# ADVANCEMENTS AND CHALLENGES IN SUSTAINABLE AVIATION FUEL PRODUCTION

**Introduction**

**The aviation industry plays a pivotal role in global transportation, serving as the linchpin connecting people and economies worldwide. However, its heavy reliance on conventional fossil fuels comes at a significant cost, contributing substantially to carbon emissions and environmental degradation. Recognizing these challenges, the aviation industry has undergone a paradigm shift, spearheading the development and widespread adoption of sustainable aviation fuels (SAFs). This term encompasses non-conventional aviation fuels that are derived from sustainable and renewable sources, as identified by the aviation industry [1].**

## Feedstock Selection and Production Methods

SAFs are derived from the following five feedstocks: oils and fats, sugar and cereal, municipal solid waste, wood and agricultural residue, or renewable energy and carbon [2]. Each feedstock category has distinct constraints and specific production technologies. Recognizing the importance of a diversified approach, the aviation sector is seeking to use a wide range of feedstocks in SAF production.

There are two primary methods of SAF production: standalone units and co-processing. In standalone units, sustainable feedstocks are utilized to produce synthetic kerosene (SK), which is then blended with conventional jet fuel to create SAF. On the other hand, co-processing involves the simultaneous processing of up to 5% sustainable feedstocks alongside fossil feedstocks through hydro-processing in a refinery [2].

In the case of standalone units, the feedstock undergoes conversion in a biorefinery to produce SK, which is then certified to the relevant annex in ASTM D7566 standard. Subsequently, this SK is blended up to 50% with conventional jet fuel, certified to ASTM D1655 or Defense Standard 91-091, and supplied as a conventional Jet A/Jet A-1 fuel [2]. This dual approach of standalone units and co-processing reflects the diverse strategies employed in the production and certification of SAF, aligning with industry standards to ensure the quality and compatibility of the resulting fuels.

## Hydrotreated Esters and Fatty Acids (HEFA) Pathway

The prevalence of the hydrotreated esters and fatty acids (HEFA) pathway in SAF production arises from its cost-effectiveness and the accessibility of feedstocks, specifically waste fats, oils, and greases [2]. A majority of the SAF currently provided is obtained through this pathway, employing primary feedstocks like waste fats and oils that undergo pre-treatment and subsequent processing in standard hydrocracker units.

Despite the current prevalence of HEFA synthetic paraffinic kerosene (SPK) as the primary commercial pathway for SAF production, there is a critical need for the rapid mobilization of large-scale sustainable feedstocks. This urgency stems from the formidable challenge of meeting the soaring demand for SAF, which must increase by 9000% to align with targets set for 2030 [12]. Moreover, the sustainability of some SAF sources may not be as robust as initially assumed as a recent report from the non-profit U.S. Center for Biological Diversity points out that top SAF producers are using certain subsets of feedstocks (Generation 1 and 2) that aren't as sustainable as many assume, particularly food-based feedstocks, wood biomass and forestry residues, used cooking oil, animal fats, and manure [12]. This underscores a necessity for enhanced monitoring of emissions across fuel producers to optimize the return on investment in sustainability.

To address this, exploration into alternative high-energy crops such as algae, camelina, pennycress, tallow tree, and carinata is underway [3]. The use of cover crops, such as carinata, is encouraged, particularly when they contribute to sustainable farming practices without requiring additional land demand, supporting soil carbon accumulation, soil quality, and biodiversity.

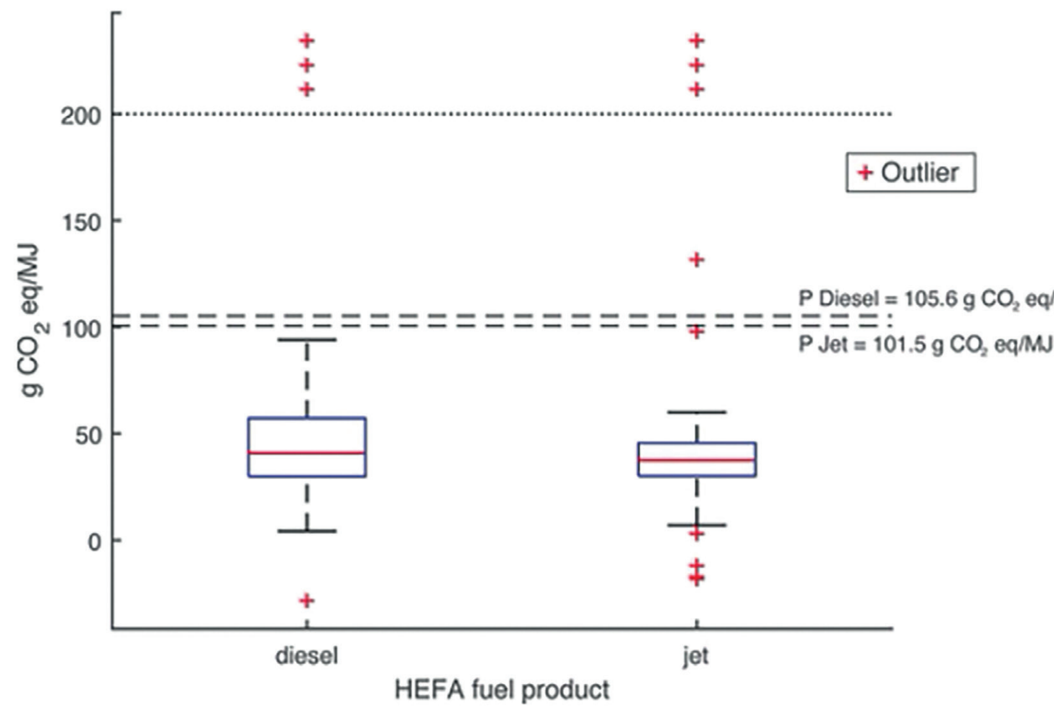



*Figure 1: Distribution of Reported Lifecycle GHG Emissions for HEFA Diesel and HEFA Biojet Compared to Conventional Petroleum Fuels [19]*

Furthermore, in a review by Zemanek et al. on life-cycle greenhouse-gas emissions assessments of HEFA from oilseeds, it was found that despite a 61–63% reduction in median life-cycle GHG emissions of HEFA biojet and renewable diesel compared with conventional petroleum fuels, the wide range in reported life-cycle GHG emissions for HEFA fuels is one of the barriers to the development of a HEFA drop-in fuel supply chain [19]. This is seen in Figure 1, as it shows the reduction of both diesel and jet oil, with outliers. The aim of this review was to analyze feedstock, co-product allocation method, the inclusion of GHG emissions from land-use change, and refining technology as potential sources of variability in the LCA of HEFA fuels such that these important aspects of LCA methodology and scope could be better understood.

Zemanek et al. reviewed twenty LCAs, comparing scenario analyses from selected studies with previous reviews. When compared with fuel from other feedstocks, life-cycle GHG emissions were the highest for HEFA fuels from canola, most likely due to high nitrogen fertilizer requirements. Forest to cropland land-use change scenarios were associated with the highest life-cycle GHG emissions reported in the literature [19].

Their study also found that across different co-product allocation methods compared in the literature, life-cycle GHG emissions tended to be higher for market-based allocation than for mass- or energy-based allocation. They were the lowest and in some cases even negative when displacement allocation (D/D) was applied. The importance of refining technology was not widely compared in the literature, but the quantity of co-products produced strongly impacted life-cycle GHG emissions if displacement was applied as the co-product allocation method.

Feedstock, co-product allocation method, and land-use change inclusion were confirmed as important sources of variability. Ten of the twenty studies reviewed compared two or more co-product allocation methods, in accordance with recommendations by the International Standards Organization [19]. Aspects of LCA methodology, including the co-product allocation method, have been defined for renewable fuel accounting in standards published by the European Renewable Energy Directive (RED) and Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which use energy-based allocation methods; Roundtable on Sustainable Biomaterials (RSB), which uses market-based allocation; and the second phase of the United States Renewable Fuel Standard program (RFS2), which uses displacement. All methodologies account for emissions from indirect land-use change, which were only included in one study reviewed. Ultimately, LCA is a relative process and standardized methodology is the only way to enable decision making.

Despite variability in reported life-cycle GHG emissions, oilseeds are likely to be used for drop-in fuel production in Canada and elsewhere due to their availability and the commercial status of hydroprocessing technology [19]. The LCAs reviewed here also indicate both the need to mitigate land-use change concerns surrounding feedstock production for biofuels, and the advantages of oilseeds that require fewer agricultural inputs, such as camelina and carinata, as feedstocks for HEFA production.

Nonetheless, while flights fueled by SAF from the HEFA pathway have increased, the limitation in current feedstocks anticipates a significant rise in SAF production from pathways like alcohol to jet (AtJ), and Municipal Solid Waste (MSW) beyond the year 2030 [4]. This underscores the ongoing efforts to expand feedstock options and pathways, ensuring a sustainable and resilient future for SAF production in the aviation industry.

## Alcohol to Jet (AtJ) Technology

Alcohol to jet (AtJ) technology, relying on sugarcane and corn grain, stands as another approved pathway, with its viability influenced by the timing of ground fuel electrification. This method involves converting sugary, starchy biomasses like sugarcane and corn grain through fermentation into ethanol or other alcohols, as shown in Figure 2. These can then be transported before conversion into fuel. While these feedstocks are easily cultivated and transported by train, the requirement to process sugarcane into ethanol within 48 hours of being cut, or else, the sucrose content within it will fall [4]. Thus, to optimize cost efficiency, minimize carbon emissions, and enhance infrastructure utilization, it is advantageous for ethanol plants to be situated near both feedstock production mills and refineries.

In regions like the Americas, corn and sugarcane serve as commercial feedstocks for fuel production [4]. However, the demand from sectors like ground fuel and petrochemicals limits their availability for aviation use, resulting in no commercial SK plants using the AtJ production pathway. The crucial factor in considering the AtJ pathway is its timing, with the shift of ground fuels towards electrification expected to free up feedstock supply for aviation, eventually leading to commercial SAF production.

A Techno-Economic Evaluation conducted by Geleynse et al. in 2018 provided a more economical view on the process. The study emphasized the importance of considering both ethanol and isobutanol pathways for ATJ production, with a focus on understanding their respective conversion costs and product distributions [13]. One of the key findings of the analysis was the significant cost advantage of isobutanol over ethanol in the core ATJ process. This can be seen in Table 1, which showed

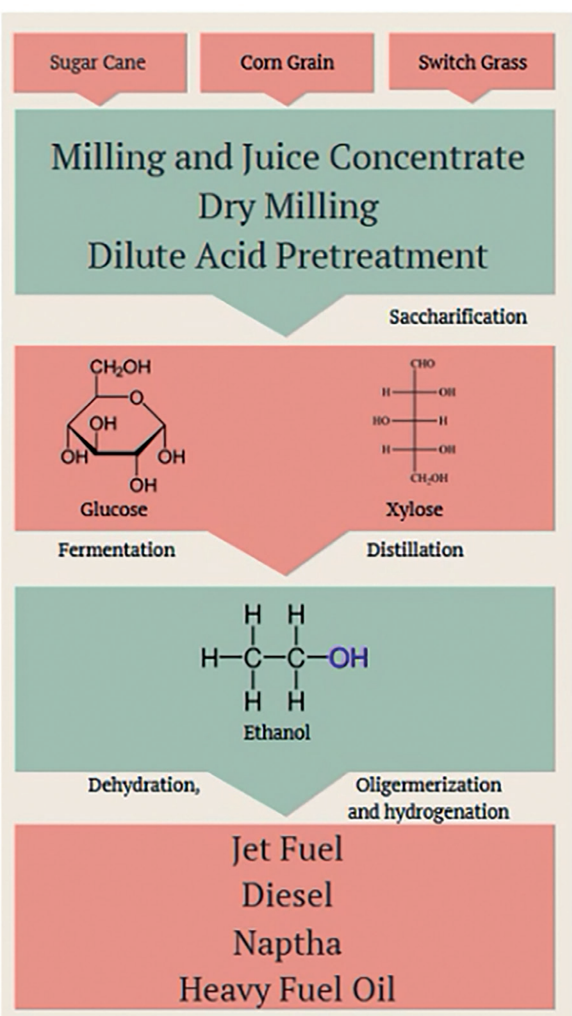



*Figure 2: A simplified schematic of the ATJ process*

*Table 1: Mass balance achieved in the core ATJ simulation [14]*

| Property | Ethanol to jet | Isobutanol to jet |
|---|---|---|
| overall mass yield | 0.6 | 0.75 |
| fuel production rate [kt yr−1] | 39.15 | 49.25 |
| oligomerization recycle ratio | 1.27 | 0.02 |
| product distribution (gasoline/jet/diesel) [%] | 10/70/20 | 30/70/0 |

*Table 2: Sugars-to-fuel conversion cases [14]*

| Property | Ethanol fermentation | Isobutanol fermentation | |
|---|---|---|---|
| | | low cost | high cost |
| mass yield | 0.274 | 0.277 | 0.277 |
| alcohols processed [t per day] | 200 | 161 | 161 |
| total capital investment [MM$] | 77.4 | 55 | 94.2 |
| OpEx [MM$ y−1] | 15.8 | 13.9 | 18.4 |
| jet-fuel production rate [MMgal y−1] | 7.56 | 7.65 | 7.65 |
| gasoline production rate [MMgal y−1] | 1.29 | 3.92 | 3.92 |
| diesel-fuel production rate [MMgal y−1] | 2.26 | 0 | 0 |
| conversion cost [$ gal−1 jet fuel] | 2.84 | 2.23 | 3.37 |

that isobutanol had an overall higher mass yield and fuel production rate.

This advantage was attributed to differences in oligomerization behavior, resulting in a more favorable product distribution for jet fuel. By examining mass balances, yields, and economic parameters, the study underscored the potential economic benefits of leveraging higher alcohols, particularly isobutanol, for ATJ conversion. Moreover, the study delved into the complexities of the complete ATJ process, starting from sugar fermentation. This can be seen in Table 2 in which the study shows the mass yield of isobutanol and ethanol formation are quite similar, with the higher yield of isobutanol to jet fuel canceling out the lower fermentation yield. Notably, in both cases of isobutanol conversion, the reduced volume of alcohols and added efficiency of ATJ through higher alcohols resulted in reduced capital costs for the core ATJ unit, as shown in Table 2. However, while isobutanol fermentation theoretically offers higher yields compared to ethanol, actual yields may vary depending on the fermentation process employed. This highlighted the need to carefully consider alcohol production costs, which play a pivotal role in shaping the overall process economics.

Furthermore, sensitivity analysis revealed that feedstock cost is a critical factor influencing ATJ production costs, as shown in Figure 3 [13]. The study, thus, advocated for an optimal pathway that integrates fermentation to higher alcohols with the low-cost production of fermentable feedstock, aiming to maximize cost-effectiveness.

Additionally, alternative alcohol-upgrading conversion pathways, such as the Guerbet reaction, an attracting process for the synthesis of branched monoalcohols, value added compounds for industrial production of plasticizers and detergents, and direct conversion of ethanol to isobutene, were explored for their potential to enhance fuel profiles and introduce valuable coproducts. These pathways represent promising avenues for further research and development in the pursuit of enhancing the commercial viability of alternative jet fuel production.

## Municipal Solid Waste (MSW) Derived SAFs

For SAF produced from Municipal Solid Waste (MSW) using Fischer-Tropsch (FT) technology, a catalytic chemical reaction in which carbon monoxide (CO) and hydrogen (H2) in the syngas, mixture of hydrogen and carbon monoxide, in various ratios, are converted into hydrocarbons of various molecular weights [21], the primary environmental benefit arises from preventing the waste from decomposing in landfill sites. The global generation of MSW exceeds 2 billion tons annually and is projected to reach 3.4 billion tons by 2050, as reported by the World Bank [5]. This can be seen in Figure 4, which shows the projected waste generation by region. Despite the widespread availability of MSW as a feedstock, it is generally a more cost-effective option than other raw materials. However, certain regions face competition for MSW access between aviation and other sectors, including the energy industry.

In the European Union (EU), there is active advocacy for the recognition of recycled carbon fuels derived from the non-organic portion of MSW as SAF under the EU's planned SAF blending mandate [6]. It is important to note that the use of recycled plastics as a standalone feedstock source for SAF is not supported. The production of SAF from MSW through FT technology involves a capital-intensive process, including the production of FT wax, which is subsequently refined into SK before being blended into SAF.

Encouragingly, ongoing research and development efforts aim to enhance the efficiency of FT technology for MSW-derived SAF. Collaborative initiatives have led to the development of user-friendly and cost-efficient FT technology, operating effectively at both large and small scales, economically converting synthesis gas from MSW into long-chain hydrocarbons suitable for SAF production [2]. As for other feedstocks, commercially deployed pathways are lacking, but progress with ASTM involves biomass pyrolysis in both

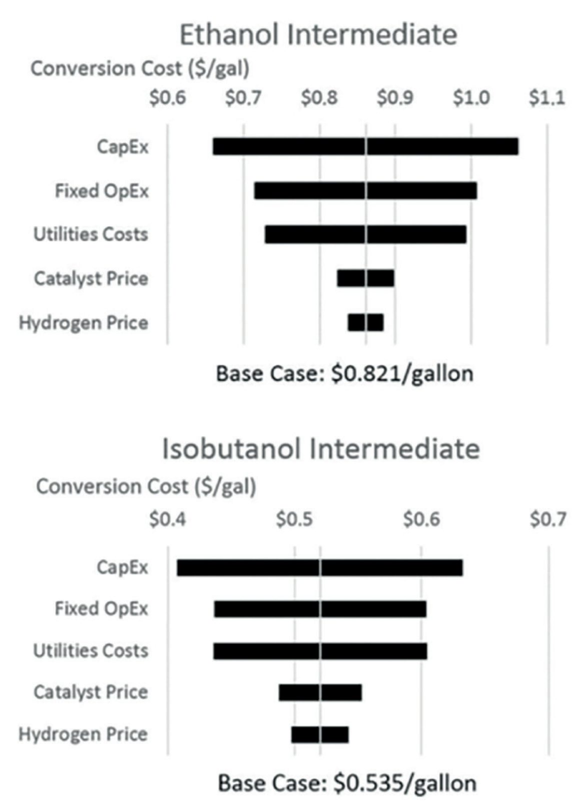



*Figure 3: Sensitivity analysis of model parameters on jet fuel conversion cost for ethanol-to-jet and isobutanol-to-jet scenarios from an alcohol feedstock. [14]*

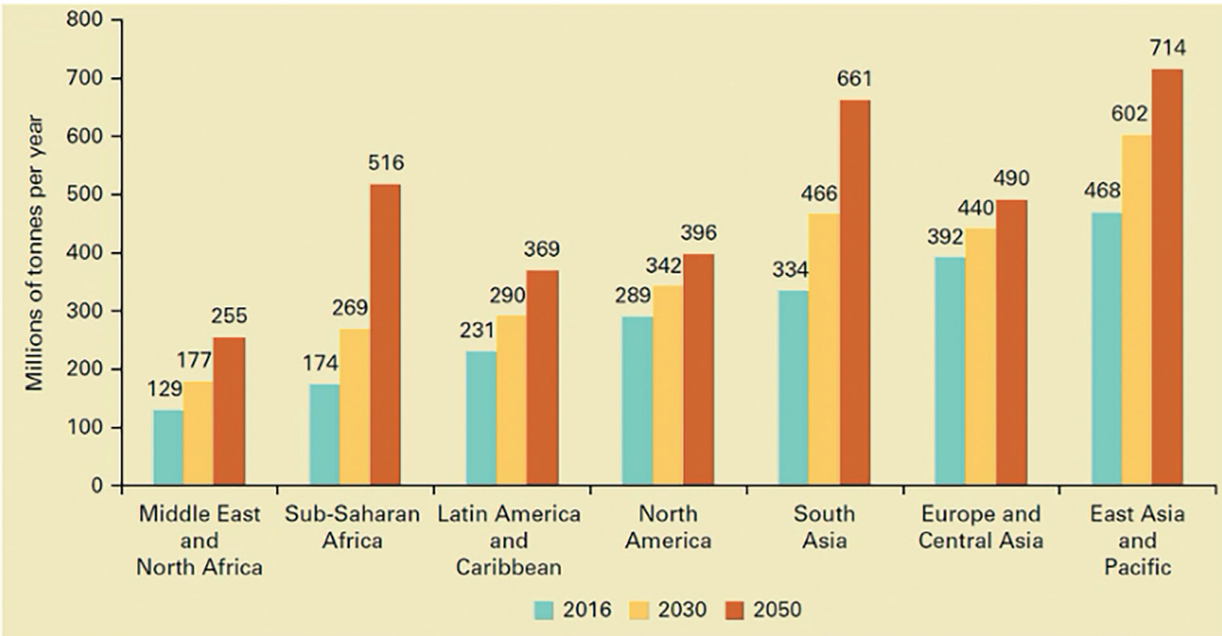



*Figure 4: Projected waste generation, by region (millions of tons/year) [5]*

standalone production and co-processing in refineries. Challenges lie in transportation for second-generation biomass, and power-to-liquid (PtL) technology, which while promising, faces cost hurdles. Green hydrogen from renewable sources is used in PtL to convert carbon dioxide to carbon monoxide, later synthesized into a wax upgradable to SK. Cost-effective carbon dioxide sourcing from industrial sectors, alongside the expansion of green hydrogen plants, is crucial for PtL's commercial viability. German mandates and anticipated European directives provide regulatory support, with ongoing work exploring new pathways, including methanol to jet, as a competitive alternative [7].

## Biofuels

Biofuels, a prominent subset within the realm of SAFs, are liquid fuels derived from renewable biological sources, such as plants and algae [8]. This category has gained prominence due to its potential to mitigate the aviation industry's reliance on finite fossil resources. The biofuel production process involves using organic materials as the feedstock to create liquid fuels suitable for aviation, with a notable distinction being the potential for achieving a neutral or even negative overall carbon footprint. Biofuels can be categorized into generations, with first-generation biofuels relying on established technologies and readily available feedstock like vegetable oils and crops such as corn and sugar cane. In contrast, second, third, and fourth-generation biofuels aim to address environmental concerns and resource constraints by utilizing non-food feedstock, such as algae or waste, and employing advanced technologies for more sustainable and efficient production processes.

The advantages of first-generation biofuels, in comparison with later generations, are noteworthy. These biofuels benefit from well-established technology, utilizing processes such as fermentation, esterification, and distillation that have been refined over centuries [14]. Additionally, the readily available feedstock, including vegetable oils and crops like corn and sugar cane, ensures accessibility. Furthermore, first-generation biofuels contribute to the reduction of greenhouse gas emissions and enhance energy security by shifting reliance from foreign oil to domestic sources. They also offer potential economic benefits by creating new market opportunities and income for farmers. However, these advantages are tempered by several disadvantages. The first being competition with food crops raising concerns about increased food prices as well as land and water resource encroachment [15,16]. Environmental impacts, such as deforestation and biodiversity loss, are also associated with production processes. Technical limitations, including compatibility issues with existing infrastructure and higher production costs compared to fossil fuels, present further challenges. Moreover, dependence on specific crops like soybeans can lead to feedstock supply constraints, highlighting the limitations of first-generation biofuels [14].

Second-generation biofuels offer several advantages over their predecessors. Firstly, they utilize non-food feedstock such as lignocellulosic biomass, agricultural residues, and organic waste, thereby reducing competition with food crops and addressing food security concerns. Additionally, these biofuels provide environmental benefits by producing fewer greenhouse gas emissions and being more efficient in land use. They also offer diverse feedstock options, including waste materials, which contribute to their potential for higher energy yields per acre compared to first-generation fuels. Moreover, second-generation biofuels promote long-term sustainability by reducing reliance on finite fossil fuel resources and minimizing environmental impact [14]. However, the transition to second-generation biofuels is not without its challenges. Technical hurdles remain, as production processes are still in development, resulting in high production costs and technological uncertainties [14]. Furthermore, existing infrastructure for harvesting, storage, and transport may not be adequate for large-scale production, posing limitations to widespread adoption. Policy uncertainty adds another layer of complexity, hindering investment and development. Additionally, some biomass sources may still compete with land use for food production or other agricultural activities, and the complex production processes required to extract sugars from lignocellulosic biomass may demand more energy and resources compared to first-generation biofuels.

Third-generation biofuels offer several advantages over earlier generations. Firstly, they boast high productivity, with algae capable of producing more oil per acre compared to traditional oilseed crops. Additionally, their year-round cultivation ensures a consistent supply of feedstock, while their versatile growth capabilities allow them to thrive in various conditions, including saline or brackish water, thereby reducing competition for land and freshwater resources [17]. Moreover, the reduced environmental impact of algae cultivation, requiring fewer herbicides or pesticides and utilizing wastewater nutrients, contributes to their appeal. Lastly, the biodegradability of algae-based biofuels presents a lower risk to the environment in case of spills. However, third-generation biofuels face several challenges. The technical complexity involved in cultivating algae and converting it into biofuels requires advanced and potentially costly processes [14]. Implementing infrastructure such as photobioreactors may necessitate significant capital investment and technical expertise. Additionally, scaling up production to a commercial level remains a challenge, and resource constraints such as land, water, and nutrient inputs still apply, albeit to a lesser extent than in traditional agriculture [14]. Moreover, despite their promise, third-generation biofuels are still in the development stage and may not yet be commercially viable on a large scale, highlighting the need for further research and innovation in this field.

The newest generation of biofuel, fourth-generation biofuels, offers several advantages over previous iterations. These include higher yield and lipid content compared to other biofuels, along with a greater capability to capture CO2 and potentially higher manufacturing rates [14]. However, there are notable disadvantages to fourth-generation biofuels, such as the high initial investment required for algae production and the fact that research is still in its early stages, with significant results yet to be published in peer-reviewed journals. Further, despite the promise of fourth-generation biofuels, challenges remain in achieving economic viability. Overall, while technological advancements are progressing, further research is needed to address manufacturing costs and make biofuel production commercially feasible.

In addition to the ongoing research on fourth-generation biofuels, there is also an emerging effort to develop fifth-generation biofuels. According to an article by Green Car Congress, six Japan-based companies have established the Research Association of Biomass Innovation for Next Generation Automobile Fuels for this purpose [18]. This association focuses on technological research aimed at utilizing biomass and efficiently producing bioethanol fuel for automobiles. Their goal is to achieve a carbon-neutral society by optimizing the circulation of hydrogen, oxygen, and CO2 during production of bioethanol fuel. Specific research areas include enhancing the production technology for second-generation bioethanol fuel, studying the utilization of byproducts such as oxygen and CO2 generated during production, investigating the efficient operation of the overall system, and developing optimal cultivation methods for raw material crops. Through these research efforts, the association aims to advance the development of fifth-generation biofuels and contribute to the sustainability of automotive fuel sources.

## Innovative Studies and Solutions

One significant study, led by Alherbawi et al., focuses on addressing the aviation sector's carbon footprint through the development of Jet Biofuel (JBF). This research highlights the creation of seven certified pathways for JBF production,

*Table 3: Breakdown of jet biofuel's lifecycle carbon footprint [9]*

| Stage | Sub-stage | Value (tonne CO2-e/lifespan) |
|---|---|---|
| | Land set-up | 3.82 × 103 |
| | Fertilisers | 259.2 × 103 |
| | Irrigation | 1,665 × 103 |
| | Machineries | 1,222 × 103 |
| Cultivation | Jatropha emissions uptake | −1.44 × 107 |
| | Transportation | 8.9 × 103 |
| | Refinery construction | 16.9 × 103 |
| | Raw materials | 6.9 × 103 |
| | Processing emissions | 409 × 103 |
| | Manure utilisation (saving) | −614 × 103 |
| | Landfill diversion (saving) | −653 |
| Production | Electricity substitution | −1,058 × 103 |
| End-use | Fuel combustion | 2.2 × 107 |
| Total (tonne CO2-e/lifespan) | | 16,675 × 103 |
| Carbon footprint | | 53 (gCO2-e/ MJ jet biofuel) |

catering to specific biomass sources over the past decade [9]. Despite these advancements, challenges persist regarding feedstock availability, sustainability, and feasibility.

In response, the study proposes a state-of-the-art hybrid biorefinery designed for Qatar, integrating diverse biomass feedstocks, and utilizing advanced technologies such as hydro processing and Fischer-Tropsch synthesis [9]. The biorefinery, modeled with Aspen Plus, a process modeling tool used for process monitoring, optimization, and conceptual design [10], showcases the potential to produce 328 million liters of JBF, meeting international standards. It also demonstrates a 41% reduction in greenhouse gas emissions compared to traditional Jet-A fuel throughout the JBF lifecycle [9]. This can be seen in Table 3 in which it shows that net carbon footprint of JBF was estimated at 53 $gCO_{2-e}$/ MJ (JBF), which indicates a 41 % mitigation in GHG emissions as compared to Jet-A fuel which is 90$gCO_{2-e}$/ MJ [22].

Economically, the model proves advantageous, with a minimum selling price of JBF at $0.43/kg, 22% lower than the 2019 market price of conventional Jet-A fuel [9]. The generated JBF has the potential to substitute 15.3% of Qatar's jet fuel needs, powering around one-third of its fleet with a maximum allowable jet biofuel blend of 50%. Alherbawi's research provides a holistic solution for sustainable aviation fuel production, emphasizing the economic and environmental benefits of the proposed hybrid biorefinery.

Another notable study, conducted by S. H. Hassan and his team, proposes a unique solution by focusing on the conversion of non-edible Jatropha oil into biofuels, specifically biodiesel and bio-jet fuel, as a viable alternative to petroleum fuels [11]. The motivation behind this study lies in the urgent need to combat depleting petroleum reserves and address environmental concerns. The researchers delve into the hydrocracking process, employing activated natural clay as a catalyst within a high-pressure batch reactor [11]. This investigation encompasses variations in reaction time, temperature, and catalyst type, with comprehensive characterization of the catalyst using SEM, FTIR, XRF, and XRD analyses.

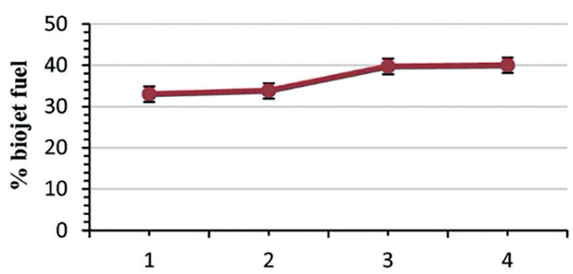



*Figure 5: Catalyst to oil ratio effect on yield of bio-jet fuel production [11].*

The study's findings reveal that the optimal conditions for the hydrocracking process involve a temperature of 350 °C, H2 pressure of 4 bars, and a reaction time of 18 minutes. Under these parameters, the research achieves a notable 40% yield of bio-jet fuel, as seen in Figure 5 where at 3 and 4 percent catalyst concentration it yields 40%. Importantly, the produced bio-jet fuel meets ASTM D1655 specifications, boasting favorable characteristics such as a freezing point of −56 °C, a flash point of 53 °C, and an existent gum content of 5.9 mg/100 ml [11]. This research significantly contributes to the exploration of sustainable alternatives in biofuel production, showcasing the potential of Jatropha oil hydrocracking under specific operational conditions to yield bio-jet fuel with promising specifications.

## Conclusions

The pursuit of SAFs represents a crucial step towards mitigating the environmental impact of the aviation industry and achieving global climate goals. From advancements in feedstock selection and production methods to the exploration of various pathways such as HEFA, AtJ technology, and MSW derived SAFs, the aviation sector has demonstrated a commitment to innovation and sustainability.

Despite significant progress, challenges remain in scaling up SAF production to meet growing demand and ensuring the economic viability of alternative fuel pathways. However, innovative studies and solutions, such as hybrid biorefineries and novel conversion processes for non-edible feedstocks like Jatropha oil, offer promising pathways forward.

As the aviation industry continues to navigate the transition towards sustainable fuel sources, collaboration between stakeholders, investment in research and development, and supportive policy frameworks will be essential. By embracing innovation and leveraging emerging technologies, the aviation sector can chart a course towards a more sustainable and resilient future, reducing carbon emissions and environmental impact while ensuring continued connectivity and economic growth on a global scale.

## References


(1) IATA. (n.d.). What is Saf? https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-what-is-saf.pdf

(2) Air bp. (n.d.). How all sustainable aviation fuel (SAF) feedstocks and Production Technologies can play a role in decarbonising aviation. Air bp. https://www.bp.com/en/global/air-bp/news-and-views/views/how_all_sustainable_aviation_fuel_SAF_feedstocks_and_production_technologies_can_play_a_role_in_decarbonising_aviation.html

(3) U.S Department of Energy. (n.d.). Sustainable Aviation Fuel Review of Technical Pathways. Energy.gov. https://www.energy.gov/sites/default/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf

(4) Aviation Pros. (2023, April 27). How all sustainable aviation fuel (SAF) feedstocks and Production Technologies can play a role in decarbonizing aviation. Aviation Pros. https://www.aviationpros.com/ground-handling/fuel-distributors-suppliers-manufacturers/sustainable-aviation-fuel/press-release/53058708/air-bp-how-all-sustainable-aviation-fuel-saf-feedstocks-and-production-technologies-can-play-a-role-in-decarbonizing-aviation

(5) The World Bank. (n.d.). Trends in Solid Waste Management. worldbank.org. https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html

(6) EASA. (n.d.). Sustainable Aviation Fuels. EASA Eco. https://www.easa.europa.eu/eco/eaer/topics/sustainable-aviation-fuels

(7) European Commission. (n.d.). European Green Deal: new law agreed to cut aviation emissions by promoting sustainable aviation fuels. European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_2389

(8) Department of Energy. (n.d.-a). DOE Explains...Biofuels. Energy.gov. https://www.energy.gov/science/doe-explainsbiofuels

(9) Alherbawi, M., McKay, G., & Al-Ansari, T. (2023). Development of a hybrid biorefinery for jet biofuel production. Energy Conversion and Management, 276, 116569. https://doi.org/10.1016/j.enconman.2022.116569

(10) Saha, P. (n.d.). Aspen Plus® Simulation Software - A Basic Course for beginners. https://onlinecourses.nptel.ac.in/noc21_ch44/preview

(11) Hassan, S.H., Attia, N.K., El Diwani, G.I. et al. Catalytic hydrocracking of jatropha oil over natural clay for bio-jet fuel production. Sci Rep 13, 13419 (2023). https://doi.org/10.1038/s41598-023-40500-2

(12) Singh, A. (2023, November 2). The top challenges of Scaling Sustainable Aviation Fuel. Publicis Sapient. https://www.publicissapient.com/insights/sustainable-aviation-fuel-challenge

(13) S. Geleynse, K. Brandt, M. Garcia-Perez, M. Wolcott, X. Zhang, ChemSusChem 2018, 11, 3728.

(14) Datta, A., Hossain, A., & Roy, S. (n.d.). An Overview on Biofuels and Their Advantages and Disadvantages. https://elar.urfu.ru/bitstream/10995/90205/1/10.14233-ajchem.2019.22098.pdf

(15) N. Eisberg, Chem. Ind., 17, 24 (2006); https://doi.org/10.1002/cind.001

(16) A. Perimenis, H. Walimwipi, S. Zinoviev, F. Muller-Langer and S. Miertus, Energy Policy, 39, 1782 (2011).

(17) S. Behera, R. Singh, R. Arora, N.K. Sharma, M. Shukla and S. Kumar, Front. Bioeng. Biotechnol., 2, 90 (2015); https://doi.org/10.3389/fbioe.2014.00090.

(18) Six Japan-based companies establish Research Association of biomass ... Green Car Congress. (n.d.). https://www.greencarcongress.com/2022/07/20220720-japanfuels.html

(19) Zemanek, D., Champagne, P. and Mabee, W. (2020), Review of life-cycle greenhouse-gas emissions assessments of hydroprocessed renewable fuel (HEFA) from oilseeds. Biofuels, Bioprod. Bioref., 14: 935-949. https://doi.org/10.1002/bbb.2125

(20) Yao, G., Staples, M.D., Malina, R. et al. Stochastic techno-economic analysis of alcohol-to-jet fuel production. Biotechnol Biofuels 10, 18 (2017). https://doi.org/10.1186/s13068-017-0702-7

(21) National Energy Technology Laboratory. (n.d.). 10.2. Fischer-Tropsch synthesis. netl.doe.gov. https://www.netl.doe.gov/research/carbon-management/energy-systems/gasification/gasifipedia/ftsynthesis

(22) Hongjian Wei, Wenzhi Liu, Xinyu Chen, Qing Yang, Jiashuo Li, Hanping Chen, Renewable bio-jet fuel production for aviation: A review, Fuel, Volume 254, 2019, 115599, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2019.06.007.


## About the Authors

**Dr. Raj Shah** serves in the role of Director at Koehler Instrument Company in New York, boasting an impressive 28-year tenure with the organization. Recognized as a Fellow by eminent organizations such as IChemE, CMI, STLE, AIC, NLGI, INSTMC, Institute of Physics, The Energy Institute, and The Royal Society of Chemistry, he stands as a distinguished recipient of the ASTM Eagle award. Dr. Shah, a luminary in the field, recently coedited the highly acclaimed "Fuels and Lubricants Handbook," a bestseller that unravels industry insights. Explore the intricacies at ASTM's Long-Awaited Fuels and Lubricants Handbook 2nd Edition Now Available (https://bit.ly/3u2e6GY).

His academic journey includes a doctorate in Chemical Engineering from The Pennsylvania State University, complemented by the title of Fellow from The Chartered Management Institute, London. Dr. Shah holds the esteemed status of a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute, and a Chartered Engineer with the Engineering Council, UK. Recently honored as "Eminent Engineer" by Tau Beta Pi, the largest engineering society in the USA, Dr. Shah serves on the Advisory Board of Directors at Farmingdale University (Mechanical Technology), Auburn University (Tribology), SUNY Farmingdale (Engineering Management), and the State University of NY, Stony Brook (Chemical Engineering/Material Science and Engineering).

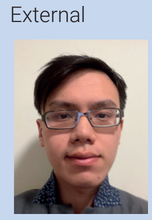
In tandem with his role as an Adjunct Professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical Engineering, Dr. Shah's impact spans over three decades in the energy industry, with a prolific portfolio of over 625 publications. Dive deeper into Dr. Raj Shah's journey at https://bit.ly/3QvfaLX.

**For further correspondence, reach out to Dr. Shah at rshah@koehlerinstrument.com.**

**Dr. Vikram Mittal,** is an Associate Professor at the United States Military Academy in the Department of Systems Engineering. He holds a PhD in Mechanical Engineering from MIT, an MS in Engineering Sciences from Oxford, and a BS in Aeronautics from Caltech. Dr. Mittal is also a combat veteran and a major in the U.S. Army Reserve. Previously, he was a senior mechanical engineer at the Charles Stark Draper Laboratory. His current research interests include various energy technologies, system design, model-based systems engineering and modern engine technologies. He has numerous publications in various peer reviewed journals.

*Vikram Mittal*

Simultaneously, within the dynamic internship program at Koehler Instrument Company in Holtsville, **Mr. Jeff Gao** is a standout participants. He is a student of Chemical Engineering at Stony Brook University, Long Island, NY, where Dr's Shah and Mittal are part of the External Advisory Board of Directors at that university.



*Jeff Gao*


### Author Contact Details

**Dr. Raj Shah, Koehler Instrument Company • Holtsvile, NY11742 USA • Email: rshah@koehlerinstrument.com**
**• Web: www.koehlerinstrument.com**