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Review

Multi-criteria decision analysis for the evaluation and screening of sustainable aviation fuel production pathways

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SUMMARY

The aviation sector, a significant greenhouse gas emitter, must lower its emissions to alleviate the climate change impact. Decarbonization can be achieved by converting low-carbon feedstock to sustainable aviation fuel (SAF). This study reviews SAF production pathways like hydroprocessed esters and fatty acids (HEFA), gasification and Fischer–Tropsch Process (GFT), Alcohol to Jet (ATJ), direct sugar to hydrocarbon (DSHC), and fast pyrolysis (FP). Each pathway's advantages, limitations, cost-effectiveness, and environmental impact are detailed, with reaction pathways, feedstock, and catalyst requirements. A multi-criteria decision framework (MCDS) was used to rank the most promising SAF production pathways. The results show the performance ranking order as HEFA > DSHC > FP > ATJ > GFT, assuming equal weight for all criteria.

INTRODUCTION

The aviation industry plays a vital part in fostering international trade and fast transportation of people to several destinations.[1] Despite all these positive effects, the primary drawback of the industry is the significant contribution that air travel makes to greenhouse gas (GHG) emissions. Reports state that the aviation sector is responsible for more than 2% of all anthropogenic CO_2 emissions worldwide[2] This is approximately one billion tonnes of carbon dioxide (CO_2) being emitted into the atmosphere annually.[2] It should be mentioned that the aviation industry also contributes to global warming also via non-CO_2 climate impacts.

Estimating the impact of non-CO_2 emissions from aviation on the environment has been quite difficult. The main non-CO_2 emissions include nitrogen oxides (NO_x), water vapor, and soot, which can lead to the formation of contrails or vapor trails left by planes.[3] Aviation aerosols, tiny particles made of soot, sulfur and nitrogen compounds, also contribute to this. The most significant contributors to global warming, besides CO_2, are contrails and changes in the atmosphere's chemical makeup caused by NOx.[3] A study by Lee et al. found that aviation's CO_2 emissions contribution to global warming is about 1.59% of the total contribution from all human-made CO_2 emissions.[4] Furthermore, when combining the effects of both CO_2 and non-CO_2 emissions from aviation, they accounted for about 5% of the total global warming effect caused by humans.[4] In the transportation section, close to 12% of all CO_2 emissions are from the aviation sector.[5] The aviation industry is regarded as one of the fastest-growing contributors of greenhouse gas (GHG) emissions as a result of the increasing need for air travel, and it is hard to ignore the impact of these emissions on climate change.[6] Therefore, there is an urgent need to reduce or eliminate emissions from the aviation industry, as the industry continues to expand.

The primary cause of emissions in the aviation industry has been identified as the combustion of conventional (fossil fuel-based) aviation fuel. The development of commercial electric (battery-powered) airplanes, hydrogen-fuel aircraft technology,[7] and biofuels as sustainable aviation fuel,[8] have been identified as technologies for decarbonizing the aviation industry and reducing GHG emissions. Owing to how challenging it is to electrify planes[9] and the technological limitations on developing low-carbon aircraft, researchers have focused on the use of sustainable (biomass-based) aviation fuel (SAF) and the improvement of the fuel efficiencies of aircraft as possible measures for reducing carbon emissions from the aviation industry.[10] One approach for achieving a carbon-neutral environment in the aviation sector is through the

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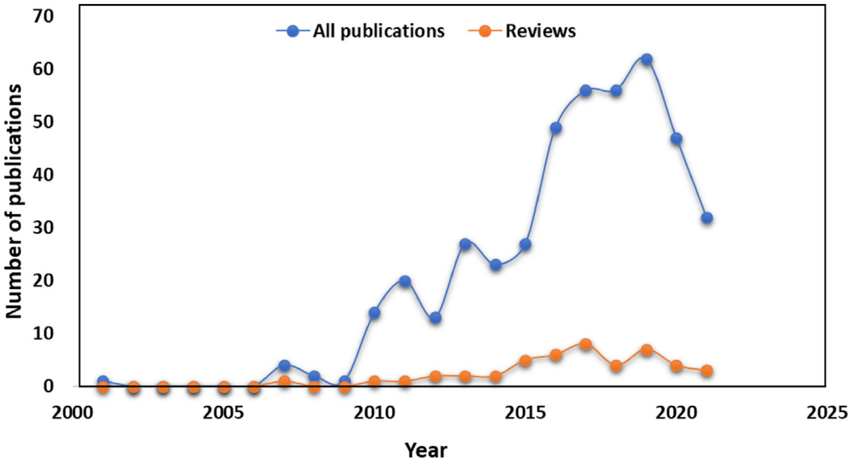

Figure 1. Bibliometric trend for SAF production over the past 20 years

Data was obtained from the Scopus database.

utilization of SAF, which could be replaced or blended with conventional aviation fuel to reduce the number of carbon emissions by 50–80%.[11] It should be mentioned that while SAF is a key part of the solution, achieving a carbon-neutral environment in the aviation sector will require a multi-faceted approach.

SAF commonly referred to as bio-jet fuel, is a renewable, clean-burning biofuel that has similar chemical properties to conventional aviation fuel derived from fossil fuels. SAF refers to a group of non-petroleum-based fuels (including renewable sourced fuel from non-biogenic precursors), which can include biofuels and synthetic fuels, developed to reduce greenhouse gas emissions in the aviation industry.[12] Aviation fuels could be drop-in or non-drop-in fuels. Drop-in aviation fuels are alternative fuels that can be used as direct replacements for conventional jet fuel (typically Jet A or Jet A-1) without requiring any modification to the aircraft engines or fuel infrastructure.[12] These fuels have similar chemical and physical properties to conventional jet fuel and can be blended with it, allowing for seamless integration into existing systems. SAFs that meet certain specifications can be considered drop-in fuels. In contrast, non-drop-in aviation fuels, are alternative fuels that cannot be used interchangeably with conventional jet fuel without modifications to the engines, fuel systems, or fuel infrastructure.[3,12] These fuels have properties that differ significantly from conventional jet fuel, and as a result, they require dedicated infrastructure and engine adaptations to be used in aviation.

The International Energy Agency (IEA) estimates that if the production of SAF is developed sustainably, it will be able to meet 10% of global aviation fuel demand by 2030.[13] Meanwhile, in 2019, only 1% of the 363 billion liters of aviation fuel used in the aviation industry were SAF.[14] Numerous researchers have explored the development of alternative pathways for SAF production to aid the decarbonization of the aviation industry.[5,8,11,13,14] SAF can be obtained from a variety of feedstocks such as lignocellulosic biomass, vegetable oils, wastewater sludge, algae, forestry and wood residues, lignin, municipal solid waste (MSW), energy crops, and animal fats.[15] Waste cooking oil has also been recognized as a suitable biowaste for the production of SAF via the Hydroprocessed Esters and Fatty Acids (HEFA) process.[16] Ng et al.[17] presented a comprehensive review of the current development and commercialization of sustainable aviation fuel. To reduce the demand for food/feed crops and, consequently, alleviate the competition between food and fuel, they suggested the use of biomass materials as feedstocks to produce SAF. They recommended concentrating efforts on developing SAF production technologies that make use of these feedstocks, such as alcohol-to-jet fuel, gasification and Fischer-Tropsch process, and the hydroprocessing of direct sugars to hydrocarbons.[17]

Various pathways and technologies like gasification and Fischer-Tropsch synthesis and fast pyrolysis of biomass have also been considered and utilized for the production of SAF by several researchers. Figure 1 shows the bibliometric trends of SAF research over the last decade including review articles. The figure indicates that studies related to SAF are still not much considering the interest in SAF as a pathway toward the decarbonization of the aviation industry. In addition, Table 1 outlines previous reviews in SAF

Table 1. An overview of previous studies related to SAF production

Study title	Key focus	References
Hydrogen for aircraft power and propulsion	• Presents an overview of nuclear fission and subsequent applications of the aerospace vessel. • Outlines the suitability of hydrogen as an aircraft fuel.	Petrescu et al.[7]
Unprecedented Impacts of Aviation Emissions on Global Environmental and Climate Change Scenario	• Comprehensively studied the role the aviation industry emissions in promoting global warming.	Sher et al.[6]
Global biorenewable development strategies for sustainable aviation fuel production	• Compares four different SAF production pathways: Fischer-Tropsch (FT); hydro-processed esters and fatty acids (HEFA); alcohol-to-jet (ATJ); and hydroprocessing of fermented sugars (HFS)). • Discuss the current technological maturity and future research gaps.	Ng et al.[17]
Progress in the utilization of waste cooking oil for sustainable biodiesel and biojet fuel production	• Discussed the current status and progress on the conversion of waste cooking oil to SAF • Techno-economic analysis of different pathways for the conversion of waste cooking oil to SAF Was reviewed.	Goh et al.[16]
Bio-jet fuel conversion technologies	• Current technologies for SAF including alcohols-to-jet, oil-to-jet, syngas-to-jet, and sugar-to-jet pathways are reviewed. • The challenges of each technology, as well as different conceptual designs, were outlined.	Wang et al.[18]
Techno-economic and environmental analysis of aviation biofuels	• Compares the economic and environmental impacts of four different SAF production processes located in northern Germany. • Studied the impact of two different biomass precursors on each process.	Neuling and Kaltschmitt[19]
Life cycle analysis of greenhouse gas emissions from renewable jet fuel production	• Compared the GHG emission of several SAF production pathways • Studied the impact of co- production allocation on GHG emissions	De Jong et al.[20]
A comprehensive review of sustainable aviation fuel production pathways	• Comprehensively reviewed the current status and progress of five different SAF production pathways: hydro-processed esters and Fatty acids (HEFA), gasification and Fischer-Tropsch Process (GFT), Alcohol to Jet (ATJ), Direct sugar to hydrocarbon (DSHC), Catalytic fast pyrolysis. • Outline individual reaction pathways and the influence of process parameters on SAF quality. • Comparative evaluation of the five reviewed production pathways in terms of cost and environmental impact. • The status and progress of SAF pathways are meticulously presented. • Multi-criterial analysis to evaluate the most promising production pathway	This study

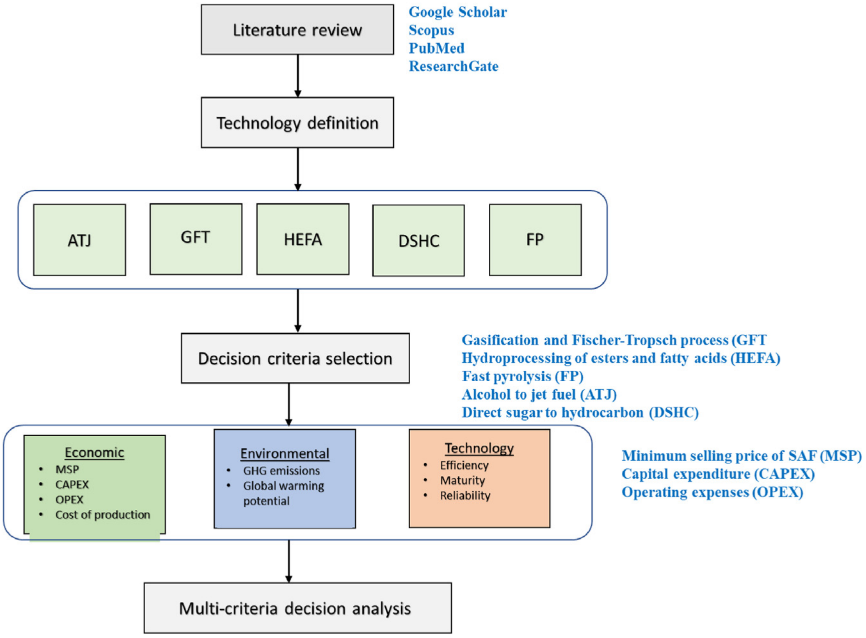

Figure 2. Overview of the methodology adopted in this study

production. Based on the information reported in Table 1, there is a limited review on the comparative evaluation of different SAF production pathways. Moreover, most of the available studies are scattered considering the increasing interest in SAF production. To address the study gaps, this paper presents an overview of the current developments in the production of SAF and prepares a comparative evaluation of five different production pathways including gasification and Fischer-Tropsch process (GFT), hydroprocessing of esters and fatty acids (HEFA), fast pyrolysis (FP), alcohol to jet fuel (ATJ), and direct sugar to hydrocarbon (DSHC). This research is carried out to consolidate the effort of previous researchers and determine the advantages and disadvantages of these various pathways as well as any potential areas for improvement, which is crucial for achieving effective processes that produce affordable and environmentally benign SAF. This article will contribute to the technological advancement of the aviation industry and promote its sustainable growth.

METHODOLOGY

Schematics of the methodology adopted in this study are presented in Figure 2. Research and review articles are collected from several databases including Scopus, Google Scholar, PubMed, and Research Gate. The search was focused on several keywords related to SAF, biokerosene, bio-jet fuel, jet fuel, and sustainable jet fuel. All review and research articles were included while articles related to thermochemical or biological conversion processes without considering the subsequent conversion of feedstock to SAF were excluded. In addition, articles that focused mostly on feedstock pre-treatment were excluded. The technological overview and research trends obtained from the literature review were comprehensively presented in sections 3 and 4. Based on the literature review studies, five key SAF production pathways and three key decision criteria were selected (Figure 2). After which a multi-criteria decision support framework (MCDS) was implemented.

MCDS provides formalized methodologies for screening and identification of optimum parameters by considering several factors. MCDS involves the selection of the optimal technology alternative by combining information about the evaluation criteria information and decision-making preference to obtain the final alternative ranking. The method has been adopted by several researchers for different energy systems. Liu and Du.[21] applied the MCDS to evaluate and select the most effective renewable energy storage technology. Santoyo-Castelazo and Azapagic[22] developed a framework based on MCDS for assessing different energy systems using a case study of electricity generation in Mexico. However, to the best of the authors' knowledge, the application of MCDS for assessing the sustainability of a wide range of SAF

Table 2. Properties of standard specification fuels (Jet A and Jet A-1)

Composition	Jet A	Jet A-1
Density at 15°C (kg/m^3)	775–840	775–840
Viscosity (mm^2/s)	8	8
Initial boiling point (°C)	N/A	170
Final boiling point (°C)	300	300
Minimum Flashpoint (°C)	38	38
Total acidity (mg KOH/g)	0.1	0.1
Freezing point (°C)	−40	−47
Aromatics (wt %)	18.53	18.0
Cycloparaffins (wt %)	31.80	N/A
n-paraffins (wt %)	19.98	N/A
Iso-paraffins (wt %)	29.69	N/A
Net heat of combustion (MJ/kg)	43.28	42.8

methods is scarcely reported. The results of MCDS help in the screening and selection of the most promising SAF production pathway. Detailed information and mathematical computation of MCDS can be found elsewhere.[21,22]

SUSTAINABLE AVIATION FUEL PROPERTIES

SAF's development and market penetration is laborious, largely because they often undergo strict tolerances and extreme qualification hurdles compared to alternative fuels for automobile transportation. SAFs could contain hydrocarbons with very little amounts of heteroatom, oxygen-containing compounds or olefinic compounds. The presence of these materials could adversely impact fuel performance and safety metrics.[23] SAF should be fungible with petroleum fuels and should exhibit similar performance with fossil-based jet fuels. The Carbon Offset and Reduction Scheme for International Aviation (CORSIA) suggests that SAF must satisfy the ASTM D1655 standard, as they will be blended with regular jet fuel.[24,25] SAF is therefore being produced as "drop-in" fuels that are largely compatible with conventional fuels in the aviation industry. It is therefore important for any possible alternative fuel to be properly tested and examined to ensure its properties are compatible with the aircraft's operation and engine. Consequently, SAFs must share many of the same characteristics and properties as conventional aviation fuels if they are to substitute them.

International standard specifications for jet fuels, which are majorly kerosene-based, have been adopted because the same aircraft can be fueled in different countries. Jet A and Jet A-1 fuels are the most commonly used fuels for commercial planes. Except for Russia and the Commonwealth of Independent States (CIS), Jet A-1 is the standard specification fuel used worldwide whereas Jet A fuel is the standard specification fuel that is used in the US.[26] The standards that are most frequently used to assist in ensuring that the fuel is appropriate for global usage include UK MOD Defense Standard 91-091 (DEF STAN 91-91),[27] ASTM International D1655 (D1655), and the US military MIL-DTL-83133 and MIL-DTL-5624.[28] The ASTM D7566 standard is an expansion of the D1655 standard that adds fuel-specific requirements and specifies vital properties for bio-jet fuel.[29] Therefore, the properties of any SAF produced must satisfy the ASTM D7566 requirement, and the properties of the fuel, after it is blended with Jet A-1, must satisfy the ASTM D1655 standard. To use SAF in commercial aircraft, it must fulfill the standard aviation turbine fuel specifications, which are usually defined by ASTM International. ASTM 7566 requires SAF to be blended with at least 50% of fossil kerosene.

Jet A and Jet A-1 fuels are mostly composed of n-paraffins, naphthenes, aromatics, iso-paraffins, and other hydrocarbons, with a carbon distribution number ranging from 8 to 16. The carbon number is a very important parameter for obtaining desirable jet fuel properties. Some chemical properties of Jet A and Jet A-1 fuels are found in Table 2.[18,30] According to the American Society of Testing and Materials (ASTM),[28,29] the important properties that any aviation fuel must meet before it can be considered for use include.

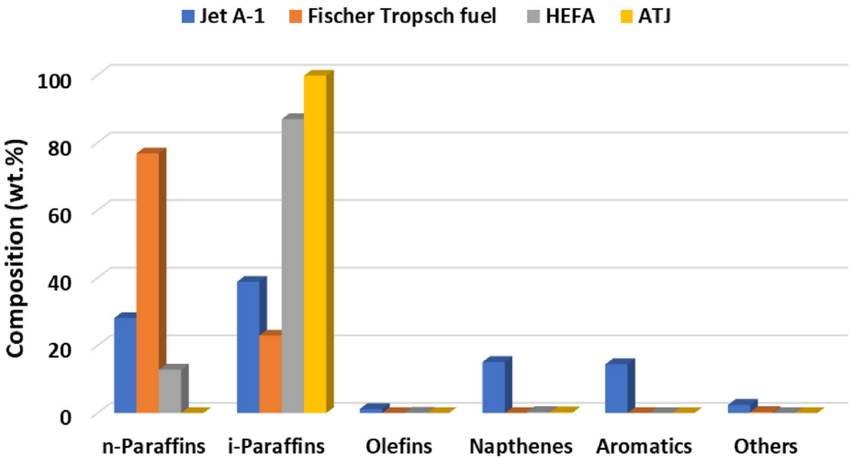

Figure 3. Compositional analysis of different SAF

Data extracted from Goh et al. [17] with permission from Elsevier.

i. The fuel must have a chemical structure that is similar to jet fuels.
ii. The fuel must be able to be easily blended with conventional aviation fuels.
iii. The fuel must be suitable for direct use without any modification of the aircraft.

SAFs are generally composed of linear paraffins, cycloparaffins, olefins, and aromatic compounds, in the C_8–C_{16} range. The chemical composition of Jet A-1 fuel as well as other SAF is summarized in Figure 3.[31] The figure shows that the production pathways greatly influence the SAF composition. Although, SAF must satisfy numerous requirements which include being non-toxic, widely accessible, having a low freezing point, significant energy density, low viscosity, fast evaporation, and better atomization, especially when compared to current Jet A-1 fuels.[32] Cost competitiveness is a non – ASTM requirement that should also be considered. The freezing point of the fuel is an important fuel property that is influenced by the length of the paraffinic carbon chain and the number of iso-paraffins, and aromatics present in it.

Five different types of synthetic paraffinic kerosene (SPK) have been certified and specified in the standard ASTM D7566-18 as blending components for conventional aviation fuel to produce SAF. They include FT-SPK produced from the gasification and Fischer-Tropsch pathway, ATJ-SPK produced from the alcohol-to-jet pathway, HEFA-SPK, synthesized iso-paraffins (SIP) from the sugar-to-jet pathway, and FT-SPK with increased aromatic content (FT-SPK/A).[33] According to an experimental test carried out by,[34] the combustion of SAF produces less soot when compared to the amount of soot produced by the combustion of jet fuels.[35] also confirmed SAF lower global warming potential (GWP) and fossil fuel use when compared to conventional aviation fuels using well-to-wake simulations. Besides that, HEFA fuel is cleaner than traditional jet fuel because it contains less sulfur and fewer harmful substances, and it releases less CO_2 during combustion. However, if we only consider the CO_2 released during burning, it is similar to fossil jet fuel. The reduction in CO_2 comes from using different raw materials. So, when we consider the entire process from production to use, most SAFs like HEFA fuel, release less CO_2 than fossil kerosene.

The thermal stability, fluidity, combustion properties, volatility, pollutant, corrosivity, and additives of SAF must be properly examined before it can be utilized. When the fuel parameters such as oxygen content, lower heating value, cetane/octane number, and density are known, the fuel consumption of various bio jet fuels may be predicted and evaluated. Process modeling has been used as an alternative to engine tests to try to determine how well SAF would perform in use. The process simulation is based on measured fuel properties and experimental data from the literature.Kroyan et al.[36] developed a mathematical model to estimate the influence of the chemical properties of SAF on fuel consumption and engine performance. The effect of the viscosity, hydrocarbon content, density, and lower heating values of the SAF was used to investigate the relationship between fuel consumption and fuel properties.Quan et al.[37] also aimed to correlate the fuel qualities to their combustion characteristics for alternative biofuels because assessment of engine performance with alternative fuel mixtures is rarely found in previous literature.

Table 3. SAF production pathways certified by ASTM

Conversion pathways	Feedstock	Year of approval	Producers	Blending rate
Fischer-Tropsch synthesis of Synthetic Paraffinic Kerosene (FT-SPK)	Municipal solid waste (MSW), Forestry wastes, natural gas, coal	2009	Shell	Up to 50%
Hydroprocessing of esters and fatty acids (HEFA)	Triglyceride-based feedstocks like vegetable oil, algae, waste oil, animal fat	2011	Honeywell, Neste Oil	Up to 50%
Hydroprocessing of Fermented sugars to Synthetic Isoparaffins (HFS-SIP)	Cellulose, Starch, carbohydrates	2014	Total, Amyris	Up to 10%
Fischer-Tropsch synthesis of SPK with aromatics (FT-SPK/A)	MSW, agricultural waste, natural gas, forestry waste, cool, energy crops	2015	Shell, Sasol	Up to 50%
Alcohol-to-Jet synthesis of SPK using isobutanol and ethanol (ATJ-SPK)	Cellulose, agricultural waste, starch, carbohydrates	2016 2018	Gevo (Isobutanol) LanzaTech, Byogy (ethanol)	Up to 30% Up to 50%
Catalytic hydrothermolysis jet fuel (CHJ)	Triglyceride-based feedstocks	2020	Applied research associates (ARA), Euglena	Up to 50%
Hydroprocessing of high hydrogen content hydrocarbons, esters, and fatty acids to SPK (HC-HEFA-SPK)	Oils found in biologically derived hydrocarbons like algae	2020	IRI corporation	Up to 10%

OVERVIEW OF DIFFERENT PRODUCTION PATHWAYS

Currently, several pathways are certified by the ASTM for the production of SAF and blending with conventional aviation fuel.[31] These pathways are listed in Table 3. The pathways are based on the utilization of several feedstocks including lignocellulosic biomass, starchy materials, sugars, industrial waste materials and triglycerides. Most common SAF production pathways are classified into the following categories: gas to jet fuels (such as the GFT process), oil to jet fuel (such as the HEFA processes), sugar to jet fuel (such as the DSHC processes) and alcohol to jet fuels. Details of these pathways are described in Figure 4.

Hydroprocessing of esters and fatty acids (HEFA) to SAF

The hydroprocessing of esters and fatty acids (HEFA) is currently the most popular and economically viable technology for producing sustainable aviation fuel because of the high product yield and minimum selling price of SAF.[5] The HEFA route is the most advanced and frequently used SAF technology. It is an ASTM-certified technology that converts triglycerides into synthetic paraffinic kerosene (SPK) also known as SAF.[38] SAF produced from this pathway has been confirmed to have properties similar to those of conventional aviation fuel. Besides that, HEFA fuel has a lower sulfur content, a lower aromatic content, and fewer emissions of carbon dioxide. It also has a higher cetane rating than conventional aviation fuel and can be blended up to 50% with conventional aviation fuel.[39] HEFA also offers the possibility of producing SAF at a large scale over a short period.[40]

The HEFA pathway entails two major processes: (1) feedstock pre-treatment and catalytic hydrogenation to produce free fatty acids (triglycerides) and propane, and (2) the hydrodeoxygenation and decarboxylation processes to convert triglycerides into long-chain paraffinic alkanes (hydrocarbon fuels) in the presence of hydrogen. Detailed information on SAF production pathways via HEFA is presented in Figure 5. In addition, Table 4 presents an overview of feedstock and catalysts used for HEFA process.

Triglycerides are commonly generated from a variety of feedstock sources (vegetable oil, algae, used cooking oil, and animal fats) and have carbon chain lengths ranging from C_{14} to C_{20}. They are composed of long fatty-acid chains attached to a glycerol backbone.[41] The feedstock used is also one of the most important factors that influence the minimum fuel selling price (MFSP) of the biojet fuel produced in the HEFA pathway.Long et al.[42] evaluated 20 different feedstocks that can be utilized for producing triglycerides. The feedstocks considered were from vegetable oil (palm kernel, coconut, castor, corn, soybean, canola, jatropha, flax, sunflower, rapeseed, pennycress, groundnut, safflower, mustard, camelina, and cottonseed),

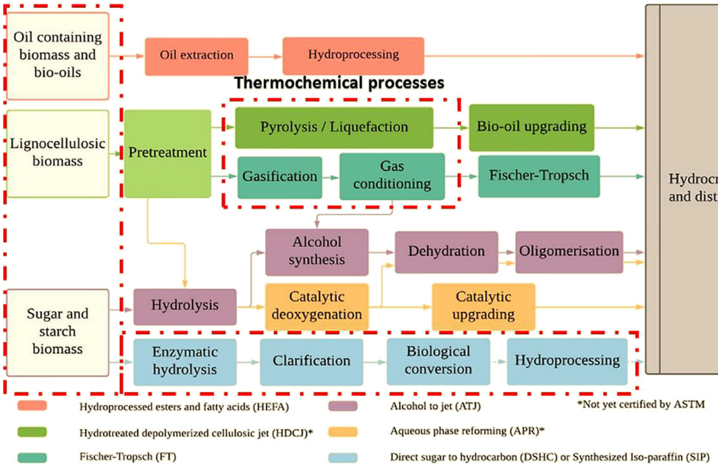

Figure 4. An overview of different pathways for the production of SAF

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animal fats (pork fat, beef fat, and chicken fat), aquatic microorganism (algae), and grease sources (yellow and brown grease). Their results show that most of the produced oil from various feedstocks mostly contains C_{16} and C_{18} fatty acids. Furthermore, the MFSP of SAF derived from the feedstocks ranges from \$3.8 and \$11.0 per gallon.

Refined bleached deodorized palm oil (RPO) and palm kernel oil (PKO) derived from palm oil refineries were explored as feedstock for SAF.[43] The results showed that temperature played a major role during the hydroprocessing of RPO and PKO to SAF. The optimal temperature, pressure and liquid hourly space velocity (LHSV) were reported as 477°C, 5.6 MPa and 1.5 h^{-1} of LHSV respectively.[43]

Several researchers have also explored different renewable feedstock including vegetable oils, animal fats, and algal oils.[40] It should be emphasized that some edible oil crops are unsuitable for SAF production because of the food versus energy competition. Regardless, the choice of feedstock for HEFA is very important because it determines if an extra pre-treatment step is required as well as the quality of the fuel produced. For instance, feedstock with larger impurities and moisture would require additional heating and moisture removal. Also, the cracking and distillation steps could be avoided with feedstock containing mostly fatty acids with carbon chain length within the jet fuel range.[40] Highly unsaturated feedstock often needs an additional process to saturate the double or triple bonds of the corresponding fatty acids. These steps necessitate large amounts of hydrogen consumption at moderate pressure and temperature thereby improving the overall processing cost.

To improve the quality of SAF produced via HEFA to meet the ASTM standards described in section 2, processes such as hydrocracking and hydroisomerization of the feedstock could be implemented.[43] A solid catalyst can also be used to drive chemical reactions and promote the formation of desired molecules.[44] After the triglycerides have been combined with hydrogen, they are sent into a catalytic reactor where the double bonds in the fatty acids chain are saturated with hydrogen. Good HEFA catalysts should exhibit improved catalytic activity, selectivity, and stability. In addition, the catalysts should be mechanically and thermally stable, reusable and cost-effective. Several heterogeneous catalysts that have been explored for SAF production via HEFA include monometallic catalysts such as Pd, Pt, Mo, and Ru metals.[31] These metals are supported by porous materials containing acidic sites. Overall, HEFA catalysts with superior acidity enhance hydrocracking and are susceptible to carbon deposition., In contrast, less acidic catalysts demonstrate poor catalytic activity during HEFA.[31] Bimetallic catalysts such as PtPd, Pt/MoOx and Ni-MoS_2 have also been explored as promising catalysts for SAF production via HEFA.[31] Table 3 compares different feedstock and catalysts reported for SAF production via HEFA.

Various organizations in the aviation industry like Virgin Atlantic, Japan Airlines, Honeywell, Air China, Boeing, Etihad, and many others, have used the bio-fuel produced from this pathway for test flights.[45,46] Until

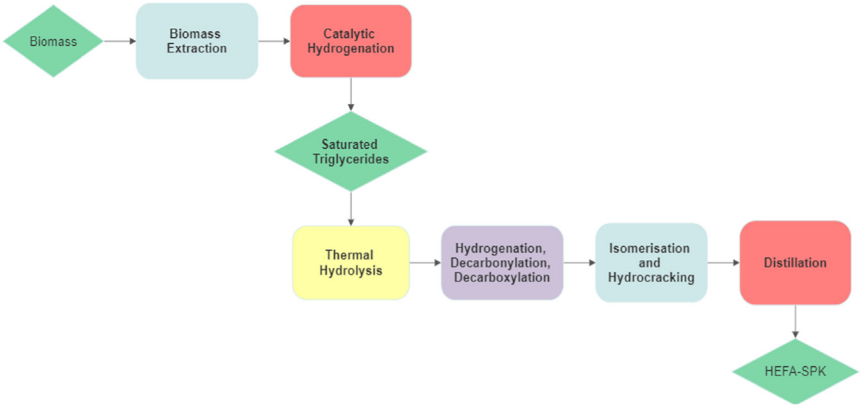

Figure 5. An overview of the HEFA Pathway for SAF production

now, the HEFA pathway has produced the vast majority of sustainable aviation fuels. However, there are still some barriers that are limiting this pathway. The availability and cost of the feedstocks are frequently constrained, and some of them are environmentally hazardous.[47] Also, inadequate knowledge of the conversion process's mechanism is one of the biggest barriers to the HEFA pathway.

Gasification and Fischer-Tropsch Process (GFT)

The GFT conversion pathway involves both gasification, a thermochemical process that converts biogenic materials into syngas, and Fischer-Tropsch (FT) synthesis. The latter is a technology that converts the syngas to liquid SAF via catalytic cracking processes. The major processes in the GFT route are the gasification of biomass into hydrocarbons, the conversion of the hydrocarbons into liquid products by reaction with hydrogen in the presence of a catalyst, and the refining/upgrading of the liquid hydrocarbons into jet fuel as shown in Figure 3.[48]

During gasification, the biomass is treated at high temperatures (800–1000°C) in partial oxidation conditions, yielding syngas mostly composed of H_2 (6–55%), CO (8–53%), and methane gas (CH_4) (2–26%).[49] The gasifying agent, catalyst, operating pressure, equivalence ratio (E/R), and reactor conditions are a few other elements that influence the gasification process and the components and yield of the syngas produced. The pre-treatment of biomass, gasification, gas cleaning, acid gas removal, FT synthesis, and liquid fuel refining are the six operations that make up the GFT production pathway as displayed in Figure 6. To remove impurities from the syngas, such as particulates, ash, tar, and trace metals, a clean-up stage is frequently used in conjunction with the gasifier before it is introduced into an acid gas removal system to remove the acid gas content (H_2S and CO_2). As the H_2 to CO ratio is crucial for FT synthesis, the syngas is sent to the gas conditioning system to be adjusted by the water-gas reaction. Although gas cleaning and acid gas removal processes might not be required if hydrothermal gasification is adopted in place of conventional gasification.[49] Detailed information about the unique feature of supercritical water used during hydrothermal gasification as well as the reaction mechanism and catalysts required can be found elsewhere.[50]

FT synthesis is a pathway that converts the syngas to liquid fuels via catalytic cracking processes. The primary reactions throughout the FT synthesis process are the formation of alkanes and alkenes as shown in Equations 1 and 2.[51]

$$nCO + (2n + 1)\,H_2 \leftrightarrow C_nH_{2n+2} + nH_2O \qquad \text{(Equation 1)}$$

$$nCO + 2nH_2 \leftrightarrow C_nH_{2n} + nH_2O \qquad \text{(Equation 2)}$$

Controlling the product composition as well as refining synthetic oil to attain SAF range is a major challenge during the FT process. Catalysts that are used for FT synthesis include cobalt (Co), iron (Fe),

Table 4. Overview of different feedstock and catalysts used for SAF production via HEFA

Feedstock	Catalysts	Optimum operating conditions	Key findings	Reference
Hydrolyzed macauba almond fatty acid	Pd/charcoal	Temp: 300°C Pressure: 10 bars of H_2, and 700 rpm stirring for 5 h	• Hydrocarbon range of $C_{10} - C_{25}$ was obtained. • Oxygen removal was improved when the free fatty acids contain long carbon chains. • Optimal hydrocarbon content of 85% w/w was obtained.	Silva et al.[96]
Stearic acid	Pd/beta zeolite	Temp:270°C, Pressure: 15 bar N_2pressure and 300 rpm stirring for 1 h	• Hydrocarbon range of C_{12} – C18 was obtained • The proportion of hydrocarbons in the jet-fuel range was 69.3%	Choi et al.[97]
Soybean oil	Pt/Al_2O_3/SAPO-11	Temp: 370°C, Pressure:30 bar and 200 N ml/min H_2flow. LHSV of 1 h^{-1}	• SAF with aromatic content greater than 12% was obtained. • A specific amount of poly-unsaturation of the fatty acids is required to produce relatively high aromatics content.	Rabaev et al.[98]
Castor oil	Ni supported on acidic zeolites.	Temp:300°C Pressure:3 MPa, with a H_2 flow rate of 160 mL min^{-1} at atmospheric pressure.	• SAF yield of 91.6 wt % was obtained at optimal conditions. • Various fuel ranges of alkanes are produced by varying the degree of hydrodeoxygenation (HDO) and hydrocracking.	Liu et al.[99]
Oleic acid	Fe-Cu/SiO_2-Al_2O_3	Temp: 320°C under H_2pressure of 2.1 MPa and reaction time of 8 h	• Optimal SAF yield and range hydrocarbons selectivity of 76.8% and 71.7% respectively were obtained.	Ayandiran et al.[100]
Oleic acid	Monometallic Cu/ SiO_2-Al_2O_3	Temp: 340°C 2.07 MPa H_2pressure and reaction time of 8 h	• Optimal jet-fuel range hydrocarbons yield of 59.5% and 73.6% selectivity were reported respectively. • The improved catalytic activity is attributed to the mild Brønsted acid sites present in this catalyst.	Ayandiran et al.[101]
Fast pyrolysis-derived oil	Ru/Activated carbon	Temp:350°C, 200 bar H_2pressure, 5 wt % catalyst, 1300 rpm stirring for 4 h	• Catalysts reduced the acid and water content of the oil • About 60% SAF yield and 90 wt % deoxygenation efficiency was obtained. • Higher heating value of oil increased to 40 MJ/kg.	Wildschut et al.[102]
Jatropha oil	PtPd/Al_2O_3	Temp: 390°C, 3 MPa and 2 h^{-1} feed in a fixed-bed reactor	• Products mostly comprises of C_{15-18}*n*-paraffins, and small amounts of C_{4-14} alkanes and C_{15-18} *iso*-paraffins. • Little quantities of cycloalkanes and C_{15-18}aromatics present. • SAF yield of 81.2% obtained at optimum conditions.	Gong et al.[103]
Palm kernel oil	Ni-MoS_2/γ-Al_2O_3	Temp: 330°C, H_2 pressure of 50 bar, LHSV of 1 h^{-1} and H_2/oil ratio of 1000 N (cm^3 cm^{-3}).	• SAF optimum selectivity of 58% was obtained. • Fuel hydrocarbon ranges from $C_{10\text{-}12}$	Itthibenchapong et al.[104]
n-hexadecane	Pt(1)Mo(8)/ AlSBA-15	Temp: 360°C, 5 MPa hydrogen pressure,	• Hydrocarbon fuels with composition ≤ C_9 and C10–C_{15} were obtained. • Optimum SAF yield of 91.2%.	Jaroszewska et al.[105]

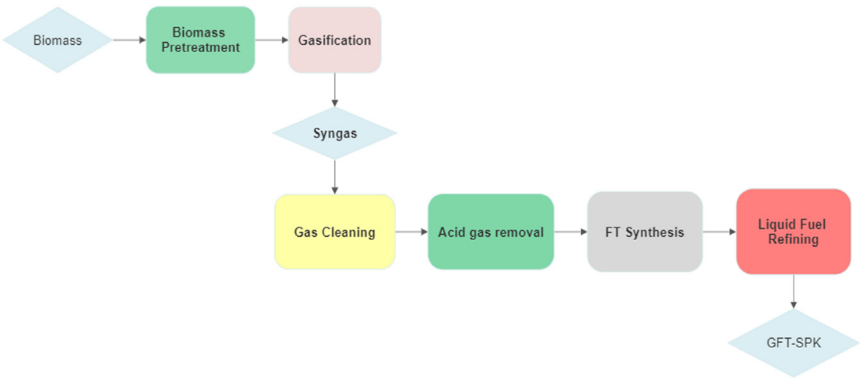

Figure 6. GFT Production pathway

nickel (Ni), and ruthenium (Ru) to attain the desired product yield, composition and selectivity. To alter the activity and selectivity of the catalysts, promoters such as alkali metals, transition metals, and alkaline earth metals can be introduced.[52] Linear waxes are created using low-temperature FT synthesis (200–240 °C), whereas gasoline and olefins are produced using high-temperature FT synthesis (300–350 °C).[53] A previous study showed that the activity of FT catalysts for hydrocarbon fuel production decreases as follows: Fe > Co > Ni > Ru when there is no support.[51] In contrast, the use of alumina support for each active metal influenced the activity as follows: Ru > Fe > Ni > Co. It should be mentioned that Ru catalysts are less desirable because of their high cost and low availability. Moreover, Ni is cheaper but susceptible to coke formation. Therefore, Co and Fe are the preferred catalysts for the FT process.

Numerous researchers have paid attention to the GFT pathway because the hydrocarbon fuels produced are similar to conventional fuels.[51–53] Li et al.[54] life cycle assessment study showed that the implementation of GFT pathway could lead to a significant reduction in process economics and CO_2 emissions.[54,55] also designed a process for the gasification and Fischer-Tropsch synthesis of biomass and plastics into biojet fuel. The calorific value, pour point, density, flammability, and kinetic viscosity of the biojet fuel satisfied the ASTM D7566 standard whereas the process produced about 1697.45 kg/h of SAF. Pereira, MacLean [87] also reported that the FT pathway has high financial risks and the highest fixed capital costs in comparison to any other jet fuel production pathway. Several experimental studies related to the use of single and bifunctional catalysts have also been reported in the literature.[56–58]

When used in airplanes, FT fuel has few pollutants, is free of sulfur and nitrogen, has a high specific energy content, and is thermally stable. The fuel's disadvantages are its low aromatic concentration and low energy density, which results in low efficiency and high production costs for the process.[59] The most complicated stage is producing syngas which must have a high carbon and hydrogen concentration and be devoid of tar, chlorine, and sulfur for it to be suitable for FT synthesis.[53,58] Although biomass gasification and Fischer-Tropsch synthesis are technically feasible for producing biofuels, the large scale required for a financially viable technology will necessitate vast quantities of biomass and high investment costs.

Alcohol to SAF (ATJ)

The alcohol-to-jet (ATJ) pathway involves converting biomass into alcohol and then processing the alcohol into long-chain hydrocarbons (SPK) that are used as aviation fuel as shown in Figure 4. In essence, alcohol produced by the biochemical fermentation and thermochemical conversion of lignocellulosic carbohydrates and starch is catalytically upgraded to produce SPK.[60] These alcohol feedstocks are transformed into hydrocarbon fuel-blending components through dehydration, oligomerization, and hydroprocessing (Figure 7).

There are various processes available for converting biomass into alcohol. Starches can be hydrolyzed directly to yield sugar, and sugars can be fermented directly to alcohols using yeasts or microorganisms. Meanwhile, lignocellulosic biomass can be hydrolyzed before fermenting, and/or hydrolyzed before using any other thermochemical conversion procedures capable of producing the desired alcohol. In essence, other feedstocks are less complicated than lignocellulosic biomasses because of their recalcitrant nature.[61]

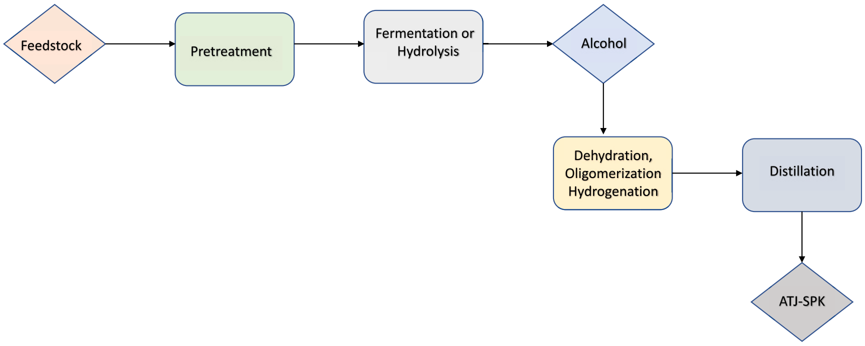

Figure 7. Schematics of the reaction pathway for SAF production via ATJ

It should be emphasized that first-generation edible feedstocks are not preferable for alcohol production because of the food versus fuel competition. Future advances in conversion technologies are expected to enable alcohol production without the use of food sources. Figure 8 outlines the conversion of biomass to alcohols which is used SAF via other biomass resources.

Lower alcohols (C_1-C_3) can be produced from biomass feedstock via several pathways such as FT synthesis,[63] gasification,[64] thermochemistry or fermentation.[65]

Given the various processes that can be used to produce alcohol from biomass, numerous types of feedstocks can be used in the ATJ pathway. These feedstocks may include agricultural residues, sawdust, sugarcane, forest residues, sugar beet, straw, switchgrass, corn grains, and many more. Ethanol has been produced by fermenting simple sugars (sugar, starch crops) and complex sugars (lignocellulosic biomass, microalgae), whereas isobutanol has been produced through biological fermentation employing microbial strains and chemical synthesis procedures such as carbonylation Alcohol is dehydrated with the use of catalysts to synthesize olefins. Oligomerization processes convert short-chain olefins to long-chain olefins and hydrocarbon fuels are produced by deoxygenating and hydrogenating these olefins during the hydrotreatment process.[62,66]

ATJ fuels produce less particulate matter and sulfur oxides and can decrease CO_2 life cycle emissions at least by 80%.[67] ATJ have higher MFSPs, because of lower conversion yields and the high cost of feedstock extraction and fermentation. The MFSP for ATJ-SPK is currently higher than that of Jet A-1 and GFT-SPK fuels despite better performance in terms of carbon utilization and thermal efficiency. A techno-economic and environmental analysis was carried out by[68] on the FT and ATJ paths for making biofuels from MSW. Their research showed that creating biojet fuel from MSW has greater costs than producing standard jet fuel. However, FT and ATJ reduce life cycle GHG emissions by 63% and 41%, respectively, when compared. They both also show a 93% rise in net present value as a result of reduced GHG emissions.

The ATJ conversion pathway's economic success is strongly contingent on technological flexibility.[69] conducted a techno-economic analysis of the ATJ production pathway using three different biomass feedstocks (sugarcane, switchgrass, and maize grain) and discovered that sugarcane is the most cost-effective and environmentally sustainable feedstock for this pathway. Romero-Izquierdo also employed bioethanol derived from lignocellulosic wastes to model and simulate a basic ATJ production process.[70] To reduce the quantity of energy required and the impact on the environment, process intensification and energy integration technologies were applied to the separation process and the overall process, respectively. Their findings show that the separation process intensification allows for a 5.31% reduction in energy requirements. The intensified process's energy integration also resulted in a 34.75% and 30.32% reduction in heating and cooling requirements, as well as a 4.83% and 4.99% reduction in total annual costs and CO_2 emissions.

Few companies are already commercializing the ATJ pathway for the production of hydrocarbon fuels. Using an established fermentation process, Gevo Inc. developed and produced Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK) from isobutanol.[64,65] This fuel has been examined, certified to meet the ASTM D7566 standard, and permitted to be blended with Jet A or Jet A-1 up to 50%.[71] Another ASTM-certified ATJ method, the production of bio-jet fuel from ethanol has been utilized by Byogy Renewables to produce jet fuel.[65] This ethanol is

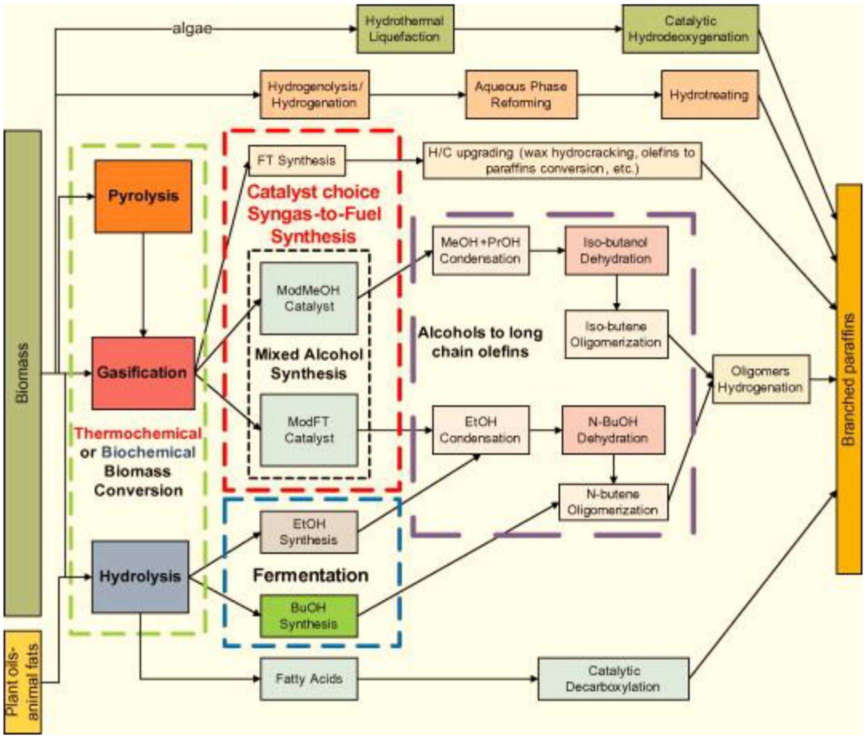

Figure 8. Overview of several pathways that are used to convert biomass to alcohols

Reproduced from Atsonios et al.[62] with permission from Elsevier.

usually produced via biochemical fermentation and the long-chain hydrocarbons are derived from ethanol dehydration before it is synthesized catalytically to produce hydrocarbon fuels.[65]

Direct sugar to hydrocarbons (DSHC)

The direct sugar to hydrocarbons (DSHC) is a biochemical production pathway for producing SAF. The DSHC is a conversion pathway for directly converting sugars into hydrocarbon fuels. In contrast to the alcohol-to-jet pathway, which requires an alcohol intermediate, the DSHC pathway directly converts the sugar feedstock without the need for an intermediate.[72] The fuels produced from this conversion pathway are also known as synthesized iso-paraffins (SIP). SIP has a distinct specification because of its unique elemental composition, which contains at least 97 wt % farnesene.[72] It should be emphasized that farnesene is a hydrocarbon molecule that serves as a potential substitute for petrochemicals in several products such as diesel and SAF.

The feedstocks used during the DSHC pathway are identical to the feedstock used to produce ethanol including sugar cane, beets, and maize. After appropriate pre-treatment, lignocellulosic biomass can also be used as feedstock for the DSHC conversion pathway.[73] Process operations involved in the DSHC pathway include feedstock pre-treatment, enzymatic hydrolysis, hydrolysate refining, microbial conversion, product separation, and hydroprocessing. Generally, the DSHC pathway consists of four major steps as shown in Figure 9. These steps include pre-treatment, which separates sugars from lignin; fermentation or enzymatic hydrolysis, which converts sugar into farnesene; recovery of farnesene through solid-liquid separation; and hydroprocessing, which converts farnesene into farnesene ($C_{15}H_{32}$), the biojet fuel.

Lignocellulosic or starch-based sugars are fermented for the production of long-chain hydrocarbons. The fermentation process employs the use of microbes to directly metabolize the sugar which results in Farnese.[74] The farnesene is then further processed through technologies such as hydrocracking, isomerization, and finally distillation for the production of liquid fuels. Various factors influence the DSHC pathway, including the type of feedstock, fermentation technique, and microbes utilized.

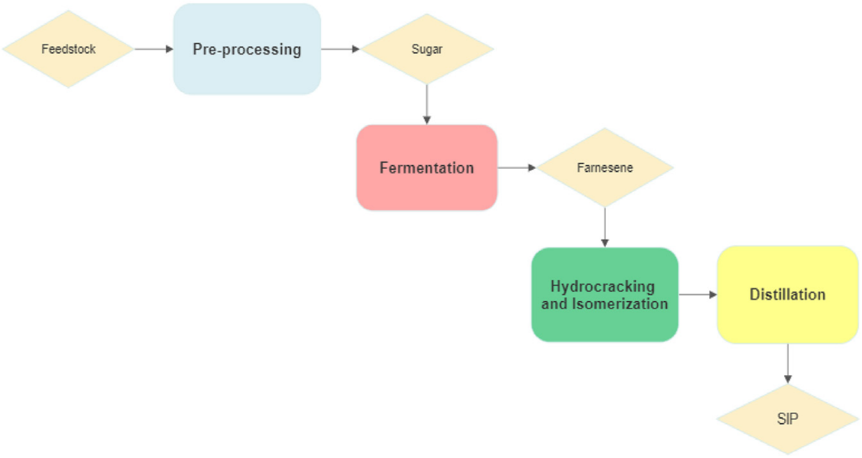

Figure 9. An overview of the DSHC Production pathway for SAF production

The hydrocarbon fuel produced from the hydrotreating of farnesene has been tested and certified by the ASTM to be blended with conventional jet fuels at a blending ratio of 10%. For a prospective blend of conventional and alternative fuels, Flora et al.[75] suggested a predictive computational tool that calculates their optimum blending ratios. For a variety of characteristics including flash point, density, net heat of combustion, viscosity, aromatic content, and cetane number, they implemented the hydrocarbon blending rule and because of SIP's viscosity, the blending ratio of Jet A and SIP was restricted to 22%.[75]

It has been determined that DSHC is more suited for producing high-value compounds than fuels. The low temperature of the fermentation results in low energy input and because of the fuel's inability to satisfy certain performance requirements, it is also restricted to a 10% blending rate.[76] Because of poorer conversion yields and the high capital cost of lignocellulosic sugar fermentation, fuels produced from the DSHC have a higher minimum fuel selling price (MFSP). Therefore, the DSHC pathway still requires a lot of improvement and is currently not economically feasible.[77]

Michailos[78] carried out a comprehensive sustainability assessment that encompassed the process design, life cycle assessment, and economic evaluation of the direct fermentation of glucose and xylose into jet fuel. The results showed a 26.5% energy efficiency and a poor yield of biofuel that has a negative impact on the economic and environmental performance of this pathway.[78] A biotechnology company, Amyris, is currently working on improving its fermentation technique to process complicated lignocellulosic sugar streams under close collaboration with the US National Advanced Biofuels Consortium. The direct biological conversion of sugar to fuel has also been commercialized by a company, LS9. The company has focused on developing a one-step fermentation technique that produces alkanes.[79]

Fast pyrolysis (FP)

FP is a thermochemical conversion process that involves the conversion of biomass into solid, liquid and gaseous products at moderate pyrolysis treatment temperatures (400–600°C), rapid heating rates of feedstock (>100 °C/min), combined with short residence times (0.5–2 s).[80] The liquid product from FP also known as bio-oil can be further upgraded into drop-in fuel. Bio-oil cannot be used as a drop-in fuel directly because of the presence of oxygenates and unsuited characteristics like thermal instabilities, corrosiveness, and low energy density.[81] The bio-oil, therefore, needs to be refined further to meet current SAF standards and be compatible with current aircraft systems.[82]

The FP pathway involves two major steps as shown in Figure 10: (1) The direct thermochemical conversion of biomass/waste to produce liquid product (bio-oil), and (2) the further refining of the bio-oil to SAF components (hydrocarbons) that satisfy the ASTM standard and can be used directly or blended with other jet fuels like FT-SPK and HEFA fuels.[83]

Lignocellulosic biomass such as sugarcane bagasse, straw, wood residues, etc., have been utilized as feedstock for the production of SAF via FP by several researchers. Wang et al. utilized the bio-oil produced from

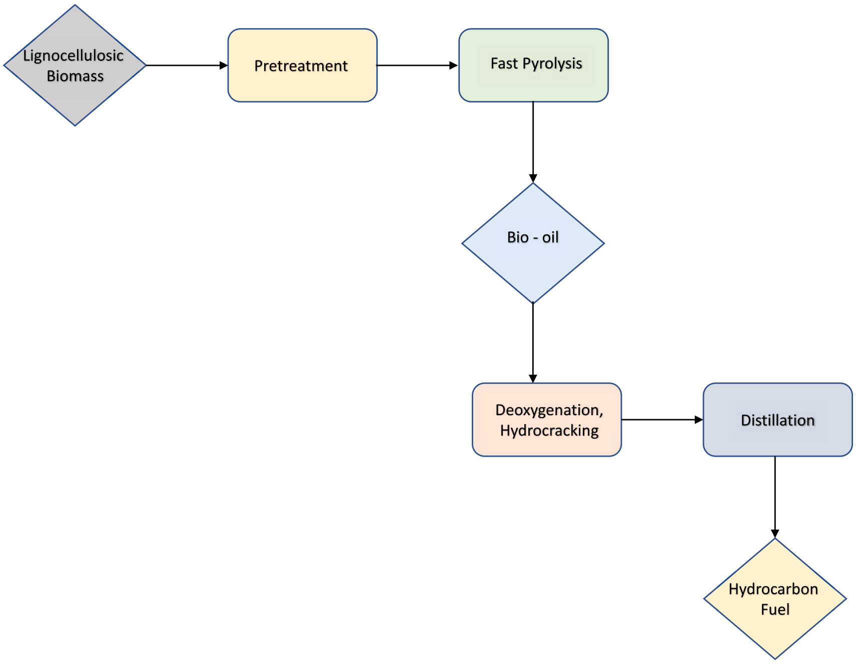

Figure 10. An overview of the fast pyrolysis pathway for the production of SAF

the pyrolysis of straw stalk to produce C_8-C_{15} hydrocarbons that satisfied the ASTM specifications of SAF.[84] The authors proposed three key reactions involved in the conversion of lignocellulosic materials to SAF; (1) the catalytic cracking of bio-oil into low-carbon aromatics and lighter olefins in the presence of HZSM-5 catalyst (2) the alkylation of lighter olefins and low-carbon aromatics to C_8–C_{15} aromatic hydrocarbons with ionic liquid catalyst of [bmim]Cl–2AlCl$_3$ under atmospheric pressure and low temperature (3) the production of C_8–C_{15} cyclic alkanes by the hydrogenation of C_8–C_{15} aromatics with 5% Pd/AC catalyst.[84]

Chen et al. also used rice husk, an agricultural waste as a feedstock for FP to produce SAF.[85] Three sequential processes were adopted for the production of SAF: FP in a fluidized bed reactor, hydro-processing and hydro-isomerization/cracking with NiAg/SAPO-11 catalyst. The final products contained key compounds such as iso- and cyclo-alkanes as well as aromatic compounds. Galadima et al. provide a comprehensive review of previous studies related to the conversion of biogenic waste into SAF via the FP pathway.[86]

In essence, different types of biogenic feedstocks can be utilized for the FP process for bio-oil production and subsequent hydro-processing to SAF. It should be mentioned that pyrolysis technologies perform best with feedstocks that are reasonably low moisture content (<10% moisture content). As a result, wet feedstocks must be dried, and for particularly wet feedstocks, such as algae, the pyrolysis process may not be practical due to the extremely high energy requirements for moisture removal. A few researchers have also started exploring hydrothermal processes in place of fast pyrolysis for liquid fuel production and subsequent hydro-processing to SAF.

Van dyk et al. evaluated the ability of three direct thermochemical liquefaction processes-fast pyrolysis (FP), catalytic fast pyrolysis (CFP), and hydrothermal liquefaction (HTL)- to generate bio-oil, which could subsequently be hydrotreated into SAF.[87] The biocrude produced from the three thermochemical processes has varying physicochemical properties. However, when each biocrude was upgraded to SAF and compared with ASTM standards the properties were not up to the specifications. Although, the authors suggested that the noticeable differences could be minimized through further optimization of the hydrotreating and additional polishing steps.[87]

COMPARATIVE EVALUATION OF DIFFERENT SAF PRODUCTION PATHWAYS

Table 5 compares the pros and cons of different SAF production pathways considered in this study. It should be mentioned that other production pathways such as co-processing, hydrothermal liquefaction,

Table 5. Advantages and limitations of different SAF production pathways considered in this study

S/N	Technologies	Advantages	Limitations
1	Hydro processed esters and Fatty acids (HEFA)	1. Reaction is exothermic, thus, the energy released from the first reaction can lead to lower energy cost for the entire process leading to a positive economic and environmental impact. 2. SAF from HEFA has been proven to have characteristics that outperform conventional Jet fuels. SAF ignites faster and has a greater heating value (44 MJ/kg) than Jet A fuels. 3. It is significantly less prone to oxidation when compared to FAME. 4. The type of feedstock utilized has been shown to have a significant impact on the quality of FAME (Fatty Acid Methyl Ester), whereas the quality of fuel made from HEFA is independent of the feedstock utilized. 5. A blend of Jet A-1 with 35% SAF via HEFA produces less reactive soot when aircraft are on the ground or during take-off. 6. Has high commercial maturity with several plants at pilot scale and demonstration (with few commercial flights utilizing SAF via HEFA).	1. Availability of resources/feedstock is still limited relative to the projected industrial demand. HVO (Hydrotreated Vegetable Oil) production is much more ideal for diesel production than jet fuels. 2. A large amount of hydrogen is required for the cracking of triglyceride (about 10–15 mol per mole of triglyceride). Steam reforming is a common technique of producing hydrogen, accounting for up to 50% of hydrogen demand worldwide. There is a need for an alternative source of hydrogen. 3. The usage of hydrogen may be lessened through process optimization, but not below the stoichiometric requirement.
2	Gasification and Fischer Tropsch Process (GFT)	1. Compared to HEFA, GFT is more attractive due to the higher feedstock options and varieties that do not have a food vs. fuel dilemma. 2. High energy efficiency of SAF via GFT (77%) is more than that of natural gas based (68%) or coal-based (64%) fuel. 3. SAF via GFT has aromatic content within the permitted range and thus can be used as stand-alone fuel without blending. 4. SAF via GFT is sulphur-free leading to less emission during engine combustion. 5. From an economic perspective of SAF via GTF as stand-alone, it increases the construction feasibility of facilities as the ratio of products can be easily altered for profit maximization.	1. Much progress is based on coal and natural gas as feedstock as CTL is still a relatively expensive technology. 2. Implementation of production in high volume via GFT is unlikely in the near future.

(*Continued on next page*)

Table 5. ***Continued***

S/N	Technologies	Advantages	Limitations
3	Alcohol to Jet (ATJ)	1. Quality SAF produced with permissible aromatic content to be used in existing engines without concerns. 2. Process can use municipal waste, and industrial waste gases to augment feedstock requirement. 3. Well-established structure for ethanol production, thus, the aviation industry can take advantage of this structure to construct an 'upgrading' facility near to ethanol factory, thus, decreasing transportation cost. 4. Butanol has a higher caloric value of 29.2 MJ/L compared to ethanol which is 19.6 MJ/L but has lower vaporization heat and is less corrosive; thus, making it a more attractive feedstock. It could decrease the cost of production due to lower temperature and pressure required during the dehydration of alcohol and oligomerization process to yield higher jet fuels. 5. Newly developed technologies for fermentation could make higher alcohol (than ethanol) production more competitive in terms of cost in the future.	1. Issues with feedstock availability. 2. Low yield in ATJ associated with the production of bioethanol. 3. Long processing routes involving sugarcane and involving starch crops, there is a long production cycle. 4. High production costs and limited research and development in this area.
4	Direct sugar to hydrocarbon (DSHC)	1. It is not energy intensive compared to other technologies as it is a biochemical process. 2. SAF from DSHC is certified to blend unto 10% of fuel for commercial flights.	1. Technological readiness level is still low; thus, the technology requires more research and development to be competitive. 2. It is not economically feasible in the near future.
5	Fast Pyrolysis (FP)	1. On a small scale, the technology requires low capital costs and has good energy efficiency when likened to other processes. 2. Second-generation (2G) bio-oil feedstocks and waste materials can be utilized. 3. Transportability and Storability of liquid fuels.	1. Low quality and stability of produced SAF. 2. Technological readiness level is still low; thus, the technology requires more research and development to be competitive. 3. For large-scale production, it is not economically feasible in the near future.

Table 6. A detailed comparison of each decision criterion used for the MCDA

Categories	Criteria	SAF production pathways				
		ATJ	GFT	HEFA	DSHC	FP
Economic	MSP of SAF (USD/L)	0.75	0.65	0.62	2.21	0.85
	CAPEX (USD/L)	0.73	0.64	0.33	0.61	0.62
	OPEX (USD/L)	0.50	0.24	0.17	1.06	0.61
	Cost of production	0.55	0.37	0.36	1.54	1.53
Environmental	GHG Emission (gCO_2eq/MJ)	39.70	12.20	47.40	18.70	8.30
	Global warming potential (gCO_2eq/MJ)	0.000	0.000	0.001	0.000	0.000
Technology	Energy efficiency (%)	0.56	0.22	0.83	0.46	0.49
	Maturity	6.00	5.00	8.00	7.00	6.00
	Reliability	7.00	6.00	8.00	7.00	7.00

Data obtained from refs.[5,17,88,90–93]

aqueous phase reforming and aerobic fermentation are outside the scope of the present study. However, readers are referred to excellent reviews by[65,88] and.[86] Tanzil et al.[89] considered the techno-economic analysis of six different pathways for producing SAF and concluded that the HEFA is the most competitive technology for producing SAF because of the low conversion costs of triglycerides and high product yield. However, a detailed comparison of different production pathways is still missing. Therefore, based on the literature overview an in-depth comparison of each decision criterion is presented in Table 6. It should be mentioned that the maturity and reliability criteria were estimated based on an overall scale of 10.

Numbers were assigned according to the authors' experience and findings from the literature overview. The higher the number the more mature and reliable the technology is.

The values presented in Table 6 are known as the decision value. The criteria in Table 6 are grouped into beneficial and non-beneficial. The latter represents the criteria whose lower value is desired. For instance, it is desirable to have lower MSP, CAPEX, OPEX, Cost of production, GHG Emissions and Global warming potential. In contrast, criteria such as Maturity, reliability and energy efficiency are beneficial criteria because higher values are desired. Normalization is performed to ensure that all the criteria are comparable. The performance value in each individual cell is divided by the maximum values (for beneficial criteria) and minimum value (for non-beneficial criteria). Since all criteria are important, an equal weight scale was assigned to the criteria and used for appraising the weighted normalized decision matrix as shown in Table 7. The ranking of each SAF pathway is also presented in Table 7. It should be mentioned that score 1 in the ranking denotes the best while score 5 denotes the worst SAF pathways based on the MCDS results. Detailed information about the computation of the MCDS can be found in the supplementary spreadsheet.

Based on the MCDS results presented in Table 7 the ranking shows that the considered SAF production pathways are in the order of HEFA > DSHC> FP> ATJ > GFT. The ranking is based on the assumption that all criteria were assigned the same weight fraction. This indicates that all criteria were equally important. However, if the MSP and GHG Emissions were assigned 30% weights while the others were assigned equally distributed 40% weight the SAF production pathways are in the following order: DHSC> HEFA> ATJ> FP> GFT (Table 8). Regardless of the priority assigned to each criterion GFT ranks the least among the SAF pathways scoring 1.01. Also, HEFA and DSHC are considered the two most promising technology regardless of the priority assigned to each criterion.

LIMITATIONS OF THE STUDY

The primary focus of the study as well as the MCDS is on five key technologies including HEFA, DSHC, FP, ATJ and GFT. It should be mentioned that although most of the technologies were selected based on their level of maturity and research interest, one of them (DSHC) is not certified for commercial use.[94] Moreover,

Table 7. The weighted normalized decision matrix and the ranking of each scenario

Categories	Criteria	ATJ	GFT	HEFA	DSHC	FP
Economic	MSP of SAF (USD/L)	0.13	0.12	0.11	0.40	0.15
	CAPEX (USD/L)	0.25	0.22	0.11	0.21	0.21
	OPEX (USD/L)	0.33	0.16	0.11	0.69	0.40
	Cost of production	0.17	0.11	0.11	0.48	0.47
Environmental	GHG Emission (gCO_2eq/MJ)	0.36	0.11	0.43	0.17	0.08
	Global warming potential (gCO_2eq/MJ)	0.11	0.11	1.11	0.11	0.11
Technology	Energy efficiency (%)	0.07	0.03	0.11	0.06	0.07
	Maturity	0.08	0.07	0.11	0.10	0.08
	Reliability	0.10	0.08	0.11	0.10	0.10
Performance score		1.60	1.01	2.32	2.31	1.66
Ranking of each SAF production pathway		4	5	1	2	3

Note that the performance score was evaluated from the sum of each criterion. A score of 1 denotes the best and 5 the worst option. All criteria were assigned the same weight fraction.

the Fischer-Tropsch process itself is certified by ASTM International for the production of SAF, regardless of whether the syngas is derived from biomass gasification or from other sources. DSHC was selected because of the significant research interest in the technology resulting from its numerous advantages. Some of the advantages of DSHC include feedstock flexibility, improved carbon efficiency, and the immediate ability to be used directly in existing engines and fuel distribution infrastructure without major modifications, making their implementation easier.[94,95]

Other certified SAF production technologies such as co–processing are not considered in this study. Although co–processing is advantageous because of its ability to use an existing petroleum refinery infrastructure, it was not considered because the technology still requires blending with petroleum-based feedstocks.

Although most of the selected technologies implicitly focus on biogenic feedstock and could potentially omit the use of renewable feedstock of non-biological origin, some technologies such as ATJ and GFT that were selected could also use feedstock with non-biological origin. Owing to the limited availability of biogenic feedstock, the non-biogenic feedstock will play a central role in the defossilation of the aviation industry, especially in the long term.

Table 8. The weighted normalized decision matrix and the ranking of each scenario

Categories	Criteria	ATJ	GFT	HEFA	DSHC	FP
Economic	MSP of SAF (USD/L)	0.4	0.3	0.3	1.1	0.4
	CAPEX (USD/L)	0.1	0.1	0.1	0.1	0.1
	OPEX (USD/L)	0.2	0.1	0.1	0.4	0.2
	Cost of production	0.1	0.1	0.1	0.2	0.2
Environmental	GHG Emission (gCO_2eq/MJ)	1.0	0.3	1.2	0.5	0.2
	Global warming potential (gCO_2eq/MJ)	0.1	0.1	0.6	0.1	0.1
Technology	Energy efficiency (%)	0.0	0.0	0.1	0.0	0.0
	Maturity	0.0	0.0	0.1	0.1	0.0
	Reliability	0.1	0.0	0.1	0.1	0.1
Performance score		1.9	1.0	2.4	2.4	1.4
Ranking of each SAF production pathways		3	5	2	1	4

MSP and GHG emissions are assigned 30% weighted average each. Other criteria are equally distributed at 5.71%.

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The present work is the first of its kind to provide an in-depth literature overview of five different sustainable aviation fuel (SAF) production pathways including hydroprocessed esters and Fatty acids (HEFA), gasification and Fischer-Tropsch Process (GFT), Alcohol to Jet (ATJ), Direct sugar to hydrocarbon (DSHC) and fast pyrolysis (FP). The technologies were selected based on their level of maturity and research interest. The status and research progress of each of the SAF production pathways were meticulously described. Past literature related to each pathway were described in terms of the research procedure, experimental findings, and future progress. Also, the properties of SAF and chemical composition were outlined in detail. Finally, a multi-criteria decision support framework (MCDS) was implemented for the first time and used to effectively rank the SAF pathways in order of importance. The MCDS was performed based on three key criteria related to economic, environmental, and technological importance.

The results of the MCDS show that the considered SAF production pathways are important in the order of HEFA > DSHC> FP> ATJ > GFT. This is based on the assumptions that the economic, technological, and environmental criteria have the same weighed factor (i.e., priority is assigned to all the criteria at the same time). Regardless of the weighted factor the GFT pathways ranked last in the MCDS. Therefore, future research studies should focus on effective heat integration in the GFT system. Feedstock selection is also another issue that needs to be addressed for all the production pathways. Although the process can handle a wide range of feedstock, drying feedstock with high moisture content is expensive and contributes to the increased process economics. Therefore, future research direction should explore the integration of hydrothermal gasification with FT synthesis. Replacing conventional gasification with hydrothermal gasification could eliminate the drying steps and reduce the process economics. Moreover, the key barrier related to the large-scale implementation of SAF is cost-effectiveness when compared to conventional aviation fuel. Therefore, different integrated technological advancements should be explored to help minimize the MSP of aviation fuel.

The MCDS proposed in this study indicates that HEFA is the highest-ranked and preferable pathway. Although further research direction is still required in catalyst development and feedstock selection. The AJF pathways were also ranked low, therefore research direction in this area could concentrate on replacing edible feedstock with non–edible biogenic materials like lignocellulosic biomass or energy crops. A polygeneration system whereby several value-added chemicals are produced alongside SAF could also help improve the process economics. In addition to the technological, environmental and economic evaluation, Policy changes such as introducing incentives and penalties as well as supply chain issues should also be considered. Government should provide policies that encourage the adoption and implementation of new SAF technologies. This would only be possible through an effective multi-stakeholder collaboration including the biofuel companies, universities and national laboratories, airports, environmental professionals, local, federal, and state governments as well as the airline companies and aircraft manufacturers.

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AUTHOR CONTRIBUTIONS

J.A.O.: Conceptualization, methodology, writing, revision, and supervision. D.A.: Writing and revision, methodology, and conceptualization. M.E.T.: Writing and revision, methodology, conceptualization. P.U.O.: Writing, revision, and supervision. E.I.E.: Writing, revision, and supervision .C.C.O.: Writing, revision. F.G.: Writing, revision, and supervision. B.O.: Writing, revision, and supervision.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse and equitable conduct of research. One or more of the authors of this paper self-identifies as an underrepresented ethnic minority in their field of research or within their geographical location. One or more of the authors of this paper self-identifies as a gender minority in their field of research.

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