RESEARCH DEVELOPMENTS AND ADVANCES IN SUSTAINABLE AVIATION FUEL TECHNOLOGY

With continued pressure to reduce aviation emissions globally, Raj Shah, Muhammad Ahmad Rao and Gavin Thomas explore what alternatives are available

Aviation is responsible for roughly 2-3% of global carbon dioxide (CO2) emissions. But its overall contribution stretches closer towards 4% when other forms of emissions, such as nitrogen oxides (NOx), contrails and particulate matter, are considered [1],[2].

The industry is constantly on the rise. Projections show air travel demand will nearly double by 2040.

The International Energy Agency warns that these carbon emissions would increase by a massive 200-250% without the usage of alternative fuels [1], [3].

Decarbonising aviation is an interesting situation. This sector requires extremely heavy energy dense fuels, an aspect only suitable for aviation.

Conventional jet fuel (Jet-A) delivers roughly 43 MJ/kg of energy. Whereas lithium-ion batteries provide only 0.9 MJ/kg of energy. This shows battery-supplied energy is completely unfeasible [3].

Electric-based propulsion has been very successful for ground transportation and low-energy density applications. However, it would be unsuitable for high-energy commercial airborne travel.

This reinforces the idea of focusing on liquid-based fuels for aviation.

With such constraints, current battery-based aircrafts are limited to ranges within 300 km with a passenger capacity of <20.

An example of this includes, but is not limited to, Pipstrel Velis Electro and the Eviation Alice. Both of these are certified pilot training flight vehicles designed for regional routes of approximately 100 km [4], [5].

Though these examples show minor feasibility, they will make minimal contribution to reduction of aviation emissions. Over 70% of aviation CO2emissions come from medium-haul to long-haul flights, rather than these short-haul [6].

Furthermore, hybrid-electric configurations have been explored. The aim is to use the batteries during takeoff and landing.

But results show a minor efficiency improvement of less than 10-15%. These figures are subpar for sector-wide usage [5].

Lastly, from a system perspective, battery-electric aviation faces various challenges from charging infrastructure, battery degradation, thermal management and lifecycle environmental impacts, including critical mineral extraction and recycling [4].

This makes their application very niche. And thus they cannot meaningfully be a solution addressing aviation emissions.

Hydrogen is another possible alternative. But it also requires a heavy need for redesigning. This makes its viability also limited.

With both possibilities proving insufficient based on their constraints, drop-in liquid fuels are the most viable near-term solution for aviation emission reduction.

Sustainable aviation fuels (SAFs) have an advantage being drop-in fuels. But they are also chemically compatible with the existing technology of engines and airport infrastructure. This means it is capable of reducing life-cycle greenhouse gases (GHG) emissions by a staggering 60-80%, depending on pathway and feedstock [1], [7], [2].

The United States of America aims to produce 3 billion gallons of SAFs annually by 2030. As well as 35 billion gallons by 2050 through a program called the "Sustainable Aviation Fuel Grand Challenge" [1]. These targets are roughly equivalent to the current demand for jet fuel in the US.

Furthermore, the International Air Transport (IATA) aims for a 65% reduction of emissions via these SAFs by 2050. This marks and reinforces this project as the primary tool for international decarbonisation [1].

This article builds on the current research to evaluate feedstock availability, production pathways, environmental performance, economic barriers and future research that is related to US SAF production.

Limitations of conventional jet fuels

Commercial aviation fuels are based almost exclusively on petroleum-derived Jet A and Jet A-1 fuels.

In 2023 alone, global jet fuel consumption exceeded 90 billion gallons. This generated 900 million metric tons of CO2 annually [1].

As previously mentioned, greenhouse emissions go beyond CO2 and also include the emitting of NOx, which increases ozone formation, SOx, a form of particulate matter, and water vapour, which leads to contrail formation.

Life-cycle assessments show that non-CO_2 impacts may account for up to two-thirds of aviation's total radiative forcing. This makes reductions in fuel carbon intensity a critical priority [2].

Alternative technologies have promise, but often run into various fundamental challenges.

For example, battery-electric aircrafts have niche uses. But they only remain useable in short-range applications.

Also, briefly mentioned, hydrogen-based fuels are another possibility. But they require about quadruple the volume that kerosene provides, even when liquified. This poses several challenges in aircraft integration [8].

Once again, we see that in terms of viability and being a possible near-term solution, SAFs are a clear distinction.

SAF feedstocks and productions

The key advantage that SAFs offer is that its production is derived from various forms of renewable feedstocks. Each pathway offers its own unique combination of environmental, economic and scalability characteristics.

Current research emphasises diversification to avoid supply bottlenecks and indirect environmental impacts.

One example is lipid feedstocks, which are typically used in oils and fats.

Used cooking oils, animal fats and corn oil are the primary inputs for hydroprocessed esters and fatty acids (HEFA) production. This process is currently the most used pathway for SAF production, covering approximately 85% of all global production [1], [7].

This process begins by having feedstocks pretreated to remove impurities.

Triglycerides are then hydrogenated to remove oxygen.

Hydrocarbons are cracked and isomerised into jet-range molecules.

This SAF shows a lifecycle GHG reduction of 60-75%, having energy density comparable to Jet-A (~42-43 MJ/kg).

Neste, the world's largest SAF producer, supplies major aviation companies such as United Airlines, Delta and American Airlines. It directly benefits from US tax credits under the Inflation Reduction Act [1], [9].

Unfortunately, however, the US used oil supplies are limited to approximately 3 billion litres annually. This is far below the 50-60 billion thresholds needed to displace Jet A fuels domestically [10], [7].

To compensate for this, additional feedstock sources need exploring.

The United States produces over 60 million dry tons of corn stover and 50 million dry tons of forest-based residues annually. Both of these are suitable for SAF production.

This category of SAFs can be referred to as lignocellulosic fischer-tropsch (FT) pathways, which is defined as a process that is derived from plant biomasses, often including the residues from agriculture, forests and energy productions that were stated above.

Biomasses, MSW and waste gases are turned into syngas, a flammable gas mixture. This is then converted to long-chain hydrocarbons.

These materials are in their own separate category. That means they will not interfere with food production and can achieve lifecycle GHG reductions of 80-85% when converted via thermochemical pathways [3].

Other key advantages of this SAF include no reliance on food-based inputs and they have broad feedstock flexibility.

Another crop that has recently gained attention are carinata and camelina. Both of these are oilseed crops.

They stand out in the United States, yielding between 2,000-2,700 kg/ha and have oil content in the range of 35-45%, with an annual output of up to 2 billion litres.

A major advantage is that they are winter crops. They improve soil carbon and do not require farmers to displace food production. Nor do they require large amounts of water as they are winter cover crops.

Furthermore, they reduce lifecycle emissions by approximately 70-75% compared to conventional jet fuel. This provides economic benefits to farmers and minimises land-use change impacts [10].

These crops are first cultivated during the off season. Oils are extracted from their seeds, which are then converted into jet fuel via HEFA.

There is municipal solid waste (MSW) as another feedstock option.

Approximately 300 million tons are produced annually. A portion of this can be synthesized into jet fuel, while simultaneously having a 70-85% reduction in landfills [3].

This process typically starts with waste sorting and preprocessing. Before then glassifying the filtered resources to prepare for liquid hydrocarbon production via FT synthesis.

Companies such as Fulcrum BioEnergy have developed facilities that specialise in MSW-based SAFs in Nevada and Canada.

Companies, most popularly United Airlines, are supplied with it under long-term offtake agreements. They're further supported by federal incentives [3], [9].

Lastly, we can highlight synthetic feedstocks that use renewable hydrogen and captured CO2 to form hydrocarbons.

This is the only pathway mentioned thus far that offers a theoretical near zero emission level. But due to its high cost, its viability is limited [7].

With the availability briefly discussed, it is time to highlight the current production pathways.

> *With enough research, supportive policies and technological innovations, SAFs can become a cornerstone of sustainable aviation in the near future*

Similarly, catalytic hydrothermolysis jet (CHJ) reduces hydrogen requirements by 30-40% compared to HEFA and has some cost reduction potential [1].

There is also FT, which was also referenced in an earlier part of the article.

This process gasifies biomasses into syngas, which is then converted to hydrocarbons.

It has a high feedstock flexibility and reduces greenhouse gas emissions by 80-85%. Especially when paired with renewable electricity [3].

We can also explore alcohol-to-jet (ATJ). This converts ethanol into jet fuel through various processes of dehydration, oligomerisation and hydrogenation.

This is especially scalable since the US annually produces 15 billion gallons of ethanol, making it very relevant in the area [11].

The last one we can explore is power-to-lipid (PtL). This works similarly to FT by producing hydrocarbons via hydrogen and captured CO2.

The process differs by having an extremely high dependence on electrical sources, with about 15-20 kWh per liter of fuel – approximately 99% dependency [7].

Regardless, it is a possible SAF production pathway that is worth highlighting.

Environmental and operational performance

Through these several listed processes, it is clear that we can reduce greenhouse gas emissions by large quantities.

It is observed that carinata HEFA has 73% reduction, FT-biomasses have 80-85% reduction, waste-based SAFs have 70-85%, PtL synthetic SAF have 90-99% and SAFs in general have 60-80% reduction [1], [10], [7], [3], [2].

It is also noted through the life cycle modeling by Han et al, that these emissions have a reliance on hydrogen sourcing, process heat and land use effects [2].

By using 50% SAF blends, there are other benefits. These include a reduction in soot emissions.

More than 450,000 commercial flights have used SAF blends without any disruptions in their performance [1], [6].

This is because these fuels meet and/or exceed various Jet A specifications, such as energy density, freezing point, combustion stability and lubrication [2], [6].

Overall, there are many benefits that also include lower contrail formation and improved local air quality near airports.

Economic and policy challenges

At the end of the day, this is a business. Costs play a huge role in the direction these industries take.

SAFs currently cost about $4-$9 per gallon, which is a 2-5x jump from commercial Jet A fuel that is approximately $2-$3 per gallon [11], [9].

Comparatively, PtL fuels costs exceed $10 per gallon. But that's due to its high dependence on electrolysers [5].

Furthermore, SAFs currently represent an extreme minority of global jet fuel usage. Current estimates suggest it is below even 0.1% [1], [8].

This restraint can be caused by the struggle to properly scale and manage resources and feedstocks.

Plus, ASTM certifications are difficult to acquire. Hileman and Stratton report that it may take as long as seven to 10 years [6].

There are also barriers we should consider such as hydrogen transportation, inconsistent feedstock supply chains and insufficient biorefinery capacity.

Besides costs, policies also need considering. They can be a determining factor to which these SAFs can scale.

Since the costs are multiple times more than conventional fuels, government incentives can help bridge the gap.

In the United States, there are a combination of financial incentives and production targets. These can help stimulate the SAF production domestically.

For example, the Inflation Reduction Act SAF Tax Credits was put in place that offers $1.25 per gallon for SAFs that achieve 50% GHG reductions. There's an additional $0.01 per additional percent reduction up to $1.75/gal [9].

This alone covers about 30-45% of the cost gap between SAF and Jet A fuels.

Incentives like these go such a long way in this industry since facilities are very capital-intensive. Costs often exceed $300-600 million per plant [7].

Furthermore, the SAF Grand Challenge establishes national goals, such as having 3 billion gallons annually by 2030 and 35 billion gallons by 2050. This roughly matches the current US jet fuel consumption.

These goals, though impressive, still require great amounts of effort. It requires domestic output to increase by more than 40x [1].

Federal funding also plays a crucial role in the growth of SAFs. More than $250 million has been given towards these projects since 2021. This resulted in the emergence of all the aforementioned pathways [6].

Overall, these US-based policies reduce risk, expand investments and scaling and help allow feasibility for SAF adoption by the 2040s [8].

Future outlook and conclusion

With this becoming a constantly growing and evolving field, new feedstock pathways are always coming out and with varieties from the current market.

As research progresses, there are new catalysts and enhancements that are added to continue making SAFs performance and yields greater than before [3].

Furthermore, PtL, though not as relevant currently, may become the new fastest growing technology once SAFs are properly established in the 2040s [7].

All in all, SAFs offer the most immediate and scalable pathway for reducing aviation emissions.

This article explored SAFs from various angles. We discussed its capabilities in reducing life-cycle emissions by 60-80%, advancements in feedstock development, conversion pathways and growing synthetic fuel technologies that have a strong trajectory towards the US and then the world overall.

With enough research, supportive policies and technological innovations, SAFs can become a cornerstone of sustainable aviation in the near future.

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Biographies

Dr Raj Shah is a director at Koehler Instrument Company in New York, where he has worked for the last 25 plus years. He is an elected fellow by his peers at ASTM, IChemE, ASTM, AOCS, CMI, STLE, AIC, NLGI, INSTMC, Institute of Physics, The Energy Institute and The Royal Society of Chemistry.

An ASTM Eagle award recipient, Dr Shah recently coedited the bestseller, Fuels and Lubricants Handbook, details of which are available here https://bit.ly/3u2e6GY.

Dr Shah earned his doctorate in chemical engineering from The Pennsylvania State University and is a fellow from The Chartered Management Institute, London.

Dr Shah is also a chartered scientist with the Science Council, a chartered petroleum engineer with the Energy Institute and a chartered engineer with the Engineering council, UK.

Dr Shah was recently granted the honorific of "Eminent engineer" with Tau beta Pi, the largest engineering society in the USA.

He is on the advisory board of directors at Farmingdale university (Mechanical Technology), Auburn University (Tribology), SUNY, Farmingdale, (Engineering Management) and State University of NY, Stony Brook (Chemical and Molecular Engineering).

As an adjunct professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical Engineering, Raj also has over 700 publications and has been active in the energy industry for over three decades.

Muhammad Ahmad Rao is a chemical and molecular engineering undergraduate student at Stony Brook University. He is also a part of a thriving internship program at Koehler Instrument company in Holtsville, NY underneath Dr Raj Shah.

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Gavin Thomas is part of a thriving internship program at Koehler Instrument Company in Holtsville, NY and is a recent graduate of the chemical and molecular engineering program at Stony Brook University. He also works as a process engineer at Mill-Max in Oyster Bay, NY where he becomes hands-on with various production processes to ultimately improve safety, efficiency, and cost-effectiveness.

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