Global Biorenewable Development Strategies for Sustainable Aviation Fuel Production

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Abstract

Over the coming years, the world is projected to witness an upsurge in "drop-in" aviation biofuel production as part of the renewable energy and bioeconomy developments. This paper presents a comprehensive review of the current status of biojet fuel development and uptake in global commercial aviation industry, including state-of-the-art certified technologies (i.e. Fischer-Tropsch (FT); hydroprocessed esters and fatty acids (HEFA); alcohol-to-jet (ATJ); and hydroprocessing of fermented sugars (HFS)); potential feedstock that can be deployed; a comparison of techno-economic and environmental performances of biojet fuel production routes; airlines' commitment in promoting higher biofuel uptake; and global initiatives and policies. This review shows that the HEFA route using oil-based crops is best performing in terms of lowest production cost and greenhouse gas emissions, however it is in competition with the existing road transport biofuel market. Lignocellulosic biomass and waste feedstock should be promoted in view of replacing food/feed crops which have high indirect land use change emissions. Therefore, further improvement should be focused on FT, ATJ and HFS routes to enhance the cost effectiveness of biojet fuel production and promote commercialisation of these technologies. The selection of feedstock and technologies for SAF production should be justified based on production cost and environmental footprint, while avoiding competition with the existing road transport biofuel market. The shortcomings in the SAF policies such as blending mandate and multiplier in RED II should be addressed to reduce the negative impacts of feedstock competition between the road and aviation biofuel sectors and to meet the decarbonisation targets.

Keywords: Decarbonisation; Net zero; Fischer-Tropsch; Techno-economic; Organic waste; Biofuel.

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List of Abbreviations

ABE	Acetone-butanol-ethanol
APR	Aqueous phase reforming
ASTM	American Society for Testing and Materials
ATAG	Air Transport Action Group
ATJ	Alcohol-to-jet
ATJ-SPK	Alcohol-to-jet synthetic paraffinic kerosene
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DCO	Decarboxylation
DEF STAN	United Kingdom Ministry of Defence, Defence Standard
DSHC	Direct sugars-to-hydrocarbon
EU ETS	European Union Emission Trading Scheme
FFA	Free fatty acids
FT	Fischer-Tropsch
FT-SPK	Fischer-Tropsch synthetic paraffinic kerosene
FT-SPK/A	Fischer-Tropsch synthetic paraffinic kerosene with aromatics
GHG	Greenhouse gas
HDCJ	Hydrotreated depolymerised cellulosic jet
HDO	Hydrodeoxygenation
HEFA	Hydroprocessed esters and fatty acids
HFS	Hydroprocessing of fermented sugars
HFS-SIP	Hydroprocessing of fermented sugars – synthetic iso-paraffins
HTL	Hydrothermal liquefaction
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
ILUC	Indirect land use change
LCFS	Low Carbon Fuel Standard
LPG	Liquefied petroleum gas
MFSP	Minimum fuel selling price
MSW	Municipal solid waste

MOGD	Mobil's olefins-to-gasoline/distillate
MTO	Methanol-to-olefins
RED	Renewable Energy Directive
RIN	Renewable Identification Number
RFS	Renewable Fuel Standard
SAF	Sustainable aviation fuel
SIP	Synthetic iso-paraffins
SPK	Synthetic paraffinic kerosene
TRL	Technology readiness level

Contents

1. Introduction

As a major mode of transport, air travel supports the global economy as a means of fast conveyance of products and people for tourism, trade, commerce and other socio-economic activities. The International Air Transport Association (IATA) forecasted a growth of more than 100% in global passenger numbers over the next 20 years from 2016 (3.8 billion) to 2037 (8.2 billion) with an annual growth rate of 3.5% based on the expectation of population growth, better living standards and lower cost of air travel in the future [1]. However, the forecast has not taken into account the medium-to-long term impact of the Covid-19 pandemic outbreak of which it still remains unclear. The United States (889 million), China (611 million), Ireland (167.6 million), United Kingdom (165.4 million) and India (164 million) have among the highest number of passengers globally in 2018 [2]. According to the IATA's 20-year Air Passenger Forecast (2019-2039), the strongest growth of international passengers can be seen in the Asia Pacific (5.5%), followed by Middle East (4.4%) and Africa (4.4%), Latin America (3.4%), Europe (2.2%) and North America (2.2%) [3]. Aviation fuel is conventionally supplied from kerosene produced from crude oil. The annual global consumption of aviation fuel is approximately 300 Mt (2017) [4]. The rapid growth in the aviation industry suggests that rising global demand for aviation fuel is expected in the next few decades and it has been projected to rise more than double by 2050 [5]. These statistics indicate that developing countries generally have stronger potential growth in the aviation industry, and thus higher demand of aviation fuel will be needed. The utilisation of fossil fuel is not sustainable and the release of greenhouse gases (GHG) has caused severe environmental impact. Globally, 859 Mt (2017) of CO_2 were emitted from flights and the aviation industry contributed 2% to the global anthropogenic CO_2 emissions [6]. There is hence a pressing need worldwide in improving the uptake of sustainable aviation fuel (SAF) in order to tackle various challenges in environmental, social and economic aspects of the industry. SAF can be defined as alternative fuel to conventional fossil-based jet fuel that is produced from either biological or non-biological sources which are nondepletable, and must be certified under the ASTM jet fuel standards [7]. In this review, SAF refers to jet fuel produced from biological (organic) resources, termed “biojet fuel”.

Existing review articles [8-11] have mostly focused on the production technologies of biojet fuels. Gutiérrez-Antonio et al. [8] presented a review on the primary existing SAF production technologies, including hydroprocessing, thermochemical processing and alcohol-to-jet routes with insights into scientific (improvement in product yield) and technological (patent development) advances. The paper compared technical specifications and performances of these routes such as feedstock, operating conditions (pressure, temperature, catalysts) and yield of biojet fuel. Hydroprocessing technology has been found to be the most prevalent route for biojet fuel production and has been adopted by most of the test flights [8]. Whist significant scientific and technical details have been presented, this paper has not reviewed the techno-economic and environmental performances of different routes and the policy aspects relevant to promoting SAF are also missing. Wang and Tao [9] reviewed four major biojet fuel conversion routes, including alcohol-to-jet, oil-to-jet, gas-to-jet and sugar-to-jet. The review provided insights into process design, techno-economic performance and GHG emissions associated with these technologies that were obtained from various studies. Wei et al. [10] reviewed a number of existing and emerging biojet fuel production routes and discussed the economic and environmental performances of these technologies, however without an in-depth review of the policies. Hari et al. [11] provided high-level discussions on feedstock, production routes and the opportunities and challenges faced by various biojet fuel production technologies. These challenges include feedstock availability, compatibility of biojet fuels, environmental impacts and logistic issues [11]. This review has specifically presented the various industry commitments and collaboration but has not included any information related to techno-economic and environmental performance of the different routes. Both Wei et al. [10] and Hari et al. [11] suggested that the hydroprocessed esters and fatty acids (HEFA) and Fischer-Tropsch (FT) synthesis routes are particularly attractive in substituting conventional jet fuels. While all these review papers have constituted towards a wider understanding of the potential of biojet fuel production technologies, policy aspects have been either neglected or given limited considerations. An integrated review considering global initiatives and policies, technological development and performances (including economic and environmental performances) and potential feedstock in mitigating GHG emissions in aviation sector, is currently lacking. Moreover, SAF is a fast-evolving subject and it is inextricably intertwined with the road transport sector, hence an up-to-date and a more comprehensive review using a whole-system approach is highly needed. Consolidating this knowledge is vital in producing feasible strategies and guiding policies for promoting SAF and to meet the net zero emissions agenda by 2050.

This review aims to provide new insights into the SAF industry and generate strategic recommendations for future adoption of SAF feedstock, technology pathways and policies, analysed via a whole-system perspective. The objectives of this review article are to (i) provide structured information on the existing certified routes of valorising biomass and organic wastes (e.g. municipal solid waste, wood chips, agricultural and forestry residues) into biojet fuel; and (ii) identify the potential for future development and uptake of biojet fuel by examining the techno-economic and environmental performances of different technologies as well as the relevant policies for promoting SAF and reducing GHG emissions in the aviation sector. The potential feedstock for SAF considered in this review excludes the types of feedstock that compete with food/feed production. The review is structured as follows. First, the biojet fuel production routes and the fuel specifications to be used as 'drop-in' fuel in the aviation industry are outlined in section 2. This is followed by detailed discussions on selected SAF production technologies, focusing on the conversion processes, potential organic feedstock, techno-economic performance and environmental impact, presented in section 3. Insights into international policies in relation to addressing GHG emissions in the aviation sector and initiatives in promoting SAF are presented in section 4. The challenges associated with uptake of SAF are further discussed in section 5, incorporating recommendations for the next steps of SAF development. Lastly, key findings from the present review are drawn in section 6.

2. Biojet fuel production routes and specification

2.1 Biojet fuel production routes

At present, and for the next few decades, SAF are/will be represented by "drop-in" fuels which are compatible with current aircraft engines and airport infrastructures, i.e. no mechanical modification is needed. To date, six biojet fuel production routes, as follows, have been approved for blending with conventional jet fuel under ASTM D7566 [12].

- Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK),
- Fischer-Tropsch synthetic paraffinic kerosene with aromatics (FT-SPK/A),
- Hydroprocessed esters and fatty acids (HEFA),
- Hydroprocessing of fermented sugars – synthetic iso-paraffins (HFS-SIP),
- Alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK),
- Co-processing.

In addition to the certified routes, emerging routes to SAF production include hydrotreated depolymerised cellulosic jet (HDCJ) or also known as "pyrolysis-to-jet" [13], hydrothermal liquefaction (HTL) [14-16], aqueous phase reforming (APR) [17, 18] and aerobic fermentation of second generation sugars to hydrocarbons [19]. HDCJ, the controlled thermal decomposition of dry biomass at moderate temperatures to produce liquid bio-oil, gas and biochar, is a relatively more developed emerging route (awaiting ASTM certification) with a technology readiness level (TRL) of 5-6 [20]. On the other hand, HTL and upgrading as an emerging route (TRL 4) has shown increasing potential with the ability to process very wet biomass such as sewage sludge, manure and food waste in contrast to HDCJ which requires dry biomass [14]. However, HTL is currently limited to lab-scale requiring additional process optimisation and further development before reaching commercialisation [20]. Virent/Tesoro APR (high temperature reforming process using catalyst) as well as aerobic fermentation (using air at atmospheric pressure assisted by heterotrophic algae, yeast or bacteria) of second generation sugars have also been developed where sugars are converted via biochemical conversion to produce hydrocarbons, followed by upgrading processes to obtain jet fuel [20]. Both APR and aerobic fermentation are at TRL 4-5. These emerging routes are beyond the scope of this review. Nevertheless, a comparison of these emerging routes via strength, weakness, opportunity and threat (SWOT) analysis is given in Table A.1 in the Supplementary Materials.

2.2 Specification for biojet fuel

The requirements for fuel specification, quality, standards and safety for aviation fuel are particularly stringent. Conventional jet kerosene is primarily derived from the fractional distillation of crude oil, as a middle distillate between the cut points of gasoline and fuel oil. Crude oil produced from oil fields around the world are fed into the distillation units of oil refineries, where the crude is separated into various streams based on their boiling points. Jet kerosene is typically distilled from crude oil between the boiling point range of 150°C and 300°C, comprising C_8 to C_{16} hydrocarbon molecules [21]. The distillate stream undergoes further processing to remove contaminants, before being blended with other high-octane streams and additives to meet aviation fuel performance specifications. The yield of jet kerosene to a large extent depends on the quality and composition of the crude oil feedstock employed for oil refining and the competitive demand for other products in the market. Global refinery output was estimated at 4.1 Gt of products (2017 data), including ethane, liquefied petroleum gas (LPG), naphtha, gasoline, aviation fuel, middle distillates, fuel oil and other products, out of which aviation fuel accounted for 7.6%, estimated at 315 Mt [22]. Aviation fuel can be categorised into commercial and military jet fuels. The most commonly used jet fuel in commercial aviation is the kerosene-type (C_8-C_{16}), Jet A and Jet A-1, while JP-8 is mainly used in military aviation [23]. Naphtha-type (C_5-C_{15}) Jet B is less common compared to the kerosene-type jet fuels [23]. Table 1 summarises the jet fuel specifications for Jet A/Jet A-1, JP-8 and Jet B. The main difference between Jet A and Jet A-1 fuel is the freezing point. The specifications for ASTM D1655 and DEF STAN 91-91 are almost identical except the acidity level. Biojet fuel must meet the requirements outlined in ASTM D7566 [24] and must be blended with conventional jet fuel of at least 50% by volume to comply with the standards [25]. The blended biojet fuel that meets all the requirements in ASTM D7566 will also be recognised under ASTM D1655 [26] as well as DEF STAN 91-91 [27].

Table 1: Jet fuel specification.

Jet fuel type	**Kerosene**				**Naphtha**
	Jet A and/or Jet A-1			**JP-8**	**Jet B**
Specification	ASTM D1655	ASTM D7566	DEF STAN 91-91	MIL-DTL-83133J	ASTM D6615
Reference	[26]	[24]	[27]	[28]	[29]
Acidity, max (mg KOH g^{-1})	0.1	0.1	0.015	0.015	–
Aromatics, max (vol%)	25	25	25	25	25
Sulphur, max (wt%)	0.3	0.3	0.3	0.3	0.3
Distillation temperature (°C)					
10% recovery, max	205	205	205	205	–
20% recovery	–	–	–		90 (min) - 145 (max)
50% recovery	–	–	–	–	110 (min) -190 (max)
90% recovery	–	–	–	–	245
Final boiling point, max	300	300	300	300	–
Flash point, min (°C)	38	38	38	38	–
Freezing point, max (°C)	−40 (Jet A); −47 (Jet A-1)	−40 (Jet A); −47 (Jet A-1)	−47	−47	−50
Density at 15°C (kg m^{-3})	775 - 840	775 - 840	775 - 840	775 - 840	751 - 802
Viscosity at −20°C, max (cSt or mm^2 s^{-1})	8	8	8	8	–
Net heat of combustion, min (MJ kg^{-1})	42.8	42.8	42.8	42.8	42.8

Note:

ASTM: American Society for Testing and Materials

ASTM D1655: Standard Specification for Aviation Turbine Fuels [26]

ASTM D7566: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons [24]

ASTM D6615: Standard Specification for Jet B Wide-Cut Aviation Turbine Fuel [29]

DEF STAN: United Kingdom Ministry of Defence, Defence Standard

DEF STAN 91-91: Turbine Fuel, Kerosene Type, Jet A-1 [27]

MIL-DTL-83133H: US Department of Defense, Military Standard, Detail Specification – Turbine Fuel, Aviation and Kerosene Type JP-8(NATO F-34), NATO F-35, and JP-8+100 (NATO F-37) [28]

3. Technology assessment of certified biojet fuel production routes

This section comprises discussions on four certified biojet fuel production routes, i.e. Fischer-Tropsch (FT) synthesis (section 3.1); hydroprocessed esters and fatty acids (HEFA) (section 3.2); alcohol-to-jet (ATJ) (section 3.3); and hydroprocessing of fermented sugars (HFS) (section 3.4). This is followed by detailed evaluation of opportunities and barriers of various potential biomass and organic waste feedstock that can be adopted for SAF production (section 3.5). Lastly, the techno-economic performance and environmental impact of the four technologies are compared (section 3.6).

3.1 Fischer-Tropsch (FT) Synthesis

FT can be coupled with various biomass conversion processes such as gasification, pyrolysis and liquefaction to produce synthetic fuel. This review will focus on gasification-FT route since it is the certified and commercial route for jet fuel production. A detailed review of biomass to FT liquid fuel production technologies can be found in Ail and Dasappa [30]. Gasification converts carbonaceous materials such as biomass into syngas under high temperature (i.e. typically above 1000°C). Syngas contains primarily CO and H_2 which are important building blocks for synthesising FT liquid. Integrating gasification of biomass with FT synthesis and refining, shown in Figure 1, enables cleaner and high quality jet fuel to be produced. Typically, 5-6 t of biomass can give 1 t of FT liquid fuel [31].

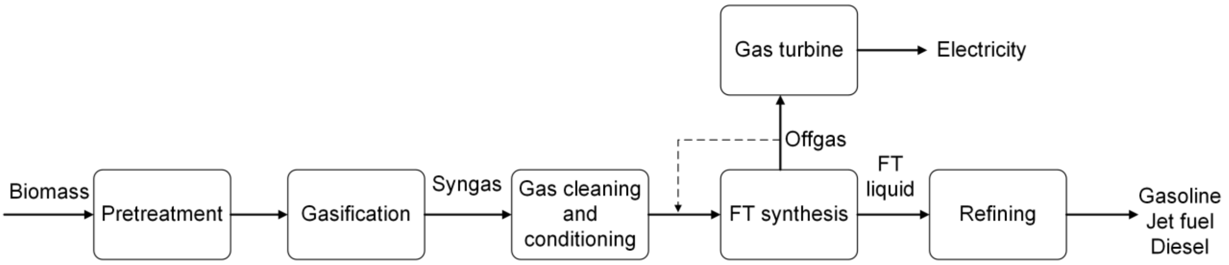

Figure 1: Integrated biomass gasification, Fischer-Tropsch synthesis and refining process for the production of gasoline, jet fuel, diesel and electricity.

FT synthesis produces hydrocarbon with various carbon chain length, including light hydrocarbons (C_1-C_4) which are light gases and can be used directly in gas turbine to generate heat and power or refined into LPG; naphtha (C_5-C_{10}) and kerosene (C_{10}-C_{16}) which can be blended into gasoline and jet fuel; distillate (C_{14}-C_{20}) which can be refined into diesel fuel; and waxes (C_{20+}) which can be hydrocracked to form diesel [32]. One of the salient advantages of FT liquid is that it is completely free of sulphur and contains a minimal amount of aromatics compared to gasoline and diesel, which consequently causes less pollution to the environment [33]. This factor, along with the need to avoid catalyst poisoning, in turn implies that the requirement of the feed for FT synthesis is more stringent. Therefore, the syngas has to be cleaned in order to be free from solid, tars, nitrogen and sulphur-containing compounds as well as other contaminants which might cause fouling in the equipment [34]. Syngas cleaning still remains a major issue for the integrated system of biomass gasification with FT synthesis and this requires more development into it to guarantee a satisfactory cleaning standard of the FT feed while achieving significant cost reduction [35].

FT synthesis has been operating commercially mainly by Shell (Bintulu in Malaysia; and Qatar) using natural gas based syngas, and Sasol (South Africa) using coal based syngas [30]. Most of the biomass gasification-FT technologies are still in the demonstration phase such as the

BioTfueL project by Total (France), Velocys/Red Rock Biofuels (Austria and U.S.) and Syndièse-BtS project by CEA/Air Liquide (France) [36]. The first commercial biomass gasification and FT plant, Sierra BioFuels Plant has been constructed by Fulcrum Bioenergy in Nevada, U.S. (expected to operate in 2020), and it is capable of producing 42 ML y^{-1} (11 Mgal y^{-1}) of synthetic crude oil from 175 kt y^{-1} of municipal solid waste (MSW) feedstock [37].

3.2 Hydroprocessed esters and fatty acids (HEFA)

The HEFA process utilises vegetable oils, animal fats, waste cooking oil, pyrolysis oil and also algal oil in hyroprocessing to formulate jet fuel. Typically, 1.2 t of vegetable oil will be needed to produce 1 t of HEFA fuel [31]. The process, shown in Figure 2, involves a series of reactions to extract free fatty acids (FFA) from the biomass, followed by isomerisation (rearrangement of molecules) and hydrocracking (reducing carbon chain length of molecules) reactions to obtain jet fuel that meets the jet fuel specification.

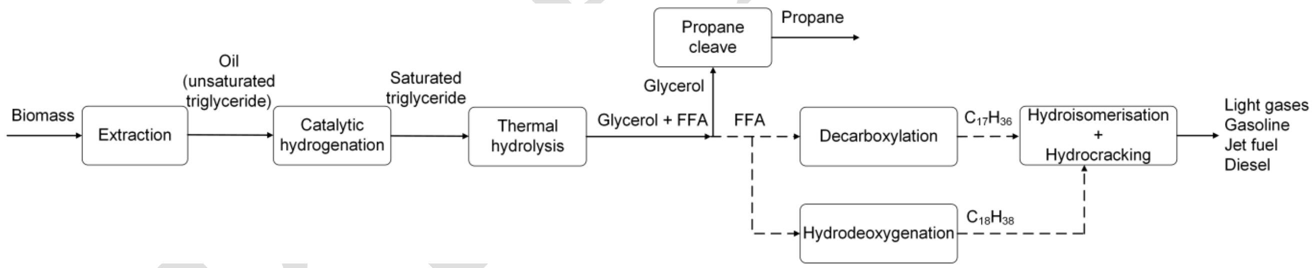

Figure 2: HEFA process for the production of jet fuel from oily biomass.

The process begins with extracting oil from oil-bearing biomass. The extracted oil contains unsaturated fatty acids / glycerides (consisting of double bonds) and needs to be saturated to remove the double bond via catalytic hydrogenation reaction, forming saturated triglycerides. Hydrogenation is carried out at pressure of 0.7-4 bar with nickel catalysts at 150-220°C, while lower temperature at 80-120°C is also possible if palladium and platinum catalysts are used [38]. Triglyceride can be broken down into 1 molecule of glycerol and 3 molecules of FFA through thermal hydrolysis reactions, and glycerol is further converted into propane by addition of hydrogen [39].

The oxygen content in the FFA is removed via either hydrodeoxygenation (HDO) or decarboxylation (DCO) reaction, producing octadecane ($C_{18}H_{38}$) and heptadecane ($C_{17}H_{36}$), respectively. The main difference between these two reactions is that the former requires 9 mole of hydrogen and generates water as by-product while the latter generates carbon dioxide. Large amount of hydrogen consumption at high pressure is required for HDO reaction. The process is typically carried out at temperatures of 300-600°C, accompanied by a heterogeneous catalyst such as sulphided NiMo and CoMo supported on alumina [40, 41]. Besides HDO, DCO is another processing option for removing the oxygen content in FFA, by which CO_2 is rejected instead of H_2O as in HDO. The advantage of DCO is that it occurs favourably under lower pressure and hence lower hydrogen consumption [42].

Straight chain paraffins ($C_{18}H_{38}$ from HDO or $C_{17}H_{36}$ from DCO) are produced, however, the resulting products do not meet the specifications for jet fuel application such as flash point, freeze point and cloud point [43-45]. Therefore, the straight chain paraffins are further processed in hydroisomerisation reaction to form branched chain paraffins in view of lowering the freeze point to meet the jet fuel standard [43, 45]. Hydrocracking reaction, which occurs sequentially or concurrently with hydroisomerisation is also involved to crack and saturate the hydrocarbons to form synthetic paraffinic kerosene (SPK), consisting of carbon chain length from C_9 to C_{15} [43, 45]. UOP, Neste Oil, AltAir and Dynamic Fuels are among the companies that produce HEFA fuel.

3.3 Alcohol-to-Jet (ATJ)

The ATJ process involves conversion of shorter chain alcohol (e.g. methanol, ethanol, butanol) into longer chain hydrocarbon (C_8-C_{16} alkane). There are two major processing routes for producing jet fuel from alcohol: (1) methanol-to-olefins (MTO) followed by Mobil's olefin-to-gasoline/distillate (MOGD); (2) ethanol/isobutanol/butanol/other alcohols processing via dehydration, oligomerisation and hydrogenation. Alcohol can be produced from biomass via thermochemical such as gasification and pyrolysis [46] or biochemical routes such as fermentation [47]. Emerging technology such as microbial synthesis in producing alcohol is also becoming attractive [48, 49]. A conceptual schematic diagram showing these various processing strategies of jet fuel production from biomass is given in Figure 3.

Methanol can be converted into jet fuel via MTO followed by MOGD, shown in Figure 3, of which the technologies were developed by ExxonMobil [50]. UOP/Hydro also possesses a license for their MTO technology [50]. Methanol is sent to MTO fluidised bed reactor which is operated at 482°C and 1 bar using ZSM-5 catalyst, and the products generated are methane (1.4 wt%), C_2-C_4 paraffins (6.5 wt%), C_2-C_4 olefins (56.4 wt%) and C_5-C_{11} gasoline (35.7 wt%) [51]. This product slate from the MTO unit is fractionated in the olefin fractionation unit to obtain light gases, gasoline and olefins. Light gases are recycled to the MTO unit to enhance the product yield. Gasoline is separated from the fractionation column as sole product. Olefins are further processed in the MOGD unit, a fixed bed reactor operating at 400°C and 1 bar with the presence of ZSM-5 catalyst [51]. The products from the MOGD unit contains light gases (3 wt%), gasoline (15 wt%) and distillate (82 wt%) [51]. The MOGD fractionation unit gives the fractions of light gases (C_1-C_4), gasoline (C_5-C_{11}), jet fuel / kerosene (C_{11}-C_{13}) and diesel (C_{14+}) as final products from the integrated MTO and MOGD.

The transformation from alcohols to jet fuel can also be accomplished via dehydration, oligomerisation and hydrogenation, shown in Figure 3. Alcohols are first dehydrated to form alkenes at pressure <14 bar and temperature of 288-343°C [52]. Acidic catalysts such as alumina-based catalyst, ZSM-5 zeolites, γ-type zeolites and Amberlyst acidic resins can be employed in the dehydration reaction [43]. The next step is the oligomerisation process where alkene molecules are combined to form longer-chain hydrocarbons such as dimers, trimers and tetramers, taking place at 100°C using Amberlyst-35 or Nafion catalyst [43, 52, 53]. Dimers are usually recycled to obtain higher yield of trimers and tetramers which give C_{12}-C_{16} olefins for jet fuel [52]. The last step, hydrogenation, involves saturation of olefins to produce paraffinic kerosene with external supply of hydrogen and PtO_2 catalyst [52, 53].

UOP, LanzaTech, Coskata, BRI, Gevo, Cobalt/Navy are among the companies that produce ATJ fuel. In 2014, Lufthansa has signed the agreement with Gevo to evaluate and test their ATJ fuel for commercial aviation use [54]. This shows the growing interest of ATJ in the jet fuel market.

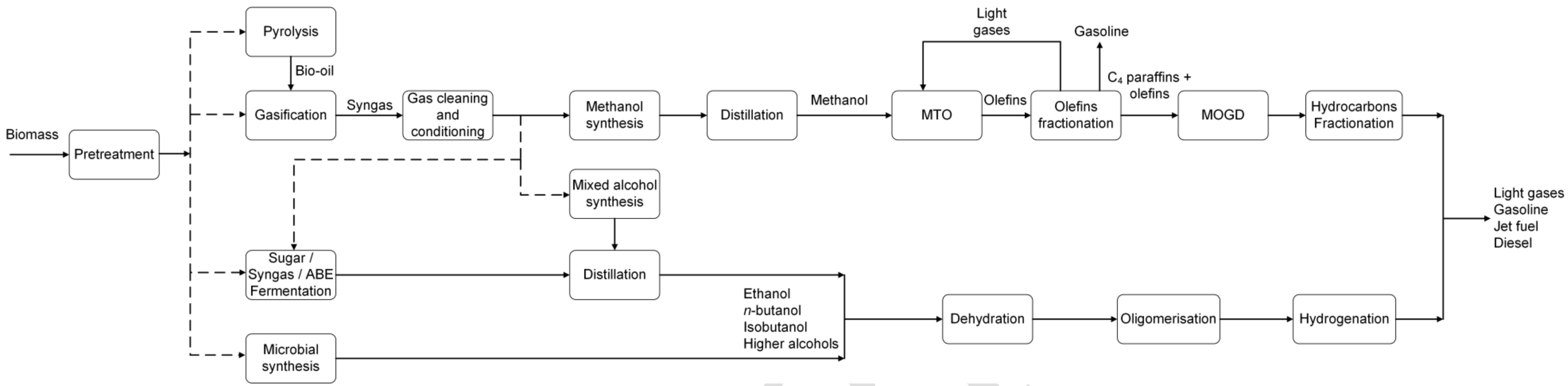

Figure 3: Production of alcohols from biomass and alcohol-to-jet (ATJ) routes. MTO: methanol-to-olefins; MOGD: Mobil's olefins-to-gasoline/distillate; ABE: acetone-butanol-ethanol.

3.4 Hydroprocessing of fermented sugars (HFS)

Figure 4 shows the biological conversion pathway of biomass to synthetic iso-paraffins (SIP) (also known as "direct sugars-to-hydrocarbon" (DSHC)) biojet fuel. The process involves (1) a pretreatment step to separate sugars from lignin; followed by (2) conversion of sugars into farnesene ($C_{15}H_{24}$) through enzymatic hydrolysis and fermentation; (3) solid-liquid separation and recovery of farnesene; and finally (4) hydroprocessing to farnesane ($C_{15}H_{32}$) which is the biojet fuel. This technology, commercialised by Amyris and Total [55] uses a *S. cerevisiae* strain (PE-2) in the fermentation process to produce farnesene via the mevalonate pathway [56, 57]. The yield of farnesene can reach up to 16.8% at a productivity of 16.9 g $L^{-1}d^{-1}$ with recovery of 95% after separation [58]. This hydrocarbon fuel can be blended up to 10% with conventional jet fuel and has been certified by ASTM in 2014 [55]. Amyris is currently developing an integrated DSHC with aspiration to attain 2 \$ L^{-1} of farnesene through the MegaBio project [59].

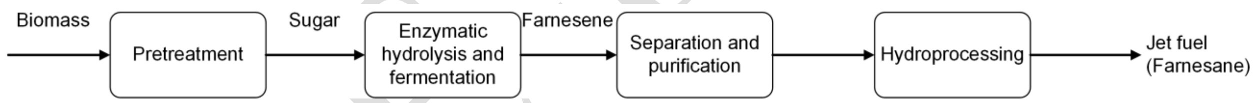

Figure 4: Hydroprocessing of fermented sugars to jet fuel.

3.5 Potential biomass feedstock for SAF production

A wide range of biomass feedstock can be exploited for biojet fuel production. This includes energy crops, forestry and agricultural residues, used cooking oil, straw, wood waste and municipal solid waste. Other first-generation food/feed crops such as rapeseed, sugarcane, corn, palm oil and soybean can also be used but these will not be included in the present review. Table 2 presents a comparison of different biomass and organic waste feedstock which are not in competition with food/feed market with respect to their opportunities and barriers to be exploited in SAF production.

From a technology standpoint, any feedstock with properties or characteristics compatible to specific types of technology can be deployed. As shown in Table 2, most of the lignocellulosic biomass feedstock (e.g. agricultural and forestry residues, woody crops and energy crops) can be processed in gasification-FT, ATJ and pyrolysis technologies. Oily feedstock such as used cooking oil and energy crops (e.g. Jatropha and Camelina) is more suitable to be processed using the HEFA technology. From an environmental standpoint, the use of food/feed crops in SAF can result in indirect land use change as well as impact on food prices and local environments with irrigation, pesticides and fertilisers [12]. It is therefore desirable to utilise feedstock which would lead to lower environmental impact. According to the European Aviation Environmental Report 2019 [12], using lignocellulosic biomass feedstock (e.g. agricultural and forestry residues, woody crops and energy crops) in the gasification-FT process and used cooking oil in the HEFA process gives the highest direct GHG savings of more than 80% compared to fossil-based aviation fuel baseline of 89 g CO_{2e} MJ^{-1}. In addition to the technological and environmental aspects, it is essential to consider the competition with existing energy and road transport biofuel markets when selecting a suitable type of feedstock for aviation biofuel production [7, 20, 60]. The aviation sector is facing strong competition with the established road transport sector in terms of policy support, availability and price of feedstock and supply chain. Road transport biofuels such as biodiesel and bioethanol produced from first-generation feedstock are currently supported by policy instruments (e.g. subsidies, mandates and tax levers) in many countries such as Brazil, the EU and the US, but there is no similar policy for SAF to date. In principle, the production of road transport biofuels and aviation biofuels can potentially share the same production facilities and supply chain. However, the cost of production of aviation biofuel will most likely be higher than the road transport biofuels if second-generation feedstock is deployed due to the requirement of additional and more advanced refining processes [31]. Additional expenses are also required for testing and certification before SAF can be commercially deployed [61]. The cost of production of biofuels is highly associated with the availability of feedstock and the practical logistic constraints to transport the feedstock from the source to the processing sites. For example, in the context of the EU, it is unlikely to utilise used cooking oil for aviation industry due to its limited availability, since there is already an established market for biodiesel used in road transportation [62, 63]. In regard to the logistic constraints, it may not be economically feasible to transport forestry residues from remote areas or wood waste from multiple distributed construction and demolition sites to the biojet fuel processing sites [20].

Table 2: Opportunities and barriers for adopting potential biomass feedstock for SAF production.

Feedstock	SAF production routes	Opportunities	Barriers	References
Municipal Solid waste (MSW)	• Gasification-FT	- Converting waste into higher value products such as jet fuel promotes higher diversion of waste from landfill. - Use of waste for biofuel production is preferable to disposal to landfill and incineration without energy recovery.	- Highly contaminated (ash, nitrogen, heavy metals) and contains high moisture content. MSW requires pre-treatment and separation before it is used in conversion process. - Formation of coke and tar in gasification.	[64, 65]
Used cooking oil	• HEFA • Pyrolysis	- Used cooking oil already widely commercialised under the HEFA process with Fuel Readiness Level (FRL) and Technology Readiness Level (TRL) of 9. - Low cost and widely available.	- Can be upgraded using other technologies such as biodiesel production, hence this may decrease availability for use in production of SAF	[12, 62, 63, 66, 67]
Straw	• Gasification-FT • ATJ • HFS • Pyrolysis	- Not in direct competition with food (except barley and oat straw used for animal fodder) - Unlikely to be contaminated - Homogenous characteristics across suppliers - Consists mainly of cellulose and hemicellulose and thus easier to extract sugars than municipal solid waste or wood	- More challenging to be used in thermochemical processes due to its high ash, chlorine and alkali metal content. - Straw is highly seasonal and has limited time for collection after harvesting, hence requiring more storage space - Incur higher cost for transportation due to its low volumetric density	[20]

Energy crops (e.g. Jatropha, Camelina, halophytes, algae)	• Gasification-FT • HEFA • ATJ • Pyrolysis	- Jatropha, algae and halophytes grown in difficult conditions in inhospitable places. - Algae particularly advantageous growing at rapid speed and can be grown on marginal lands (i.e. not competitive with lands for growing food). - Crops such as Camelina are fast growing and can be grown with wheat rotationally - Large oil and lipid content per mass (e.g. Jatropha and Camelina)	- Large investment for plantation of energy crops - Scale up may not be possible without an established supply chain - Farmers are reluctant to invest in energy crops unless a mature SAF or biofuel industry is established	[7, 60]
Forestry Residues	• Gasification-FT • HFS • ATJ • Pyrolysis	- Less competition, so widely available for advanced biofuel production - Generally contribute to lower GHG emissions	- May not be economical to transport forestry residues from remote areas to processing plants	[20, 62, 68, 69]
Wood waste	• Gasification-FT • ATJ • Pyrolysis	- Production of wood waste is fairly consistent throughout the year. - Current price is negative although depends on the local demand for the feedstock	- May cause problems to processes if lower grade wood waste is used. - Additional cost incurred to separate wood waste from other waste from sites (e.g. construction and demolition) and transporting from multiples sites	[20]

3.6 Comparison of techno-economic and environmental performances of SAF production

As discussed in sections 3.1 to 3.5, there are a variety of feedstock and technologies that can be deployed for SAF production. According to the estimation by The International Council on Clean Transportation (ICCT) [63], the cost of production of SAF can vary significantly from 0.88 € L^{-1} or 1.0 \$ L^{-1} (waste fats and oils via HEFA) to 3.44 € L^{-1} or 3.9 \$ L^{-1} (HFS) which represents 2-8 times of the price of fossil based jet fuel. In this review, information on SAF production capacity and yield, capital (CAPEX) and operating (OPEX) costs, minimum fuel selling price (MFSP) and GHG emissions have been collected from various sources (updated to 2019), presented in Table 3. Case studies of different feedstock and production capacity have been categorised into the four major certified routes, i.e. FT, HEFA, ATJ and HFS.

The economic performance of SAF production routes is best indicated by MFSP (equivalent to cost of production) which represents the minimum viable selling price of the fuel at which an investment breaks even, i.e. lower MFSP signifies the investment is more promising and competitive. The information presented in Table 3 shows the average MFSP of the HEFA route is the lowest, i.e. 1.2 \$ L^{-1} (1.07-1.32 \$ L^{-1}) which is mainly attributed to its high production yield (>1000 L t^{-1} dry feed) and relatively lower capital costs (~0.34 \$ L^{-1}). Both FT (0.92-2.59 \$ L^{-1}) and ATJ (0.75-2.77 \$ L^{-1}) routes show similar average MFSP at 1.76 \$ L^{-1}. The highest average MFSP can be found in the HFS route, i.e. 4.27 \$ L^{-1} (2.17-6.36 \$ L^{-1}). The average MFSP values have been derived by considering only the case studies reported within the last 5 years (2015-2019) mainly because the technology and cost are evolving significantly and thus most of the cost estimated prior to this period is often higher. The type of feedstock and technology adopted for producing SAF have a strong influence on the MFSP. For example, using energy crops in FT synthesis would result in higher MFSP (2.15 \$ L^{-1}) compared to using MSW or agricultural residues (1.53 and 1.98 \$ L^{-1}, respectively) at the same capacity, as indicated in Table 3. A similar trend can be observed in the case of ATJ where energy crops give the highest MFSP (2.77 \$ L^{-1}) compared to sugarcane, agricultural residues and corn grains (1.86, 2.71 and 1.86 \$ L^{-1}, respectively). Previous studies have found that the gasification-FT route is highly capital intensive, of which the capital cost contributes 50-75% to the total production costs compared to 20-50% in the case of ATJ [70]. However, the feedstock cost for gasification-FT (10-35% of the total production costs) is lower than the ATJ route (15-60%) [70]. HEFA is a relatively more mature technology, widely adopted and closer to full commercialisation, hence it is not surprising that the capital cost is among the lowest. Nevertheless, further reduction in MFSP is not anticipated as the high feedstock cost for HEFA (e.g. vegetable and waste oils) dominates the production cost [63, 70].

In terms of environmental impact, SAF can potentially reduce 20-95% of GHG emissions compared to petroleum jet fuel depending on the feedstock and technologies used [62]. Based on the trend shown in Table 3, there exists a strong correlation between GHG emissions and feedstock applied. For example, vegetable oil used in the HEFA route results in higher GHG emissions compared to other feedstock and technologies. This is primarily attributed to the indirect land use change (ILUC) emissions that are caused by increased land conversion for jet fuel production which is in competition with food sector and road biofuel application [71]. It can also be seen that utilising lignocellulosic biomass feedstock such as forest and agricultural residues and wood chips may result in lower GHG emissions. It is generally difficult to compare environmental impact such as GHG emissions as inconsistent assumptions are often being made across different case studies.

Table 3: Techno-economic performance and emissions of various certified SAF production routes.

Feedstock	Production Capacity	Yield		Capital cost (CAPEX)	Operating cost (OPEX)	MFSP	Direct GHG emissions	ILUC emissions	Year of publication	Reference
	ML y^{-1}	L t^{-1} dry feed	GJ t^{-1} dry feed	M$ ($ L^{-1})	M$ y^{-1} ($ L^{-1})	$ L^{-1}	kg CO_{2e} GJ^{-1}	kg CO_{2e} GJ^{-1}		
Fischer-Tropsch (FT) synthesis										
Forest residues	1305	271	-	678 (0.65)	793 (0.61)	0.92	3.6	-	2016	[72]
Agricultural residues	277	-	23.63	941 (3.40)	74.9 (0.27)	5.49	22.0	-	2009	[73]
Hardwood	251	114	5.32	577 (2.30)	99.9 (0.40)	0.79	18.0	-	2016	[74]
Forest residues	153	210	-	626	(1.36)	1.8	-	-	2015	[69]
Wheat straw	157	198	-	626	(2.11)	2.59	-	-	2015	[69]
MSW	230	148	-	(1.24)	(0.28)	1.53	14.8	-	2019	[63]
Agricultural residues	230	148	-	(1.24)	(0.73)	1.98	6.3	-	2019	[63]
Energy crops	230	148	-	(1.24)	(0.90)	2.15	11.7	−12.0	2019	[63]
Hydroprocessed esters and fatty acids (HEFA)										
Soya oil	230	1060	-	135 (0.59)	181 (0.78)	1.08	31.4	-	2013	[44, 75]
Palm oil	27.3	-	6.32	9.90 (0.35)	22.8 (0.84)	4.22	13.0	-	2007	[44, 76]
Pongamia	61	-	-	419 (6.88)	251 (4.1)	5.02	39.0	-	2013	[77]
Palm oil	230	1111	-	0.34	0.79	1.13	33.7	231.0	2019	[63]
Palm fatty acid distillate (PFAD)	230	1111	-	0.34	0.73	1.07	19.4	213.0	2019	[63]
Used cooking oil	935	1025	-	874	(1.19)	1.32	19.4	-	2019	[69]
Alcohol-to-jet (ATJ) Note: (a) ethanol-to-jet; (b) butanol-to-jet; (c) methanol-to-jet										
Forest residues (a)	294	419.9	5.98	56.1 (0.19)	51.4 (0.17)	2.08	91.0	-	2011	[78]
Wood chips (a)	98.6	136	-	479	85.2 (0.86)	0.75	1.6	-	2017	[74]
Wood chips (a)	90.2	125	-	500	82.4 (0.91)	1.11	10.0	-	2017	[74]
Corn grain (a)	230	432	-	(1.07)	(0.79)	1.86	65.0	14.0	2019	[63]
Sugarcane (a)	230	580	-	0.79	(1.07)	1.86	48.1	17.0	2019	[63]
Agricultural residues (a)	230	321	-	2.20	0.51	2.71	14.9	-	2019	[63]
Energy crops (a)	230	321	-	2.20	0.57	2.77	-	-	2019	[63]
Corn stover (b)	168	200	1.51	198 (1.21)	91.6 (0.55)	3.08	32.0	-	2013	[79]
Wood chips (b)	88.6	122	-	736	99.5 (1.12)	1.08	3.2	-	2017	[74]
Wood chips (b)	144	199	-	431	110.8 (0.77)	0.81	7.4	-	2017	[74]
Woody residues (c)	455	651	6.86	210 (0.46)	17.4 (0.04)	1.22	40.0	-	2011	[80]

Hydroprocessing of fermented sugars (HFS)										
Agricultural residue	114	212	-	1973 (17.4)	137 (1.20)	2.17	25.0	-	2016	[72]
Fructose	109.5	534	-	128 (2.60)	53.1 (0.48)	6.31	15.0	-	2011	[81]
Sugarcane	61	-	36.9 (41.7)	215 (3.49)	193 (3.17)	3.82	15.0	-	2013	[77]
C5 and C6 sugars	109	210	-	273	(3.69)	4.83	-	-	2015	[69]
A molasses	58	111	-	228	(5.22)	6.36	-	-	2015	[69]
Sugarcane	61	370	-	1.98	2.32	4.29	65.1	-	2019	[63]

4. International initiatives and policies

Significant efforts have been made among relevant stakeholders in the aviation industry to tackle climate change challenges. A set of targets have been agreed by Air Transport Action Group (ATAG), including 1.5% fuel efficiency improvement per year from 2009 to 2020 (this has been surpassed with an average of 2.1% achieved), stabilising CO_2 emissions through carbon neutral growth from 2020 and 50% reduction in CO_2 emissions by 2050 based on 2005 level [6]. On the other hand, the International Civil Aviation Organization (ICAO) has called for fuel efficiency improvement of 2% in aircraft, followed by a carbon neutral growth beyond 2020 [82]. ICAO has established the SUSTAF Expert Group in June 2012, building upon the outcomes from ICAO Aviation and Sustainable Alternative Fuels Workshop in October 2011 and 37th Session of the ICAO Council, to promote the development and deployment of SAF [83]. On 8 February 2016, ICAO has announced the first global "CO_2 Standards" for new aircraft launched after 2020 [84]. This mandate has an important implication towards cutting down significant CO_2 emissions from aviation industry while promoting economic growth through accelerating uptake of SAF in the future. For example, it has been estimated that 32% CO_2 emission reduction can be achieved in the aviation industry by 2050, while generating economic value up to £742 million annually and 5200 jobs in the UK by 2035 [85].

The EU aviation industry (including European Commission, Airbus, Air France-KLM, British Airways, Lufthansa and a number of biofuel producers Chemtex Italia, Neste Oil, Biomass Technology Group, UOP and UPM) has targeted 2 Mt y^{-1} of SAF by 2020 through the *Biofuel FlightPath Initiative* [86]. A broad and long-term vision for the EU aviation industry has been devised in "*Flightpath 2050 – Europe's vision for aviation*" report which outlines the European research priorities to promote EU economic growth, maintain global competitiveness, meeting societal needs as well as addressing energy and environmental challenges [87]. The European Green Deal, introduced in 2019, has further set the ambition to reduce GHG emissions in the transport sector (including road, rail, aviation and marine) by 90% by 2050, compared to 1990 level [88]. This target will be translated into legislation through the ReFuelEU initiative (to be formalised in 2021), which aims to accelerate the production, supply and deployment of SAF in the EU [89]. Various policy options including blending mandate, multiplier, central auctioning mechanism and fuel approval process, are currently explored under this initiative. In the US, the White House's National Science and Technology Council has published a report on "*Federal Alternative Jet Fuel Research and Development Strategy*" in June 2016, outlining the research and development goals to address a number of scientific and technical challenges associated with the development, production and use of alternative jet fuel for short-term (<5 years), mid-term (5-10 years) and long-term (>10 years) in these categories: (1) feedstock development, production and logistics; (2) fuel conversion and scale-up; (3) fuel testing and evaluation; (4) integrated challenges such as improving environmental sustainability of alternative jet fuel production and use [90]. Table 4 presents the SAF blending mandate and aspirational targets in different countries or regions. It can be seen that the current policies in different countries are not particularly strong to promote the uptake of SAF. There are only two countries that have introduced blending mandate, i.e. Indonesia and Norway, while others have recommended an aspirational target [85]. Nonetheless, there have been numerous international initiatives underway, established by non-governmental stakeholders (i.e. airlines, research institutes, airports, biofuel producers) to promote SAF. A comprehensive list of worldwide initiatives in promoting SAF can be found in the Supplementary Materials, Table A.2.

Table 4: International SAF uptake targets [31, 85, 91-95].

Country/Region	Organisation	Target	Type of Target	Timeframe
Indonesia	Ministry of Energy and Mineral Resources (MEMR)	2% 3% 5%	Blending mandate	2018 2020 2025
Norway	Government	0.5% 30%	Blending mandate	2020 2030
The Netherlands	Government	14%	Proposed blending mandate	2030
Sweden	Government	1% 30%	Aspirational blending target	2021 2030

EU	EC (Biofuels Flightpath)	2 Mt	Aspirational blending target	2020
EU	EC (Transport White Paper)	40%	Aspirational blending target	2050
Israel	Fuel Choice Initiative (FCI)	20%	Aspirational blending target	2025
France	Government	2% 5%	Proposed blending mandate	2025 2030
Spain	Government	2%	Proposed blending mandate	2025
Germany	Aviation Initiative for Renewable Energy	10%	Aspirational blending target	2025
Mexico	Aeropuertos y Servicios Auxiliares (ASA)	15% 50%	Aspirational blending target	2020 2040

Research and commercialisation activities in promoting biojet fuel are heavily relying on close collaboration among major aircraft manufacturers (e.g. Boeing and Airbus), airlines, airports and biofuel producers. A number of airline companies have committed to utilising aviation biofuel supplied by various suppliers to the respective airports, shown in Table 5. A comprehensive list of biofuel producers with great interest in producing large scale SAF alongside their favoured feedstock and production routes are presented in Table A.3 in the Supplementary Materials.

Table 5: Airlines commitments to SAF [31, 85, 96, 97].

Airline	**Biofuel supplier**	**Targeted distribution facilities / airports**	**Volume (kt y^{-1})**	**Product**	**Duration**	**Start delivery**	**Contract date**
United	Altair	Los Angeles International Airport	17	HEFA (oil – tallow)	3 years	2015	2013
Cathay Pacific	Fulcrum	Los Angeles International Airport	100	FT (from MSW)	10 years	2017	2014
Southwest Airlines	Red Rock	n/a	10	FT (from forest residue)	n/a	n/a	2014
British Airways	Solena	London City Airport	50	FT (from MSW)	10 years	2017	2012
Lufthansa [a]	Gevo	n/a	24	ATJ fuel (sugar, isobutanol)	5 years	n/a	n/a
Qantas	SG Preston	Los Angeles International Airport	24	n/a	10 years	2020	n/a
JetBlue	SG Preston	John F Kennedy Airport	30	n/a	10 years	2019	n/a

Note: This table provides examples based on the best available data to date from published literature. There could be other agreements between airports and SAF producers which are not covered here.

Strong and supportive governmental policies are also essential in promoting the uptake of SAF. This has been demonstrated globally in different countries, as presented in Table 6. At the global level, the ICAO, where 193 members states are involved, is playing a vital role in reducing GHG emissions in the aviation sector through accelerating the development and deployment of SAF. The commitment of 2% improvement in annual fuel efficiency by 2050 [98] has been constantly reviewed during the ICAO assembly that is held once every three years. Although some targets (i.e. 2%, 32% and 50% share of SAF by 2025, 2040 and 2050, respectively) have been proposed in the ICAO's Vision 2050 during the 2nd Conference on Aviation and Alternative Fuels (CAAF/2) held in Mexico City in 2017, these have not been agreed by most member states due to various concerns over actual SAF contribution towards mitigating carbon emissions, lack of land resources to provide sufficient feedstock as well as political and technical uncertainty in different countries, which are yet to be fully evaluated [99]. In the EU, SAF production has been encouraged through Renewable Energy Directive (RED) [100]. The original target of achieving 10% share of renewable energy in the transport sector has been revised to 14% by 2050 (it is an obligation for road and rail transport to meet the target but not for aviation fuel) in the latest RED II [101]. A multiplier of 1.2 has also been introduced, implying that the non-food renewable fuel produced for the aviation sector is counted as 20% more energy content compared to the fuel used for road transport [101]. The European Union Emission Trading Scheme (EU ETS) provides financial incentives to aircrafts which adopt SAF that complies with the sustainability and GHG emission criteria defined in RED/REDII [102]. SAF is eligible for the Renewable Identification Number (RIN), which is a credit used for compliance under the Renewable Fuel Standards (RFS2) in the United States [103]. This policy is primarily aimed to address GHG emissions from ground transportation, while aviation fuel is considered as an "add-on" option to this policy [104]. The status of aviation fuel as an "opt-in" fuel appears in the Low Carbon Fuel Standard (LCFS) where aviation fuel blended in California is eligible for a lower compliance credits than renewable diesel [104, 105]. Other similar programs also exist in Oregon (US) and British Columbia (Canada). Mexico and Brazil have been supporting blend of biofuel in gasoline and diesel, however there is no mandate to date specifically for aviation fuel. The UK is committed to the net zero emission target and this would eventually lead to a series of initiatives to decarbonising the transport sector [106]. The ten-point plan for a green recovery and the "Jet Zero Council" recently established in the UK in 2020 has indicated a starting point for introducing relevant strategies to decarbonising aviation sector [107, 108].

Table 6: Legislation and policy relevant to SAF.

Region / Country	Legislation / Policy	Main Objective	Reference
International	Resolution A37-19 (adopted by 37th ICAO Assembly, October 2010)	• To achieve a 2% improvement in global annual fuel efficiency until 2050. • A medium term goal to stabilise global net carbon emissions from international aviation at 2020 level.	[98]
	Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)	• To achieve a Carbon Neutral Growth from 2020 onwards by limiting the GHG emissions from international aviation to the average 2019-2020 level (Note: the GHG emission baseline has been adjusted to 2019 level due to the impact of Covid-19 pandemic on the aviation sector). • CORSIA eligible fuel was introduced with the following sustainability criteria: (i) The fuel should lead to GHG emission savings of at least 10% compared to the baseline fossil-based aviation fuel. (ii) The fuel should not be produced from biomass obtained from land with high carbon stock (e.g. forest, wetlands, peatlands).	[109, 110]
European Union	Renewable Energy Directive (RED), Directive 2009/28/EC	• To promote the adoption of renewable sources with a target of 20% share of renewable energy by 2020 in the EU. • A target of 10% share of renewable energy to be achieved in transport sector, including road and rail transport. This target does not apply to aviation fuel. However, this is amended in 2015 where aviation fuel can opt in to contribute to the target (i.e. not an obligation).	[100, 111]
	Renewable Energy Directive (RED II), Directive 2018/2001/EU (Recast)	• To promote the adoption of renewable sources with a target of 32% share of renewable energy by 2030 in the EU.	[101]

		• A target of 14% share of renewable energy to be achieved in transport sector, including road and rail transport. Aviation fuel can opt in to contribute to the target (i.e. not an obligation). • Introduced ILUC impact of biofuel. • 1.2 multiplier for non-food renewable fuel used for aviation sector. • Biofuels produced from food and feed crops are capped at 7% share of target in the transport sector by 2030. • The share of advanced biofuels and biogas from second generation feedstock in the transport sector should be at least 3.5% by 2030. • Used cooking oil and animal fats are capped at 1.7% of the total renewable energy consumption for transport fuels (Note: This can be adjusted depending on the feedstock availability where Member States can apply for an increase on the cap). • Minimum GHG savings of 65% for biofuel from January 2021.	
	European Union Emission Trading Scheme (EU ETS), Directive 2008/101/EC	• To reduce GHG emissions using the "cap-and-trade" principle on the emission allowances. • Aviation activities are included in the scheme started from 2012. • All flight from, to and within EU-28 member states as well as Iceland, Liechtenstein and Norway are included in the scheme. • For aviation sector, the annual average emissions for the period 2013-2020 should be 5% below 2004-2006 level.	[102]
	White Paper 2011 Roadmap to a Single European Transport Area, 52011DC0144	• To achieve 40% use of sustainable fuel in aviation industry by 2050. • To reduce carbon emissions in transport by 60% by 2050.	[112]
United States	Renewable Fuel Standard (RFS2)	• Created under Energy Policy Act 2005. The standards were subsequently updated in the Energy Independency and Security Act of 2007 (EISA). • ILUC emissions are included in the life cycle assessment framework. • Four categories of renewable fuels are introduced with the corresponding volume requirement and percentage standards: - Cellulosic biofuel (870 ML (230 Mgal), 0.128%, 2016) - Biomass-based biodiesel (7.2 GL (1.9 Bgal), 1.59%, 2016) - Advanced biofuel (13.7 GL (3.61 Bgal), 2.01%, 2016) - Renewable fuel (68.6 GL (18.11 Bgal), 10.10%, 2016) • Four categories of renewable fuels must meet the requirements for life-cycle GHG emission reduction (from displaced gasoline/diesel based on 2005 level): - Cellulosic biofuel (60%; must be from cellulosic feedstock) - Biomass-based biodiesel (50%)	[31, 103, 113, 114]

		- Advanced biofuel (50%; not from corn starch) - Renewable fuel (20%) • Renewable Identification Numbers (RINs) is a compliance method used to show the compliance of volume requirements. It is generated by renewable fuel producer and importers and used by petroleum refiners, can be traded and carried forward to following years. • RFS2 does not put a mandate on aviation fuel but renewable fuel producers and importers can still generate RINs on the conditions that it meets the definition and requirements of the renewable fuels.	
	California's Low Carbon Fuel Standard (LCFS)	• First low-carbon fuel standard mandated in the world in 2010. • Use carbon intensity as the metric for measuring GHG emissions over the lifecycle of a fuel. • ILUC emissions are included: - Corn ethanol (19.8 g CO_{2e}/MJ) - Sugarcane ethanol (11.8 g CO_{2e}/MJ) - Soy biodiesel (29.1 g CO_{2e}/MJ) - Canola biodiesel (14.5 g CO_{2e}/MJ)) - Sorghum ethanol (19.4 g CO_{2e}/MJ) - Palm biodiesel (71.4 g CO_{2e}/MJ) • To achieve 20% reduction in carbon intensity of transportation fuel used in California by 2030 (Amendment made in 2018) • Linked with AB32 Cap-and-Trade Program Advanced Clean Cars Program and Senate Bill (SB375). All these programs do not cover aviation fuel.	[104, 105, 115]
	Oregon's Clean Fuels Program	• Similar mechanism to California's LCFS. • Started in 2016. • To achieve 10% reduction in carbon intensity of transportation fuel used in Oregon by 2025.	[116]
Canada	British Columbia's Low Carbon Fuel Standard	• Similar mechanism to California's LCFS. • Started in 2010. • To achieve 20% reduction in carbon intensity of transportation fuel used in California by 2030 • To meet 5% annual share of renewable content in gasoline and 4% in diesel. • ILUC emissions are not included.	[117]
Brazil	National Fuel Alcohol Program (ProÁlcool)	• Introduced 20-25% anhydrous bioethanol blend in gasoline. • No direct mandate on aviation fuel.	[118]
	National Production and Use of Biodiesel (PNPB)	• Introduced a 2% blend of biodiesel in regular diesel. • No direct mandate on aviation fuel.	[119]
Mexico	Law for the Development and Promotion of Bioenergy Interministerial	• To promote energy crops for biodiesel and jet fuel production • Introducing 5.8% anhydrous bioethanol blend in gasoline by 2017	[120-122]

	Commission for the Development of Bioenergy Law of Climate Change	• Introducing 15% blend in jet fuel by 2020 and 50% by 2040. • To achieve annual reduction of GHG emissions by 1.8% by 2020 in the aviation sector.	

To date, there is no internationally agreed definition of SAF – the sustainability criteria vary across jurisdictions and it is a subject of ongoing discussions. RED II has demanded a GHG emission savings of at least 65% (starting from 1st January 2021) for transport biofuel compared to fossil fuel baseline of 94 g CO_{2e} MJ^{-1} to be counted towards the 14% target and to be eligible for the financial support [101]. RED II has further introduced a new approach in considering ILUC impact of biofuel, similar to California's LCFS. ILUC takes into account the impact of displacement of land which is traditionally used for production of food and feed crops and also extension of agricultural land into areas with high-carbon stock such as forests, wetlands and peatland which would result in additional GHG emissions [101]. The Directive places a limit on the volume of high-ILUC biofuels that can be counted towards the target.

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) has been developed as a market-based mechanism using carbon credit trading which aims to limit GHG emissions from international aviation based on the average 2019-2020 level (Note: the GHG emission baseline has been adjusted to 2019 level due to the impact of Covid-19 pandemic on the aviation sector) [109]. CORSIA recommended a GHG reduction (which includes ILUC) of at least 10% compared to the fossil fuel baseline of 89 g CO_{2e} MJ^{-1} for jet fuel [123]. The EU ETS and CORSIA schemes, which operate under different mechanisms ("cap-and-trade" versus "offsetting"), and cover different geographical scopes (European Economic Area versus international), are not well integrated. A roadmap was published in 2020 to incorporate CORSIA within the EU ETS framework in view of addressing the inconsistency in the EU ETS legislation [124].

5. Discussion: Future prospects of biojet fuel

Biojet fuel can meet the aviation fuel requirement and has the potential in substituting the conventional crude oil based aviation fuel, coping with the fast-growing market in aviation while reducing GHG emissions. A number of demonstration flights using biojet fuel are presented in Table A.4 in the Supplementary Materials. Biofuel blending of up to 50% can be seen in most demonstration flights and waste cooking oil is the most widely used feedstock in biojet fuel production. Increasing the production of SAF alongside greater uptake of the fuel on commercial flights can be envisaged by integrating the supply chain of SAF through encouraging closer collaboration between biofuel suppliers and airports. Karlstad (Sweden) and Oslo (Norway) Airports have established their bioports in 2014 [31]. Amsterdam Schiphol Airport, Brisbane Airport, Helsinki Airport are undergoing planning and working towards developing bioports [31].

The selection of feedstock and technology for aviation biofuel production is not straightforward. The main barriers in promoting large scale deployment of SAF are the affordability and competitiveness with conventional aviation fuel [125]. As indicated in section 3.6, biojet fuel can be 2-8 times more expensive than conventional kerosene jet fuel [63]. This can be overcome through technological advancement and improving the economies of scales. Furthermore, scaling up the supply chain and infrastructure and technological advancement on engine design to allow 100% SAF adoption are needed to promote production of SAF at scale [125]. HEFA is the most commercially developed SAF and other production routes still require further development mainly to reduce the cost of production. However, FT-SPK is fast catching up and has potential advantages such as flexibility in terms of feedstock utilisation (i.e. wide range of feedstock such as agricultural waste or MSW can be used) while offering high GHG emission savings. The use of MSW is particularly attractive as it not only avoids the use of fossil fuels but also utilises waste that would otherwise be left to decompose in landfill sites with adverse environmental impact. Nevertheless, the availability of MSW as a feedstock for SAF remains a concern as it may not be sufficient to meet the market demand [125]. Other challenges faced by FT-SPK route are associated with syngas clean-up, catalyst contamination and economies of scale [126]. On the other hand, ATJ and HFS-SIP are likely to face complications with sugarcane and other crops as feedstock due to indirect land use change. The requirement of technologies to process wastes and residues derived aviation biofuels is generally higher than processing feed/food crops. The cost competitiveness of aviation biofuel generated from FT, ATJ and HFS-SIP routes can be enhanced by incorporating polygeneration strategy (i.e. an integrated system for simultaneous production of fuels and chemicals) into system design, which could enhance resource efficiency and product diversification through its highly flexible system configuration [127, 128]. The polygeneration concept has been demonstrated in biorefinery system design [129, 130], CO_2 reuse [131, 132] and waste-to-hydrogen [133, 134] case studies. Future adoption of SAF relies on the balance between the production cost and GHG emissions. The ICCT report [63] argued that the cost of production on the basis of GHG reduction performance serves as an important criterion for policies to incentivise SAF. Based on their evaluation, it has been found that used cooking oil derived jet fuel through HEFA (200 € t^{-1} CO_{2e} reduced or 230 \$ t^{-1} CO_{2e} reduced) and FT derived jet fuel through gasification of MSW and lignocellulosic biomass (400-500 € t^{-1} CO_{2e} reduced or 460-575 \$ t^{-1} CO_{2e} reduced) are among the cost-effective options for carbon abatement.

Apart from the technological and environmental aspects, the competition between aviation biofuel and road transport biofuel markets should not be overlooked. Policy support, availability and price of feedstock and supply chain are among the factors that need to be considered, as discussed in section 3.5. There is a growing interest in many countries in adopting blending mandates and aspirational targets for SAF, as indicated in Table 4. Imposing a blending mandate is generally perceived as an effective tool in promoting the uptake of SAF, however this may lead to the uptake of the lowest-cost option using food/feed crops as the feedstock that is associated with indirect land use change, which is not necessarily the best performing option in terms of meeting the decarbonisation targets [60, 135]. An alternative policy instrument is to introduce a GHG intensity reduction target such as the California's LCFS which is technology-neutral and tends to promote best performing options in terms of decarbonisation potential, i.e. biofuel that gives higher GHG emission savings will be given higher compliance value [135]. Sustainability criteria should be considered to avoid feedstock with high direct GHG and ILUC emissions to be utilised in SAF production [94]. RED II policies (discussed in section 4) have created greater competition between road transport and aviation biofuel sectors. The multiplier of 1.2 introduced in RED II that intends to promote the production of SAF may not be effective to stimulate producers to shift from production of road transport biofuels towards aviation biofuels, as indicated by Pavlenko et al. [63]. The study also showed that a multiplier of 1.3 is more likely to stimulate this shift among existing HEFA producers to produce more aviation biofuels through 7% increase in net incentives, however this would result in 10% lower total fuel production [63]. The RED II policy helps drive the reduction of first generation food/feed biofuel towards second generation biofuels by placing a cap on biofuels produced from food/feed crops at 7% and at least 3.5% share of advanced biofuels from second generation feedstock in the transport sector [101]. In addition, used cooking oil and animal fats are capped at 1.7% and are double counted towards the total renewable transport energy and the 14% target under RED II [101, 136]. These targets will inevitably create further competition between aviation and road transport sectors for these low-cost feedstock (i.e. used cooking oil and animal fats) and other waste and residue feedstocks which have limited availability. The shortcomings of these policies are expected to be reviewed through the ReFuelEU initiative.

A few recommendations on promoting the development and uptake of SAF are made:

- The utilisation of lignocellulosic biomass and waste feedstock should be promoted in lieu of food/feed crops unless the choice of feedstock can be justified through a lower cost and higher GHG savings. A preferred SAF feedstock should be the one which avoids competition with existing road biofuel market and land use for food production.
- Future research and development should be focused on non-HEFA routes, such as FT, ATJ and HFS-SIP routes to further improve the cost effectiveness through optimising, integrating and scaling up the technologies.
- Imposing a blending mandate is more effective than a voluntary approach. However, sustainability criteria of feedstock should be considered and food/feed crops should be avoided. An alternative policy instrument using a GHG intensity reduction target could be more effective than a blending mandate.
- Enhancing multi-stakeholder collaboration (airports, biofuel producers, aircraft manufacturers, airlines and government) is the key to accelerating the uptake of SAF.
- Introducing incentives for SAF adoption as well as penalties for GHG emissions through carbon tax schemes are needed to promote higher uptake of SAF. This should be further studied by taking into account the competition and impact between aviation and road transport sectors.

6. Conclusions

Accelerating the development of SAF is urgently needed to meet the net zero emission target in the aviation sector. Aviation fuel produced from bioresources has the potential in substituting the conventional fossil based aviation fuel, coping with the fast-growing market in aviation while reducing GHG emissions. This article delved into various aspects of SAF development, including the motivation of switching from fossil to biomass based jet fuel; potential biorenewable feedstock; overview of certified technologies in biojet fuel production;

comparison of techno-economic and environmental performances of SAF production routes; stakeholders in the aviation industry (government, biofuel producers, airlines, aircraft manufacturers); international policies and worldwide initiatives. The selection of feedstock and technologies for SAF production should be justified based on production cost and environmental footprint, while avoiding competition with the existing road transport biofuel market. Further research and development should be focused on optimising, integrating and scaling up SAF technologies to improve the cost effectiveness of SAF production. Promoting multi-stakeholder collaboration alongside governmental intervention through policy support is needed to accelerate the uptake of SAF. The shortcomings in the SAF policies such as blending mandate and multiplier in RED II should be addressed to reduce the negative impacts of feedstock competition between the road and aviation biofuel sectors.

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