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Prospects and Perspectives Foster enhanced Research on Bio-aviation fuels

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Abstract

Bio-aviation fuels are a major research and development topic, with strong interests from the aviation sector, the public, lawmakers and potential producers. Yet the development and market penetration in the air-transportation sector is slow, despite proven environmental benefits. Bio-fuels can indeed mitigate the environmental impact of the aviation sector mostly due to their low carbon intensity and favourable chemical structure. Such bio-aviation fuels must have "drop-in" characteristics with specifications and compatibility with the combustion behaviour of kerosene. The ASTM approval procedures are an important guarantee in this respect. Additional emission reductions rely on the production pathways, while optimum flight-related strategies are an additional benefit.

An analysis of both the production pathways, and the environmental and Life Cycle Assessment findings delineates important research directions to enhance the production and use of bio-aviation fuels.

Towards specific **environmental issues**, target research topics should include various topics. A better quantification of particulate and soot emissions, condensation contrails and NO_x are of primary concern. The impact of geographic parameters on the bio-aviation fuel benefits should be investigated towards using bio-aviation fuels primarily in specific climate zones. Emission prediction models should be further developed. LCA approaches should be extended. More on-flight emission patterns should be measured to provide relevant data for the above considerations; Towards **bio-aviation fuel characterization**, safety and reliability are major criteria of the ASTM approval. Towards **production pathways**, the technical viability studies of synthesis pathways should be combined with economic assessments. Towards **fuel costs,** the reason for the high production cost of bio-aviation fuel is at least partly due to the oxygen-rich bio-polymer nature of biomass with unsuitable carbon chain length. In order to reduce the cost of bio-aviation fuel, several research directions are encouraged and discussed in the paper.

Keywords: Bio-aviation fuels, bio-based feedstock; environmental impact, carbon intensity, ASTM approval, emission reductions, emission prediction models.

Abbreviations

ASTM	American Society for Testing and Materials
ATJ	Alcohol to Jet
DSHC	Direct Sugar to Hydrocarbon
EEA	European Economic Area
FRL	Fuel Readiness Level
FT	Fischer–Tropsch
GC-MS	Gas Chromatography/Mass Spectrometry
GHG	Greenhouse gas
GREET™	Greenhouse gases Regulated Emissions, and Energy use in Transportation
HEFA	Hydroprocessed Esters and Fatty Acids
LCA	Life Cycle Assessment
PAH	Polyaromatic Compounds
SPK	Synthesized Paraffinic Kerosene
TRL	TechnologyReadiness Level

1. Aviation fuel and air transportation

Aviation fuel is the main energy source of the aviation sector, the second largest sector in transportation and continuously growing. The number of flights increased by about 8% between 2014 and 2017 and is forecasted to further grow by over 40% till 2040 (EUROCONTROL, 2018).

Jet engines currently rely on kerosene produced from crude oil. Despite progressive aircraft improvements, the kerosene demand is expected to increase annually by 2 to 3% (Wang et al., 2019). As an example, relevant EU facts are illustrated in Table 1.

Table 1 EU aviation indicators for all departures from EU28 + EFTA (EEA technical report, 2019)

	2017	% change vs. 2014	% change vs. 2005
Average fuel consumption (L/100 passengers – km)	3.4	-8	-24
Passengers - km Commercial flights (billion)	1.643	+20	+60
Full-flight CO_2 emissions (10^6 ton)	163	+10	+16
Full-flight NO_x emissions (10^3 ton)	839	+12	+25

Although the average fuel consumption per passenger-kilometre decreased significantly, this reduction did not counterbalance the increased emissions due to the considerable growth in number of flights, aircraft size and flight distance.

Globally, the aviation sector is responsible for around 3.6% of the greenhouse gas (GHG) emission and for about 13.4% of the overall emission from transportation (O'Connell et al., 2019).

The average emissions from a typical two engine jet during a 1-hour flight with 150 passengers are given in Figure 1.

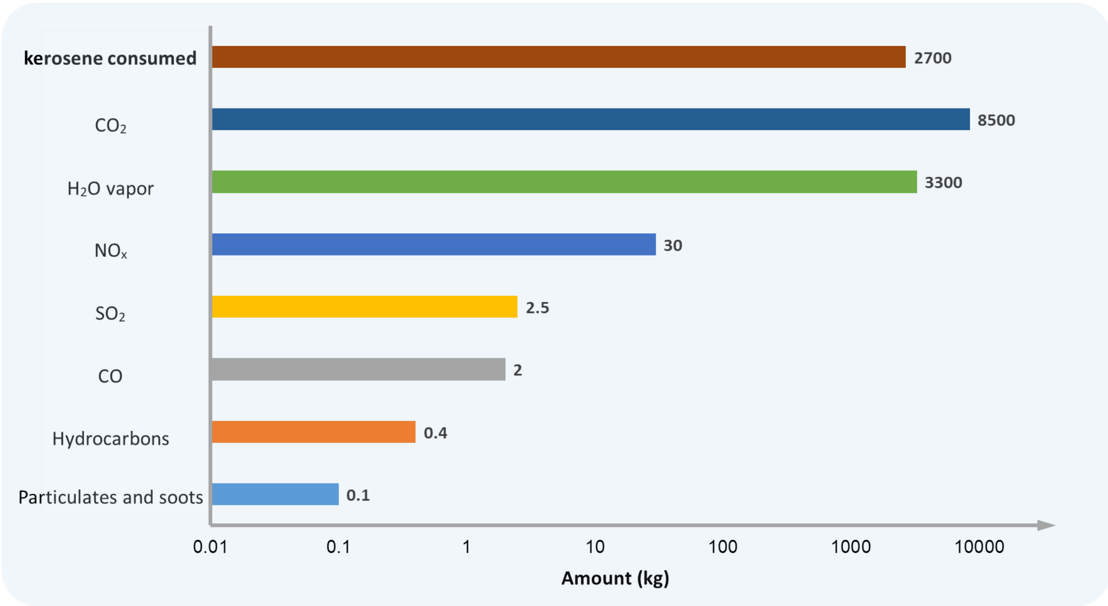


Fig. 1 Average emissions for a typical flight case (EEA technical report, 2019; "ICAO emission databank," 2018)

The fuel consumption of different models of planes for a 1-hour flight (150 passengers) in litres of jet fuel, is shown in Figure 2 (Wąsowska and Korneć, 2016). Clearly, aircraft manufactures devote a substantial amount of efforts towards technical and aerodynamic improvements.

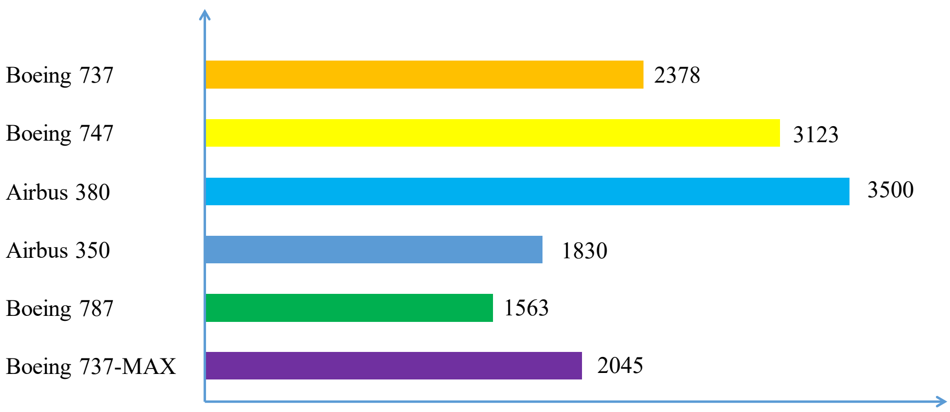


Figure 2 Fuel consumption of different planes for a 1-hour flight (150 passengers)

The worldwide expansion of the aviation sector, and the expected increasing emission levels merit special consideration. The application of bio-aviation fuel has been identified as one of the appropriate solutions to achieve a significant emission reduction by 2050.

2. Commercial and bio-aviation fuel

Commercial jet fuels (Jet A-1 in EU, Jet A in USA) are derived from crude oil and consist primarily of a mixture of alkanes (n-, i-, cyclo-), olefins, aromatics (mostly alkyl-benzenes and naphthalenes) and small quantities of non-hydrocarbon molecules including e.g. sulphur atoms at 600 to 1000 ppm_m in common kerosene. The amount of aromatics is varying but specified at a minimum of 8%. The ASTM D1655 requires a minimum specific energy of 42.8 MJ/kg. The hydrogen mass content in commercial jet fuel is typically 13.9% (Rachner, 1998). The chemical composition of different aviation fuels was determined by GC-MS, including Jet A-1 and alternative ASTM-certified aviation fuels (Pires et al., 2018). According to this research, the chemical composition of fossil aviation fuel and bio-aviation fuel varies significantly, as shown in Table 2 (Pires et al., 2018).

Table 2 The typical chemical composition of Jet A-1 and alternative aviation fuels

Fuels Type	n-Paraffins	i-Paraffins	Olefins	Naphthenes	Aromatics	Others
Fossil Jet A-1 (Shell)	28.1%	38.8%	1.2%	15.1%	14.4%	2.4%
Bio-aviation fuel from Camelina using HEFA technology (UOP)	9.1%	89.4%	0.1%	0.7%	-	0.7%
Bio-aviation fuel from Tallow using HEFA technology (UOP)	12.8%	86.9%	0.1%	0.3%	-	-
Bio-aviation fuel from sugar using DSHC technology (Amyris)	-	96.4%	0.2%	1.3%	-	2.1%
Bio-aviation fuel from alcohol using ATJ technology (Gevo)	-	99.8%	-	0.2%	-	-

As illustrated in Table 2, bio-aviation jet fuels are virtually free from aromatics and reveal a hydrogen mass content of 15 to 15.5% (Hileman et al., 2010). Their major paraffinic nature increases the specific energy (MJ/kg) due to more C-C bonds for a given number of carbon atoms, but the stretched structure of the paraffins reduces the volumetric energy density (MJ/L) in comparison with aromatic compounds. The specific energy exceeds 44 MJ/kg, depending on both the production process and the renewable feedstock applied (Blakey et al., 2011; Hileman et al., 2010; Huang et al., 2010). According to research of Moore. et al, bio-aviation fuels contain near-zero levels of sulphur and aromatic species (Moore et al., 2017). Towards the presence of nitrogen, the bio-aviation fuels are nitrogen-free (Tran et al., 2020). The nitrogen oxides (NO_x) in the engine exhausts are formed by thermal atmospheric nitrogen oxidation within the jet engine. Fuel-NO_x is not formed (Mahmoudi et al., 2010). The NO_x combustion emissions are hence almost identical for fossil and bio-aviation fuels.

Both the difference in specific composition, and the difference in energy density impact the environmental performance.

3. Production processes of bio-aviation fuels

As discussed in several review papers (IRENA, 2017; Mawhood et al., 2016; Wang et al., 2019), the production of bio-aviation fuel follows different technology routes, with several of them at pilot or demonstration scale, and having been approved by ASTM (ASTM, 2017). TRL and FRL are defined in references ("CAAFI," 2018; European Commission, EC, 2020).

The biomass to bio-aviation fuel conversion process generally involves several connected steps including the generation of an intermediate state, the carbon chain length adjustment of the intermediates to produce aviation fuel precursors, and the hydro-finishing of precursors (Vásquez et al., 2017; Wang et al., 2019). Figure 3 provides an overview of the different schemes and technologies that can be used for the production of alternative jet fuels (Morgan et al., 2019).

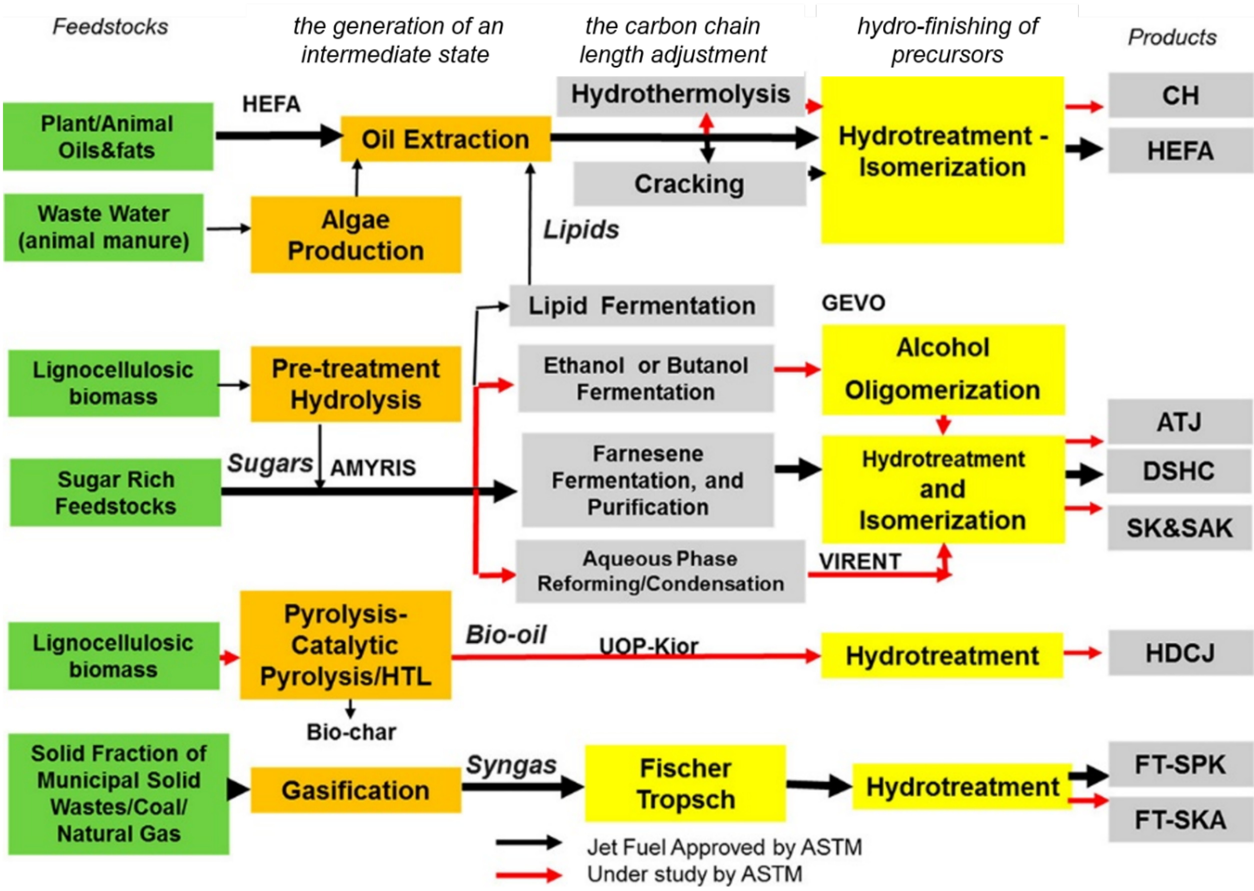
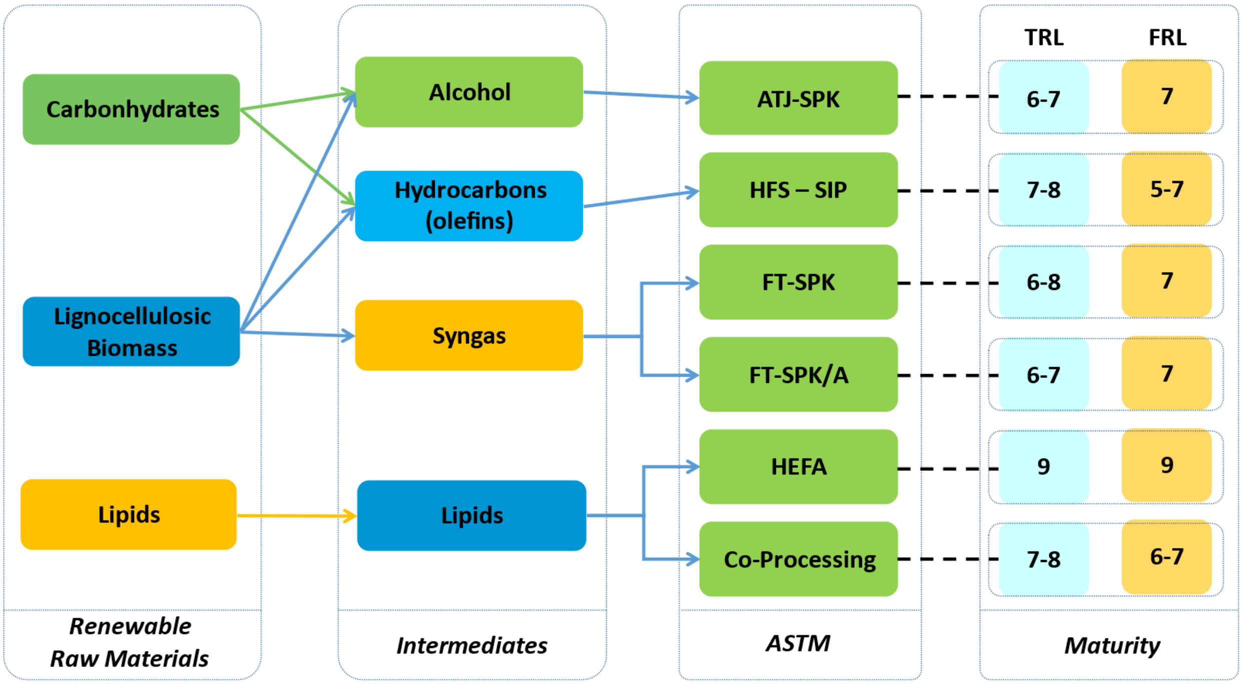


Fig.3 Production alternatives of bio-aviation fuel, adapted from (Morgan et al., 2019).

The intermediates with different chemical composition, different carbon chain length and functional group distribution, can be generated through either thermo-chemical or biochemical conversion. The C-C bond adjustment step is critical for bio-aviation fuel production and performed by consecutive reactions that can accurately control the chemical bond formation and cleavage, hence adjusting the carbon chain length. Catalyst and process conditions should be precisely managed to satisfy the requirement of bio-feedstock which feature mostly high reactivity, and multi-functionality. The hydro-finishing step is similar to that used in a petroleum refinery. The key issue to be resolved is again fitting the bio-oxygenate with the mature hydrogenation process in a petroleum refinery by catalyst and process engineering. Although bio-aviation fuel production can be divided into bio-chemical and chemical conversion groups, it can be expected that integrating both groups will result in better conversion technologies.

Six bio-aviation fuel production technologies have been approved by ASTM (Figure 4). The ASTM approval considers safety and airworthiness only. Other issues including emissions, contrail formation, operating costs go beyond the approval process.

For the HEFA production route, using e.g. vegetable oils such as soybean or palm oil, the composition of the feedstock is well-defined in terms of oleic and linoleic acid. For the ATJ and FT production routes, the definition of the molecular composition of the feedstock is more variable since a function of the nature of the biomass used.



*Co-Processing: Co-processing biocrude up to 5% by volume of lipidic feedstock in petroleum refinery processes
*HFS-SIP: Hydroprocessing of Fermented Sugars-Synthetic Iso-Paraffinic kerosene
*ATJ-SPK: Alcohol-to-Jet Synthetic Paraffinic Kerosene
*FT-SPK : Fischer-Tropsch Synthetic Paraffinic Kerosene
*FT-SPK/A: Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics
*HEFA: Hydroprocessed Fatty Acid Esters and Free Fatty Acid
*TRL: Technology Readiness Level
*FRL: Fuel Readiness Level

Fig.4 Production pathways certified by ASTM for use in commercial flights

It should be remembered that the ASTM certification process is tedious and involves several successive steps according to the Fuel Readiness Level as defined by CAAFI (2018). Initial tests (FRL3), including distillation curve, freeze/flash point, thermal stability, among others, require a small sample of 500 mL only. Testing of both neat fuel and blended fuel (50/50 with standard jet fuel) is performed during the FRL 4 step and includes a re-verification of initial results, a complete chemical characterization, the analysis of the corrosivity, the determination of the contents of hydrogen, sulphur, gum content, particulate matter, and others. About 50 L of bio-aviation fuel is required. During FRL 6.1 tests, fit-for-purpose properties including toxicity, materials compatibility are assessed on a 300 L sample. FRL 6.2 tests required 8 to 20 m³ of sample fuel and determine the hot section oxidation/erosion. A additional 3 to 30 m³ are needed in the FRL 6.3 tests for component and emissions testing. Finally, hundreds of m³ of bio-aviation fuel are required in the FRL 6.4 engine and flight test.

4. Environmental and climate impacts

Substituting conventional kerosene by bio-aviation fuel has significant positive impacts as examined through different approaches. (Moore et al., 2017)

Emission reduction has been determined as the primary benefit and validated by mostly ground tests. Emission measurements in the exhaust plume of an on-flight jet engine are limited. Secondary benefits are determined from comparing the specific energy of both fuel classes. Finally, the LCA considers reductions of GHG emissions for specific bio-feedstock and bio-conversion technology.

Primary impacts relate to the combustion of a hydrocarbon in air. When burning neat hydrocarbons in air, CO_2 and H_2O are the main combustion products together with a release of energy. Amounts of CO_2 produced will be lower for a given thrust when the fuel heating value is higher. Additional pollutants are formed: CO, unburned hydrocarbons, NO_x, aromatics, polyaromatic compounds (PAH) and other precursors of particles and soot. In an O_2-rich combustion, oxygen rich species such as ketones, peroxides, SO_2 are also formed.

The conversion mechanisms from aromatics to PAH and soot particles involve a sequence of steps (Böhm and Braun-Unkhoff, 2008; Saffaripour et al., 2014): the emission of particles is positively correlated with the aromatics' content of the specific fuel, hence more pronounced when using kerosene and of far lesser importance for bio-aviation fuels that are generally composed of alkanes. Experimental investigations were performed on the emission patterns of jet engines operated with jet-A1, bio-aviation fuels, and their blends. Mostly SPK and HEFA bio-aviation fuels were tested, but also the recently approved alternative fuel component farnesane (SIP-fuel) was included. Studies in on-flight exhaust plumes are limited. Parameters of humidity, temperature, viscosity, thrust, combustor pressure were investigated to get further insights into their effect on emissions (Braun-Unkhoff et al., 2017).

In summary, bio-aviation fuels have a different pattern if compared to Jet A-1. Major gaseous emissions (CO, CO_2, unburned hydrocarbons) were reduced slightly, depending on thrust (Bhagwan et al., 2014; Blakey et al., 2011; Braun-Unkhoff et al., 2017). Particulate emissions were significantly reduced both in mass and in number (Beyersdorf et al., 2014; Blakey et al., 2011; Moore et al., 2015). Within the ECLIF flight campaign (Le Clercq, 2017) lower soot levels were measured with lower amount of aromatics in the fuel, although type of aromatics as well as cyclic and iso-alkanes affected the amount of soot particles. The NO_x emissions show no clear trend although mostly reported to be reduced (Bhagwan et al., 2014; Blakey et al., 2011; Braun-Unkhoff et al., 2017).

The substitution of Jet A-1 by bio-aviation fuels also has secondary climate effects. Since paraffinic compounds, as main components of bio-aviation fuel, have a higher specific energy than aromatic compounds, their higher concentration in the fuel blend will reduce the aircraft fuel consumption thus also reducing the total quantity of pollutants emitted into the atmosphere: the less fuel required to carry a certain number of passengers and freight, the less pollutants will be emitted. This was confirmed by findings of 1187 scheduled Lufthansa flights between Frankfurt and Hamburg: the fuel consumption using a 50% HEFA blend was about 1% lower than that of the engine powered by neat Jet A-1 (burn-FAIR, 2011). The reduced particulate and soot production only slightly altered the contrail formation and properties (Kärcher et al., 2015).

A final assessment of the performance of the different aviation fuels towards GHG emissions was obtained from LCA studies. Key-studies published earlier were reviewed and discussed in (R.S. Capaz, 2016), and recently complemented by new results. Klein et al. (Klein et al., 2018) compared Jet A-1 with FT jet fuel from different feedstock, including coal, gas, biomass. The reference Jet A-1 GHG emission is 88.1 g CO_{2eq}/MJ. Biomass-based FT fuels score considerably better although results are particularly sensitive towards adopted process steps and efficiencies. Han et al. (Han et al., 2013) applied GREET™ (Greenhouse gases Regulated Emissions, and Energy use in Transportation) to examine the Well-to-Wake performance of bio-aviation fuels including hydro-processed renewable jet fuel from oilseeds; FT jet fuel from corn stover and its blend with coal; and pyrolysis jet fuel from corn stover. Although GHG values differ widely with the feedstock and processing method, GHG reductions between 41 to 89% were reported. O'Connell et al. (O'Connell et al., 2019) demonstrated that bio-aviation fuels exhibit lower GHG emission than conventional jet fuels with biofuels from crops, forestry and agro-industrial residues performing the best. Since certain pathways are notably more energy intensive than others, strong GHG reductions do not always coincide with high energy efficiency. The increased demand for bio-aviation fuels could moreover negatively affect GHG emissions across sectors if the net growth of producing the feedstock does not occur in a sustainable manner. This stresses the debate about how to account for indirect emissions such as cultivation, farm practice, land types. Depending on these indirect effects, GHG emissions of bio-aviation fuels as compared to conventional aviation fuel can be lower, comparable or even higher. It is hence difficult to draw LCA-based conclusions about the real benefits due to the limited number of studies, the low technical maturity levels of different production pathways, and the fact that exclusively GHG emissions are considered.

Some quantified GHG emission savings are illustrated in Figure 5. It should however be stressed that published LCA studies make a difference between a “well-to tank” and a “tank to wake” approach (Hileman et al., 2010). Whereas the former considers all steps of feedstock production, land use change and conversion to bio-aviation fuel, the latter merely considers the environmental effects of the combustion of jet fuels in the aircraft engines.

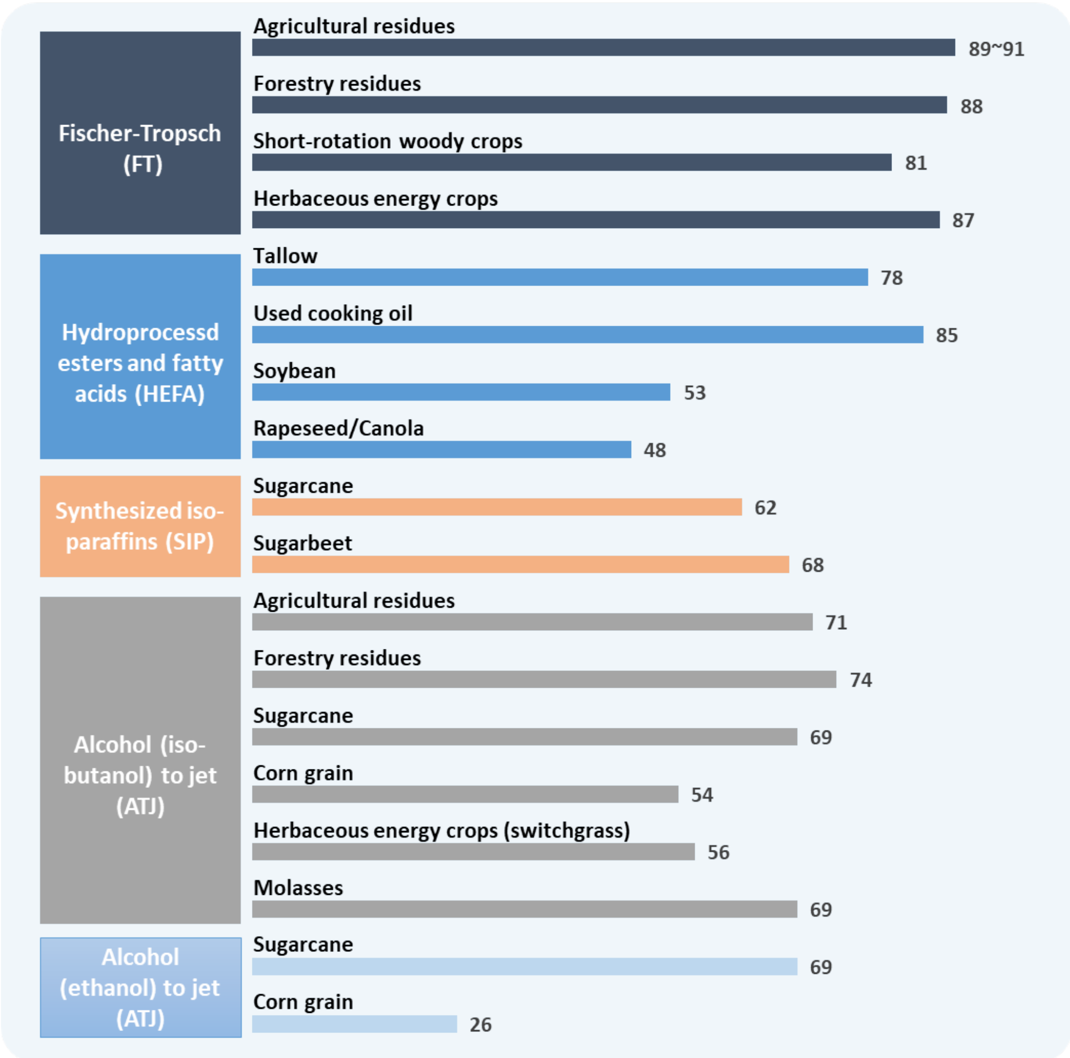


Fig.5 GHG emission savings (excluding carbon emissions from land use change) (EEA technical report, 2019)

Both the performance of the alternative bio-fuel pathways and the different approaches of the studies contribute to the differently predicted life cycle emissions. The mature HRJ technology from vegetable oils was mostly studied, and the environmental performance depended on the location and agricultural conditions of the crops. All pathways however had a better GHG emission performance than Jet-A1, which produced between 88 and 106 g CO_2 eq/MJ.

5. Conclusions and recommended priority research topics

The present paper aimed to summarize the current state of production technologies, the ASTM approval strategy, and the environmental impacts of using bio-aviation fuels.

Over the past decades, considerable progress has been made in developing bio-aviation fuels from bio-based feedstock. These biofuels mitigate the environmental impact of aviation mostly due to their low carbon intensity and favourable chemical structure. Such bio-aviation fuels must have "drop-in" characteristics with strict specifications and compatibility with the combustion behaviour of kerosene. The ASTM approval procedures are an important guarantee in this respect. Major emission reductions rely on the production pathways, while flight-related emission reductions are an additional benefit. An appropriate flight planning should indeed reduce holding times, airport taxiing, and selecting the shortest flight path to destination.

To boost the integration of bio-aviation fuels, various research actions are deemed necessary, as the result of findings reported above.

Towards specific environmental issues, target research topics are identified.

- The magnitude of non-CO_2 emissions (e.g. CO, unburnt hydrocarbons, N_2O) should be scientifically quantified, especially towards particulate and soot emissions, condensation contrails and NO_x, since these emissions are not clearly mitigated in a transition to bio-aviation fuels.

- Contrails are the water vapour condensation plume behind the jet engine. The contrails' effect of the lower soot emissions and combustion properties, needs further investigation and should include the impact of kerosene-based sulphuric acid formation and soot coating. The different surface properties of soot from kerosene versus bio-aviation fuels needs to be studied to gain insights on the required degree of soot reduction for a substantial climate benefit.

- The knowledge of geographic and climate-based parameters on the bio-aviation fuel benefits is insufficient and such studies could lead to recommendations in using bio-aviation fuels primarily in specific climate zones.

- Emission prediction models should be further developed, although this needs an adequate experimental database and requires accounting for jet engine operation and fuel properties. Once such models were validated, CFD simulations can be developed to predict the emission levels of the respective fuel under real flight conditions.
- LCA approaches should be extended to counteract shortcomings as highlighted before.
- More on-flight emission patterns should be measured to provide relevant data for the above considerations.
- Since bio-aviation fuels will be insufficiently available for the whole aviation fleet, it is required to define circumstances where bio-aviation fuels will have the largest climate impact and to apply models during the flight planning in order to balance climate and airline costs.

Towards bio-aviation fuel characterization, safety and reliability are major approval criteria of the ASTM approval. Combustion properties within a broad application range should be determined during the development of bio-aviation fuels.

Towards production pathways, findings and recommendations include:

- Though considerable progress on bio-aviation fuel has been made, the technical viability studies of synthesis pathways should be combined with economic assessments. Up till now, the cheapest bio-aviation fuel derived from waste cooking oil is around $ 1,000/ton, which is much higher than $ 600/ton for kerosene. The price (and its volatility) of bio-aviation fuels relative to crude-based kerosene hampers a greater market penetration.
- The reason for the high production cost of bio-aviation fuel, at least partly, is due to the oxygen-rich bio-polymer nature of biomass with unsuitable carbon chain length. In order to reduce the cost of bio-aviation fuel, several research directions are encouraged, i.e. (i) As described by Wang et. al (Wang et al., 2019), integrating breakthrough technologies from bio-chemistry and chemo-catalytic processes into bio-aviation fuel production; (ii) study the co-processing of drop-in biofuels with conventional refining, both to reduce capital costs and provide more product options; (iii) simultaneously producing bio-aviation fuel and value-added by-products; and (iv) enhance the drop-in percentage of bio-aviation fuel above the current 10 to 25% levels.
- All alternative aviation fuels should be ASTM-approved and sufficient samples should be supplied towards such tests: pilot and industrialization efforts are hence linked to

ASTM approval, and the technology for bio-aviation fuel production should operate at the pilot scale before it could be considered an option for further development.

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