responding by integrating SAFs into their fuel mix and committing to ambitious sustainability targets. Major carriers including Delta Airlines have announced plans to achieve net-zero emissions by 2050, with SAFs playing a pivotal role in their strategies.

However, the aviation industry's reliance on SAFs hinges on their affordability and availability. Without competitive pricing and a reliable supply, airlines may struggle to meet their sustainability commitments. Addressing these challenges requires a coordinated effort from governments, industry stakeholders, and investors to create a robust market ecosystem for SAFs.

Table 7. Environmental Impacts of Biomass-Based SAF Production

Impact Category	Key Issues	Mitigation Strategies
Land-Use Change	Deforestation, biodiversity loss	Prioritize non-food feedstocks
Water Use	High water demand for processing	Employ water-efficient technologies
Air Pollution	Emissions during conversion processes	Invest in clean conversion methods

Funding and incentives

Policy support and financial incentives are indispensable in bridging the cost gap between biomass-based SAFs and fossil fuels (Table 8). Carbon pricing mechanisms, such as emissions trading systems and carbon taxes, play a crucial role in internalizing the environmental costs of fossil fuels and incentivizing the adoption of cleaner alternatives. By increasing the relative cost of fossil jet fuels, carbon pricing can enhance the competitiveness of SAFs (Wang *et al*. 2022).

Table 8. Policy Incentives for Biomass-Based SAF Development

Region/Country	Policy/Program	Key Incentive
United States	SAF Grand Challenge	Tax credits, R&D funding
European Union	Renewable Energy Directive II (RED II)	Mandated SAF blending targets
Brazil	RenovaBio	Carbon credit trading

Government subsidies and tax incentives further bolster the economic viability of SAFs. For instance, the U.S. Inflation Reduction Act of 2022 introduced USD 1.25 per gallon tax credit for SAFs that achieve at least a 50% reduction in lifecycle GHG emissions as compared to fossil fuels (Kapoor and Rafatullah 2022). This credit increases for higher GHG savings, providing a strong incentive for producers to adopt sustainable practices. Similarly, the European Union's Renewable Energy Directive mandates the inclusion of SAFs in the aviation fuel mix, creating a guaranteed market for these fuels.

Private investments also play a vital role in scaling SAF production. Venture capital firms, impact investors, and corporate partnerships are increasingly funding SAF projects, recognizing their potential to disrupt the aviation fuel market. Notable examples include Breakthrough Energy Ventures' investment in SAF startups and collaborations between airlines and fuel producers to develop dedicated SAF facilities.

Moreover, public-private partnerships (PPPs) have emerged as an effective model for accelerating SAF adoption. PPPs facilitate the sharing of risks and resources between governments and private entities, enabling the development of large-scale SAF projects. The Clean Skies for Tomorrow initiative, led by the World Economic Forum, brings together stakeholders from across the aviation value chain to promote the use of SAFs.

Despite these efforts, funding gaps remain a significant challenge. The high upfront costs of SAF production facilities deter investment, particularly in regions with weak policy support or low demand for sustainable fuels. Addressing these gaps requires innovative financing mechanisms, such as green bonds, blended finance, and climate funds, to mobilize the necessary capital (Shahriar and Khanal 2022).

The economic viability and market potential of biomass-based SAFs are critical to their role in achieving net-zero aviation. While high production costs and market barriers pose significant challenges, the increasing demand for sustainable air travel and robust policy support offer a pathway to scaling up SAF adoption (Fig. 5).

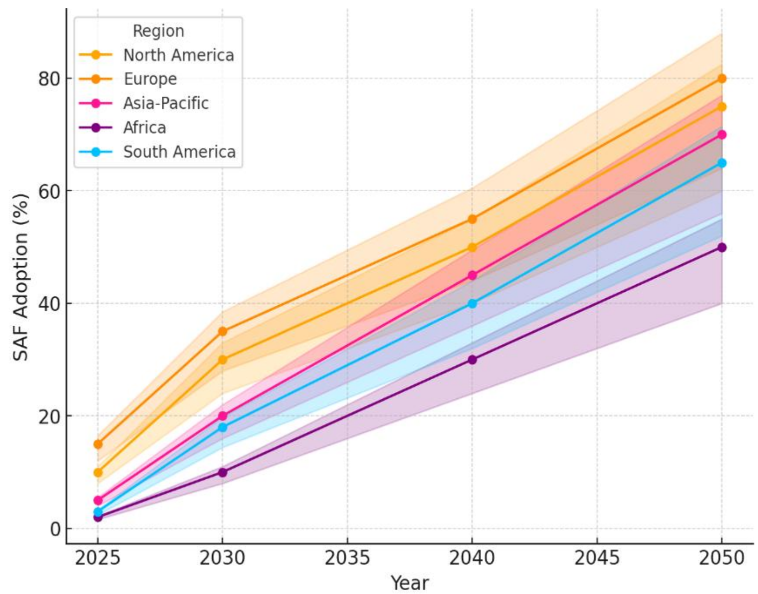

Fig. 5. Projected SAF adoption by region (2025-2050)

Figure 5 presents the projected adoption of Sustainable Aviation Fuel (SAF) across different regions from 2025 to 2050, incorporating key assumptions regarding policy incentives, international treaties, and technological advancements. These projections assume that supportive regulatory frameworks, financial incentives, and continued innovation in biomass-to-biofuel conversion technologies will drive SAF adoption at an accelerated pace. However, the realization of these projections depends significantly on the extent of policy implementation and international collaboration (Anil *et al*. 2024).

Given the complex and evolving nature of the global energy transition, substantial uncertainties exist in these forecasts. The actual trajectory of SAF adoption will be shaped by geopolitical shifts, carbon pricing mechanisms, and investment in biofuel infrastructure. To account for this uncertainty, Fig. 5 includes shaded regions representing potential variability in adoption rates, with pessimistic estimates (20% lower) reflecting potential regulatory stagnation or supply chain constraints, and optimistic estimates (10% higher) assuming aggressive policy support and rapid technological breakthroughs.

By considering a range of possible outcomes, this analysis highlights the inherent risks and dependencies influencing SAF deployment. While optimistic projections suggest substantial growth, more cautious scenarios underscore the need for consistent policy enforcement and strategic investment to ensure the scalability of biomass-derived SAF in the aviation sector (Guddaraddi *et al*. 2023).

Cost reductions through technological innovation, economies of scale, and carbon pricing mechanisms are essential for making SAFs competitive with fossil fuels. At the same time, a supportive market ecosystem, driven by consumer demand and industry commitments, is vital for fostering the growth of SAFs (Rial 2024).

By leveraging funding and incentives, such as subsidies, carbon pricing, and private investments, the aviation industry can accelerate the transition to biomass-based SAFs. These efforts, combined with advances in feedstock supply chains and conversion technologies, will play a pivotal role in decarbonizing aviation and achieving a sustainable future for air travel.

Barriers to Implementing Policy Incentives for Biofuel Development in Developing World

While policy incentives play a crucial role in promoting the adoption of sustainable biofuels, developing countries face barriers that hinder the effective implementation of the policies. These challenges span economic, regulatory, technical, and social dimensions, ultimately affecting the scalability and success of biofuel initiatives.

Economic constraints

While the cost of biofuels is decreasing, biomass-based aviation fuels are still more expensive than fossil fuels, especially when considering the costs associated with feedstock supply, processing, and transportation. The need for subsidies or incentives to make biofuels competitive is a key issue.

In many developing countries, economic constraints make large-scale investments in biofuel production and infrastructure difficult. The high cost of setting up biofuel production plants and the lack of financial incentives make biomass-based biofuels less attractive compared to fossil fuels. Many governments lack the financial capacity to provide substantial subsidies or tax incentives, limiting private sector participation. Additionally, fluctuating global oil prices can make biofuels less economically competitive, discouraging long-term investments (Shahriar and Khanal 2022).

Regulatory and institutional barriers

In some developed countries, regulatory frameworks for biofuel production and aviation fuel certification may not be sufficiently aligned to support the large-scale deployment of biomass-based biofuels. Additionally, the policy landscape for carbon pricing and emission reductions may not incentivize the aviation sector to adopt biofuels unless accompanied by strong mandates or subsidies (Wang *et al*. 2022).

In developing countries, a lack of clear policies and regulatory frameworks can prevent the establishment of a stable biofuel market. There is also a lack of standardized protocols for biofuel certification, which could hinder the adoption of biomass-based biofuels in the aviation sector. Weak governance structures and inconsistent regulatory frameworks pose major challenges to biofuel policy implementation. Moreover, political instability and a focus on more immediate economic concerns can limit the political will to invest in long-term, sustainable aviation solutions. Developing countries lack well-defined biofuel mandates, and clear long-term roadmaps for industry growth. Bureaucratic inefficiencies and a lack of inter-ministerial coordination can further delay policy execution (Rial 2024).

Technological and logistical challenges

In developed countries, technological challenges are associated with scaling up biofuel production from agricultural waste. Despite advancements in conversion technologies, the high cost of commercial-scale biomass-to-liquid (BTL) facilities and the need for advanced logistical systems to handle feedstock supply remain significant hurdles (Jamil *et al*. 2024).

On the other hand, in developing countries, the lack of technological infrastructure and expertise can delay the adoption of biomass biofuels. Limited access to advanced biofuel production technologies and insufficient investment in research and development present challenges to scaling up production. Other key challenges include the following (Brown 2019):

- Inadequate research and development (R&D) funding, restricting innovation and cost reductions.
- Poor transportation and storage infrastructure, making it difficult to distribute biofuels across regions.
- Lack of integration with existing fuel supply chains, resulting in higher logistics costs.

Addressing these challenges requires capacity-building initiatives, knowledge transfer from developed nations, and increased investment in local technological development.

Public acceptance and market readiness

Public perception and market readiness significantly influence the adoption of biofuel policies. In many developing countries, concerns over food security and land use conflicts create resistance to large-scale biofuel expansion. The competition between food and fuel production can lead to higher food prices, raising ethical concerns about biofuel policy implementation. Additionally, the dominance of fossil fuel industries and their influence on energy policies can slow down the transition to biofuels (Praveena *et al*. 2024).

Consumer awareness and trust in biofuels also remain low due to a lack of education on their benefits. To overcome this barrier, governments need to implement awareness campaigns and engage stakeholders, including farmers, local communities, and businesses, to promote biofuel adoption.

Environmental and sustainability concerns

Ensuring the environmental sustainability of biofuel production remains a challenge, particularly in regions prone to deforestation and biodiversity loss. Unsustainable feedstock cultivation can lead to land degradation, excessive water consumption, and carbon emissions from land-use changes. The absence of strict environmental regulations and enforcement mechanisms exacerbates these risks, limiting the long-term viability of biofuel policies (Rial 2024).

Overcoming the Barriers: Policy Recommendations

To enhance the effectiveness of biofuel policy incentives in developing countries, the following measures should be considered:

- *Strengthening regulatory frameworks*: Governments should establish clear and stable biofuel policies, ensuring long-term investor confidence.
- *Enhancing financial support*: Increased public-private partnerships, green financing, and international funding mechanisms can help bridge the investment gap.
- *Investing in R&D and infrastructure*: Technological advancements, local capacity building, and improvements in logistics infrastructure can make biofuel production more efficient.

- *Raising public awareness*: Educational campaigns and transparent communication on the economic and environmental benefits of biofuels can drive consumer and industry acceptance.
- *Implementing sustainability safeguards*: Policies should include sustainability criteria to prevent negative environmental and social impacts.

By addressing these challenges, developing countries can create an enabling environment for biofuel adoption, contributing to their energy security and global decarbonization efforts (Jamil *et al.* 2024).

Policy and Regulatory Landscape

The policy and regulatory landscape plays a pivotal role in shaping the adoption and scalability of biomass-based sustainable aviation fuels (SAFs). As the aviation industry strives to decarbonize and align with global net-zero targets, supportive regulations and standardization frameworks become indispensable.

To scale SAF adoption, policies have to further support its research and further commercialization. Carbon pricing schemes, direct subsidies for biofuel infrastructure, and blending mandates (the EU's 63% SAF blending target by 2050) can play a crucial role in advancing agricultural waste as a primary SAF feedstock. Additionally, advancements in biorefinery technology, particularly catalytic upgrading of bio-oils—a method that improves fuel quality by refining crude bio-oil into usable hydrocarbons—and electrofuel integration, where renewable electricity aids in synthetic fuel production, are expected to further improve cost efficiency and sustainability metrics (Praveen *et al.* 2024).

This section explores the existing global and regional policies, the role of certification systems, and the policy gaps that must be addressed to accelerate SAF deployment.

Global and regional policies

Efforts to promote SAFs are gaining momentum through global and regional policies that aim to mitigate aviation’s carbon footprint. A cornerstone of these efforts is the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Launched in 2016, CORSIA mandates that airlines offset emissions exceeding 2020 levels on international routes by investing in carbon-reduction projects or incorporating SAFs. The scheme emphasizes lifecycle emissions reductions, incentivizing the SAFs with superior environmental performance.

In the European Union, the Renewable Energy Directive II serves as a key policy instrument. RED II mandates that renewable energy constitutes 14% of the transport sector’s energy consumption by 2030, with a specific sub-target for SAFs. Additionally, the Fit for 55 package proposes a SAF blending mandate, starting at 2% in 2025 and increasing to 63% by 2050 (Michaga *et al.* 2021). Such directives signal a commitment to reducing aviation’s reliance on fossil fuels and fostering SAF innovation in the EU.

Across the Atlantic, the United States has introduced the SAF Grand Challenge, a collaborative initiative involving the Departments of Energy, Agriculture, and Transportation. The challenge aims to produce 3 billion gallons of SAFs annually by 2030 and 35 billion gallons by 2050, targeting a 70% reduction in lifecycle greenhouse gas (GHG) emissions as compared to conventional jet fuels (Blaschek *et al.* 2010). Financial incentives, such as tax credits provided under the Inflation Reduction Act, further bolster SAF development by offsetting production costs.

In Asia-Pacific, the countries such as Japan and Singapore are actively pursuing SAF strategies. Japan's Act on the Rational Use of Energy promotes research and deployment of SAFs, while Singapore's emerging SAF ecosystem includes partnerships between aviation stakeholders to scale production. These policies are complemented by regional frameworks, such as the Association of Southeast Asian Nations (ASEAN) initiatives, to foster collaboration in sustainable aviation (Jamil *et al*. 2024).

Despite these advancements, the regulatory landscape remains fragmented, with significant variations in policy ambition and implementation across regions. Harmonizing these policies is essential to facilitate global SAF adoption and streamline supply chains.

Standardization and certification

Standardization and certification systems are critical enablers for SAF deployment, ensuring safety, performance, and environmental integrity. Among the most influential standards is ASTM International's certification process. ASTM D7566 establishes technical specifications for blending SAFs with conventional jet fuels, allowing them to meet stringent performance requirements. This certification ensures that SAFs can be seamlessly integrated into existing aircraft engines and fueling infrastructure without compromising safety or efficiency (Guddaraddi *et al*. 2023).

ICAO's CORSIA complements ASTM standards by addressing the environmental aspect of SAFs. Under CORSIA, SAFs must demonstrate lifecycle emissions reductions of at least 10% as compared to fossil fuels to qualify as eligible offsets (Kargbo *et al*. 2021). The scheme also mandates robust sustainability criteria, including considerations of land use, biodiversity, and water resources, to prevent unintended ecological impacts.

The Roundtable on Sustainable Biomaterials (RSB) provides an additional layer of assurance through its voluntary certification program. RSB certification evaluates SAF feedstocks and production processes against a comprehensive set of sustainability criteria, including GHG reductions, social impacts, and ethical practices. Such certifications enhance stakeholder confidence in SAFs and enable access to premium markets.

However, achieving widespread adoption of these standards remains a challenge. The certification process is resource-intensive and time-consuming, particularly for emerging SAF pathways. Additionally, the proliferation of certification schemes can create confusion among producers and consumers, highlighting the need for harmonization. Simplifying and streamlining certification processes while maintaining rigorous sustainability benchmarks is crucial for fostering SAF market growth.

Policy gaps and recommendations

While existing policies and certification systems provide a strong foundation for SAF deployment, critical gaps must be addressed to unlock their full potential. One major challenge is the lack of harmonized regulations across regions. Divergent policies can create barriers to trade, complicate supply chains, and deter investment in SAF production facilities. Developing internationally aligned regulations under ICAO's leadership could standardize SAF requirement and facilitate global market integration (Zhang *et al*. 2024).

Another significant gap is the absence of long-term policy commitments. Many SAF-related policies, such as blending mandates and tax incentives, are subject to periodic review and renewal, creating uncertainty for investors and producers. Establishing clear, long-term targets and roadmaps for SAF adoption would provide much-needed stability and encourage private sector participation (Doliente *et al*. 2020).

Financial barriers also persist, with high production costs limiting SAF competitiveness against fossil fuels. While carbon pricing and subsidies are effective in narrowing the cost gap, their implementation is inconsistent across regions. Expanding and harmonizing carbon pricing mechanisms, such as cap-and-trade systems or carbon taxes, would create a level playing field for SAFs. Additionally, targeted funding for research and development (R & D) in advanced SAF technologies, such as lignocellulosic biomass and power-to-liquid fuels, could accelerate cost reductions and enhance scalability (Pereira *et al.* 2019).

Collaboration between public and private stakeholders is another critical area for improvement. Public-private partnerships (PPPs) can mobilize resources, share risks, and drive innovation in SAF production. Successful examples, such as the Clean Skies for Tomorrow initiative, should be scaled up and replicated in other regions to foster a robust SAF ecosystem (Guddaraddi *et al*. 2023).

Education and outreach efforts are equally important in addressing consumer and industry skepticism about SAFs. Transparent communication about the environmental benefits, safety, and performance of SAFs can enhance public trust and acceptance. Industry-led initiatives, such as green branding and passenger offset programs, can further promote SAF adoption and create a positive feedback loop for sustainable aviation.

Overall, the policy and regulatory landscape is a linchpin in advancing biomass-based SAFs as a cornerstone of net-zero aviation. Global and regional frameworks, such as ICAO's CORSIA, the EU's RED II, and the US SAF Grand Challenge, have laid the groundwork for SAF adoption by setting ambitious targets and providing financial incentives. Certifications such as ASTM and RSB ensure that SAFs meet rigorous safety and sustainability standards, enabling their integration into the aviation industry.

For this reason, addressing policy gaps is essential to accelerate SAF deployment. Harmonized regulations, long-term commitments, and expanded financial support are critical for overcoming market barriers and fostering investor confidence. Enhanced collaboration between stakeholders and transparent communication can further strengthen the SAF ecosystem (Zhang *et al*. 2024b).

By addressing these challenges, the aviation industry can leverage biomass-based SAFs to achieve significant emissions reductions while driving economic growth and sustainability. A coordinated and proactive approach to policy and regulation will be instrumental in realizing the full potential of SAFs and ensuring a sustainable future for global aviation (Oak Ridge National Laboratory 2024).

CHALLENGES

The path to establishing biomass-based sustainable aviation fuels (SAFs) as a viable alternative to conventional jet fuels is fraught with challenges, despite their immense potential to decarbonize aviation. This section delves into the technological barriers, scaling and commercialization hurdles, and the critical areas of research and development (RandD) needed to unlock the full potential of biomass-based SAFs.

Technological Barriers

One of the primary challenges in advancing biomass-based SAFs lies in the limitations of feedstock collection, conversion efficiency, and logistics. Biomass feedstocks, such as agricultural residues, forestry by-products, and organic waste, are inherently decentralized and diverse. Their collection and transportation often involve high costs, logistical inefficiencies, and environmental trade-offs. Transporting large volumes of low-density biomass over long distances can negate the environmental benefits of using the materials for SAF production (Tongpun *et al*. 2019).

Conversion efficiency remains another significant technological hurdle. Existing biomass-to-biofuel pathways, such as thermochemical and biochemical processes, often have energy-intensive steps that reduce overall efficiency. Gasification, for example, requires precise temperature and pressure conditions to optimize the yield of syngas, a precursor for biofuels. Similarly, biochemical methods such as fermentation face limitations in converting lignocellulosic biomass due to the recalcitrant nature of lignin. Overcoming these technical barriers is essential to improve the yield and cost-effectiveness of SAF production (International Renewable Energy Agency 2024).

The logistics of integrating biomass feedstocks into existing industrial ecosystems also pose challenges. Variability in feedstock quality and seasonal availability can disrupt supply chains and affect the consistency of fuel production. Developing robust pre-treatment technologies and feedstock management systems will be critical in mitigating these issues (Liu *et al*. 2018).

Scaling and Commercialization

While pilot-scale projects demonstrate the technical feasibility of biomass-based SAFs, scaling up to commercial production presents a host of challenges. High capital expenditures for building large-scale biorefineries, coupled with uncertain returns on investment, deter private sector participation. The significant cost differential between SAFs and conventional jet fuels further complicates market entry. Without substantial subsidies or carbon pricing mechanisms, SAFs struggle to compete with the low cost of fossil-based jet fuels (Chang and Tae 2020).

Supply chain bottlenecks also impede scaling efforts. A fully integrated SAF supply chain requires coordinated development across multiple stages, from feedstock procurement and processing to distribution and end-use. These stages often involve diverse stakeholders with differing priorities, creating fragmentation and inefficiencies. Streamlined policies and incentives can help align stakeholder interests and foster a cohesive supply chain (U.S. Department of Energy 2024).

Commercialization efforts must also contend with the challenge of public perception and acceptance. Despite the environmental benefits of SAFs, consumers and industry stakeholders often view them with skepticism due to concerns about cost, performance, and scalability. Transparent communication and education campaigns highlighting the safety, reliability, and sustainability of SAFs are vital to build trust and drive adoption (Kameswari *et al.* 2024).

Research and Development Needs

Innovation in biomass conversion technologies and hybrid systems will be pivotal in overcoming these challenges. R&D efforts should focus on improving the efficiency and scalability of existing processes while exploring novel pathways for SAF production.

Thermochemical conversion methods, such as pyrolysis and gasification, offer promising avenues for SAF production but require significant advancements to optimize energy efficiency and reduce by-product formation. Research into advanced catalysts and reactor designs can enhance the selectivity of these processes, increasing the yield of high-quality fuels (Prasad *et al*. 2023).

Biochemical pathways, including fermentation and anaerobic digestion, also hold potential for SAF production from lignocellulosic biomass. However, the recalcitrant nature of lignin poses a major barrier to the efficient utilization of these feedstocks. Innovative pre-treatment techniques, such as enzyme engineering and chemical hydrolysis, can improve the accessibility of cellulose and hemicellulose, enhancing the overall efficiency of the process (Doliente *et al*. 2020).

Hybrid systems that integrate multiple conversion pathways could offer a holistic solution to the limitations of individual technologies. Combining biochemical and thermochemical processes can enable the comprehensive utilization of biomass feedstocks, reducing waste and improving overall efficiency. Research into such integrated systems is essential to maximize the economic and environmental benefits of SAF production (Rai *et al*. 2022).

Another critical area of R&D is the co-processing of biomass with fossil fuels in existing refineries. This approach leverages existing infrastructure, reducing the capital investment required for SAF production. However, challenges related to feedstock compatibility, process optimization, and product quality must be addressed to ensure the feasibility of this strategy.

Research and Development efforts should also extend to enhancing the lifecycle sustainability of SAFs. This includes developing tools and methodologies for accurate lifecycle assessment (LCA) of GHG emissions, land-use changes, and water consumption associated with SAF production. Such assessments are crucial for ensuring that SAFs deliver genuine environmental benefits and meet stringent sustainability.

FUTURE DIRECTIONS

Addressing the challenges of biomass-based SAF production requires a multi-faceted approach involving technological innovation, policy support, and industry collaboration. Future efforts should prioritize the following:

Enhancing Feedstock Supply Chains

Investments in feedstock logistics infrastructure, such as regional collection centers and efficient transportation networks, can reduce costs and improve the reliability of biomass supply chains. Digital technologies, such as blockchain and IoT, can enhance traceability and transparency, ensuring the sustainability and consistency of feedstock sourcing (US Department of Agriculture 2025).

Developing Cost-effective Technologies

Scaling up pilot technologies to commercial production levels requires substantial funding and R&D. Public-private partnerships can play a crucial role in mobilizing resources and sharing risks. Focused research on reducing energy consumption and optimizing process parameters will be instrumental in lowering production costs.

Strengthening Policy and Incentives

Robust policy frameworks that provide long-term support for SAF production and adoption are essential for market growth. Mechanisms such as carbon pricing, blending mandates, and tax incentives can create a level playing field for SAFs and attract private investment. Harmonized regulations across regions will further facilitate international trade and market integration (Lahijani *et al*. 2022).

Promoting Collaboration and Knowledge Sharing

Collaboration among industry stakeholders, research institutes, and policymakers can accelerate the development and deployment of SAFs. Platforms for knowledge sharing and best practices, such as industry consortia and global forums, can foster innovation and drive collective progress (Michaga *et al.* 2021).

Engaging the Public and Industry

Effective communication strategies are vital to overcoming skepticism and building trust in SAFs. The successful case studies, such as flights powered by SAFs, can demonstrate their feasibility and inspire confidence among consumers and industry players (US Department of Energy 2024).

While the challenges facing biomass-based SAFs are significant, they are not insurmountable. Technological barriers, such as feedstock logistics and conversion efficiency, require targeted R&D and innovation to overcome. Scaling and commercialization efforts demand cohesive supply chains, cost reductions, and supportive policies to bridge the gap between pilot projects and widespread adoption.

There are a few examples of regions or cases where feedstock logistics challenges for biofuel production have been mitigated:

1. Brazil

Brazil is a leading producer of ethanol from sugarcane, and its biofuel industry has made significant strides in addressing feedstock logistics. The country has developed a robust infrastructure for harvesting, transporting, and processing sugarcane, which includes an integrated supply chain model. In regions such as São Paulo, strategic locations of ethanol mills near sugarcane plantations and advanced transportation systems (dedicated trucks, railways) have helped reduce logistical costs. Additionally, sugarcane cooperatives and farmer networks have been established to improve the coordination and transportation of feedstocks, ensuring a more consistent supply for ethanol production. This system has effectively minimized delays and waste during transportation, leading to higher efficiency and reduced feedstock losses (Pereira *et al.* 2019).

Brazil has successfully utilized sugarcane bagasse and other agricultural residues for biofuel production, with substantial investments in technology and infrastructure to convert agricultural waste into ethanol and other biofuels. Brazil has overcome many of the technological and economic barriers to biofuel production, particularly through its ethanol industry, which is one of the largest in the world. This case study shows how Brazil’s integrated systems for collecting, processing, and utilizing agricultural residues have made the country a leader in biofuels, particularly in the aviation sector. By investing in research, infrastructure, and policy frameworks, Brazil has successfully integrated agricultural waste into biofuel production, particularly for aviation. However, land use change concerns remain a challenge for large-scale biomass production (Rial 2024).

2. India

In India, agricultural residues such as rice husks, wheat straw, and sugarcane bagasse are important feedstocks for biofuel production. India has taken steps to overcome regional barriers by focusing on utilizing agricultural residues including rice husks and wheat straw for biofuel production. While the country faces economic and technological barriers to large-scale production, India's vast agricultural sector presents a unique opportunity to scale up biomass-based biofuels (Raji *et al.* 2025).

India has been experimenting with biomass-based jet fuel in collaboration with national airlines and biofuel producers, using agricultural residues like rice husks and wheat straw. However, logistical challenges in collecting and transporting these residues to biofuel processing facilities have historically hindered efficient production. In response, various states, including Punjab and Uttar Pradesh, have seen the development of local farmer cooperatives that help organize the collection and transportation of agricultural residues. These cooperatives reduce transportation costs by leveraging shared resources and optimizing routes (Guddaraddi *et al*. 2023).

Additionally, biomass collection hubs and storage facilities have been set up to ensure the feedstock is available during the off-season, minimizing disruptions in the supply chain. These efforts have helped mitigate logistical barriers and improved the viability of biomass-based biofuels in the region. This case study demonstrates how India is overcoming technical and logistical barriers to incorporate agricultural waste in sustainable aviation fuel production, with a focus on carbon neutrality and energy efficiency (Shahriar and Khanal 2022).

3. United States of America (USA)

In the Midwest (Iowa, Nebraska) of USA, cellulosic ethanol production from agricultural waste and non-food crops such as switchgrass and miscanthus faces challenges in feedstock collection and transportation. Government subsidies and the establishment of clear policy frameworks (such as the Renewable Fuel Standard) have played a significant role in promoting biofuel production (Lim *et al.* 2023).

However, the Cellulosic Ethanol Plant in Iowa have developed strategies to overcome these issues. It is using agricultural residues such as corn stover for biofuel production. The facility has significantly reduced logistical costs through the development of local feedstock collection systems. The Biomass Crop Assistance Program offers incentives for farmers to grow dedicated energy crops and ensures that feedstock collection is centralized and organized. The program covers investments in local biomass transportation infrastructure, such as improving access to roads and railways to reduce transportation costs (Shen *et al*. 2019).

Additionally, the use of crop residue collection systems and regional depots has reduced the need for long-distance transport and increased the efficiency of feedstock logistics. This case study highlights the successful scaling of biofuel production from agricultural residues, addressing challenges in feedstock logistics and demonstrating the potential for biofuels to reduce carbon emissions in the aviation industry. Nonetheless, the high cost of cellulosic biofuels and the need for better feedstock logistics remain key challenges (Jamil *et al.* 2024).

4. China

China, one of the world's largest producers of agricultural residues, has faced significant logistical challenges in utilizing these materials for biofuel production. In regions such as Anhui and Henan, the government has implemented solutions that combine feedstock logistics with waste-to-energy technologies. Local governments have built biomass collection centers close to large farming areas and partnered with energy companies to optimize transportation routes. Furthermore, China has invested in advanced biomass handling systems to reduce the logistical burden on farmers, such as compacting and baling equipment that makes transportation more efficient. These efforts have significantly reduced logistical challenges, allowing for the large-scale utilization of agricultural residues in biofuel production (Kargbo *et al*. 2021).

5. European Union (EU)

In the European Union, countries including France, Germany, and Spain have made efforts to address feedstock logistics issues, especially in relation to agroforestry biomass. Projects such as AGRO-BIOHEAT in France have focused on improving the biomass supply chain by integrating forest biomass with agricultural residues. This has involved the development of efficient collection and transport systems, including the use of specialized biomass handling equipment and the establishment of centralized biomass collection hubs. These initiatives help ensure that feedstock is available year-round and can be easily transported to biofuel plants, reducing logistical inefficiencies and costs (Han *et al.* 2013).

By addressing these challenges through strategic investments, robust policies, and collaborative efforts, the aviation industry can harness the potential of biomass-based SAFs to achieve net-zero emissions. With sustained commitment and innovation, biomass-based SAFs can play a role in the global transition to sustainable aviation.

Integrating quantitative cost assessments, lifecycle evaluations, and real-world case studies strengthens the technological strength for agricultural waste-derived SAFs as a viable option to conventional aviation fuels. By presenting this information clearly and simplifying technical explanations, this work aims to make SAF research more accessible to policymakers, industry stakeholders, and public. Despite existing cost barriers, technological progress, supportive policies, and successful pilot projects demonstrate the transformative potential of SAFs in achieving net-zero emissions for the aviation industry.

In addition to the broad approach taken in this study to address the pressing issues surrounding jet transportation and its environmental impact, it is crucial for Brazil and USA to consider alternatives that could mitigate these impacts. Among the most promising options are improvements in fast rail transportation and enhanced telecommuting capabilities. These alternatives, while overlooked in the broader discourse on sustainable travel, represent potential “low-hanging fruit” that could significantly reduce the need for jet transportation and/or for cross-sectoral strategies that address emissions from both aviation and other transport modes. Advancements in rail infrastructure could provide an efficient, lower-carbon alternative for medium-range travel, while increased adoption of telecommuting could minimize the demand for travel altogether, particularly for business-related trips. These strategies should be part of the broader conversation on reducing the environmental footprint of transportation, and their feasibility should be weighed alongside the development of cleaner aviation technologies (Anil *et al*. 2024).

CONCLUSIONS

1. *Significant emission reduction potential:* Biomass-based sustainable aviation fuels (SAFs) can reduce greenhouse gas (GHG) emissions by up to 80% compared to conventional jet fuels, as lifecycle analyses demonstrate. This reduction is influenced by feedstock type, conversion technology, and supply chain efficiency. Agricultural residues and forestry by-products, in particular, offer lower carbon footprints due to their carbon sequestration potential.

2. *Global biomass availability:* Annually, approximately 140 billion tons of biomass feedstock are globally available, with agricultural residues contributing 30% of this total. Asia, South America, and Sub-Saharan Africa collectively account for over 60% of this potential, presenting significant regional opportunities for SAF production. However, only 10% of this biomass is currently utilized for energy purposes, indicating substantial untapped resources.
3. *Advances in conversion technology:* Current biomass-to-SAF pathways, such as gasification and Fischer-Tropsch synthesis, achieve efficiencies between 45 and 60%. Innovations in co-processing and hybrid feedstock systems have the potential to raise efficiency to 70%, improving the competitiveness of SAFs with fossil-based jet fuels.
4. *Scalability challenges:* Despite promising advancements, scalability remains a critical bottleneck. SAFs currently account for just 1% of global aviation fuel, underscoring the need for large-scale production and market penetration.
5. *Economic barriers:* Biomass-based SAFs are priced at USD 1.50 to 4.50 per liter, which is significantly higher than conventional jet fuels (USD 0.50 to 0.75 per liter). Bridging this gap requires targeted subsidies, carbon pricing, and investments in research and development.
6. *Regional opportunities***:** Emerging markets with abundant feedstock resources present promising opportunities for cost-competitive SAF production. Overcoming logistical and technological barriers in these regions is essential for scaling up SAF deployment.
7. *Environmental and social considerations:* The food versus fuel debate and potential biodiversity impacts remain pressing concerns. About 20 to 30% of biomass feedstocks could compete with food systems if not managed sustainably, highlighting the need for stringent safeguards and lifecycle assessments.
8. *Policy recommendations:* Governments must strengthen policy frameworks to incentivize SAF adoption. Key measures include:
   - Expanding the mandates to cover 50% of global aviation fuel demand by 2035.
   - Implementing carbon pricing mechanisms to account for social cost of emissions.
   - Offering production subsidies or tax credits of USD 0.50 to 1.00 per liter to close the price gap with fossil fuels.

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