

# Bio-aviation fuel: A comprehensive review and analysis of the supply chain components

1 **Stephen S. Doliente<sup>1,2</sup>, Aravind Narayan<sup>1</sup>, John Frederick D. Tapia<sup>1,3</sup>, Nouri J. Samsatli<sup>4,5</sup>,**  
2 **Yingru Zhao<sup>6</sup>, Sheila Samsatli<sup>1\*</sup>**

3 <sup>1</sup>Department of Chemical Engineering, University of Bath, Claverton Down, Bath BA2 7AY, United  
4 Kingdom

5 <sup>2</sup>Department of Chemical Engineering, College of Engineering and Agro-Industrial Technology,  
6 University of the Philippines Los Baños, Los Baños, Laguna 4031, Philippines

7 <sup>3</sup>Department of Chemical Engineering, De La Salle University-Manila, 2401 Taft Avenue, Malate,  
8 Manila, Philippines 1004

9 <sup>4</sup>Process Systems Enterprise Ltd., London SW7 2AZ, United Kingdom

10 <sup>5</sup>Samsatli Solutions, Ventonlace, Flatwoods Crescent, Claverton Down, Bath BA2 7AH, United  
11 Kingdom

12 <sup>6</sup>College of Energy, Xiamen University, Xiamen 361005, China

13 **\* Correspondence:**

14 Corresponding Author

15 S.M.C.Samsatli@bath.ac.uk

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17 **production pathways, storage and transport; supply chains.**

18 **Abstract**

19 The undeniable environmental ramifications of continued dependence on oil-derived jet fuel have  
20 spurred international efforts in the aviation sector towards alternative solutions. Due to the limited  
21 options for decarbonisation, the successful implementation of bio-aviation fuel is crucial in  
22 contributing to the roster of greenhouse gas emissions mitigation strategies for the aviation sector.  
23 Since fleet replacement with low-carbon technologies may not be a feasible option, due to the long  
24 lifetime and significant capital cost of aircraft, 'drop-in' alternatives, which can be used in the  
25 engines of existing aircraft in a seamless transition, may be required. This paper presents a detailed  
26 analysis of the supply chain components of bio-aviation fuel provision: feedstocks, production  
27 pathways, storage, and transport. The economic and environmental performance of different  
28 potential bio-feedstocks and technologies are investigated and compared in order to make  
29 recommendations on short- and long-term strategies that could be employed internationally.  
30 Hydroprocessed esters and fatty acids production pathway, utilising second-generation oil-seed crops  
31 and waste oils, could be an effective immediate solution with the potential for substantial greenhouse  
32 gas emissions savings. Microalgal oil could potentially offer far greater yields of bio-aviation fuel  
33 and reductions in greenhouse gas emissions, but the technology for large-scale algae cultivation is  
34 inadequately mature at present. Fischer-Tropsch production pathway using lignocellulosic biomass  
35 has the potential for the highest greenhouse gas emissions savings, which could potentially be the

36 solution within the medium- to long-term plans of the aviation industry, but further research and  
37 optimisation are required prior to its large-scale implementation due to its limited technological  
38 maturity and high capital costs. In practice, the 'ideal' feedstocks and technologies of the supply  
39 chains are heavily dependent on spatial and temporal criteria. Moreover, many of the parameters  
40 investigated are interlinked to each other and the measures that are effective in greenhouse gases  
41 emissions reduction are largely associated with increased cost. Hence, policies must be streamlined  
42 across the supply chain components that could help in the cost-effective and sustainable deployment  
43 of bio-aviation fuel.

## 44 1 Introduction

45 The aviation industry plays a major role in the global economy, serving as a crucial backbone for  
46 nearly 57 million jobs and USD 2.2 trillion in global GDP. Businesses, especially those involving  
47 international transactions, rely on its speed and efficiency. By 2035, the Air Transport Action Group  
48 (ATAG) expects 7.2 billion passengers will be served by the airline industry through the world's  
49 major airports as shown in Figure 1(a), which is twice the number of passengers in 2016 (ATAG  
50 2012). Consequently, this surge in aviation demand is projected to result in 3.1 billion tonnes of  
51 GHG emissions by 2050, which is 4 times greater than the 2015 baseline of 0.78 billion tonnes.

52 It is a significant challenge to find a sustainable solution for the aviation industry's GHG emissions  
53 reduction due to the ambitious target set at 50% less than the 2005 baseline (IATA 2009). The  
54 International Air Transport Association (IATA) and the International Civil Aviation Organisation  
55 (ICAO) developed the four pillars to achieve this goal: 1) technological improvements, 2) operational  
56 improvements, 3) measures based on the market and 4) alternative jet fuel (AJF) (Gutiérrez-Antonio  
57 et al. 2013). Figure 1(b) displays the timeline of the various trajectories based on the actions taken  
58 by the industry. Without actions taken, the emissions will be twice as much as the 2005 level.

59 To date, technological improvements have already begun contributing to the GHG emissions  
60 reduction target. Airframe and engine manufacturers have made significant technological leaps  
61 including lighter and stronger composite materials than ever before, new innovative aircraft designs  
62 with improved aerodynamics and incrementally more efficient engines (Rye et al. 2010). For  
63 example, 15 billion L of fuel, and 80 million tonnes of CO<sub>2</sub>, were saved by retro-fitting wing tip  
64 devices to the wings of over 5000 existing aircraft (ATAG 2019). By also using weight reduction  
65 measures on cargo containers, GHG emissions decreased by 10,000 t/year (ATAG 2014). These  
66 improvements allow greater efficiency in mileage and lower fuel consumption during travel.  
67 However, the slow incremental changes in already-mature engine technology and the long lifetime (>  
68 25 years) of existing fleets point toward AJF as a much faster and potentially more cost effective  
69 option to reduce emissions (Bauen et al. 2009). AJF can be easily utilised in existing fleets, hence  
70 avoiding large capital costs involved with buying newer models. Biofuel utilisation promises  
71 tremendous cut in GHG emissions and possible achievement of the ambitious target by 2040 as  
72 depicted in Figure 1(b). Thus, bulk of the reduction can be attained by replacing conventional jet fuel  
73 (CJF) with this alternative.

74 CJF produced from crude oil is a blend of various kerosene hydrocarbons. The hydrocarbon length of  
75 jet fuel is between that of gasoline and diesel. In a classical refinery, shown in Figure S1  
76 (Supplementary Material), jet fuel (or kerosene) is the middle distillate making up to 10% of the  
77 crude oil fraction while the majority are gasoline and diesel. Table S1 shows the comparison of the  
78 physicochemical properties of gasoline, jet fuel and diesel. As fuel for aviation, jet fuel is preferred  
79 over gasoline as it less volatile and denser; while compared to diesel, jet fuel is lighter and less prone

80 to wax at low temperatures (Yang et al. 2019). An AJF should have physical and chemical properties  
81 similar to CJF. A suitable aviation fuel must have high cold stability, for temperatures -47 to 40 °C  
82 and elevations above 30,000 feet and have sufficient energy density to supply the high energy  
83 demand of long-haul flights (The Engineering ToolBox 2003, Wilbrand 2018). The industry uses  
84 two major kerosene-based CJF, Jet A and Jet A-1. With a lower melting point of -4 °C, Jet A-1 is the  
85 better choice for international flights. The desirable composition of a jet fuel should be 75–85 vol%  
86 consisting of paraffins, iso-paraffins and cycloparaffins and the remaining 15–25 vol% of olefins and  
87 aromatics. Other important characteristics include global availability, acceptable costs, good  
88 combustion characteristics, and good flow behaviour. Hence, AJF being a ‘drop-in’ fuel can be  
89 easily integrated into existing infrastructure allowing a seamless transition (Rye et al. 2010). An AJF  
90 must also have lower carbon footprints over their life cycle than CJF, which typically have a carbon  
91 footprint of roughly four tonnes per tonne of fuel (de Jong et al. 2017).

92 As an AJF, bio-aviation fuel (also called as bio-jet fuel, renewable jet fuel or aviation biofuel in some  
93 literature) or BAF (for short in this paper) is recognised as a short- to medium-term solution towards  
94 an overall reduction in the GHG emissions of the aviation industry. Table S2 shows the standard  
95 specifications for both CJF and BAF, which manufacturers must strictly comply (Wilbrand 2018,  
96 Yang et al. 2019). Clearly, the resulting emissions profiles of an aircraft running on BAF would be  
97 very similar to one on Jet A-1 (Rye et al. 2010). But the closed carbon cycle established by  
98 sequestering atmospheric CO<sub>2</sub> during biomass growth and released at the end of its life cycle as BAF,  
99 results in its significantly lower overall carbon emissions compared to CJF (Bosch et al. 2017).  
100 While this makes BAF an attractive AJF option, several issues arose in its implementation. It has not  
101 been receiving sufficient investments due to inadequate government support and industry  
102 commitment, unreliable supply of feedstocks, uncertain commerciality of the production pathways,  
103 and lack of supply chain certification (Gegg et al. 2014).

104 Figure 1(c) presents recent bibliometric trends for bio-aviation fuel research. The data were obtained  
105 from Scopus using the keywords: bio-jet fuel, biojet fuel, bio-aviation fuel, aviation biofuel or  
106 renewable jet fuel. In the last ten years, there is generally an increasing trend in research on BAF,  
107 which reflects increasing recognition of the need to decarbonise the aviation sector through AJF  
108 options. Recent reviews of BAF considered the progress and issues in the production pathways  
109 (Gutiérrez-Antonio et al. 2017) and of fuel performance (Yang et al. 2019). Reimer and Zheng  
110 (2017) discussed possible strategies for enabling commercial BAF uptake, such as the simultaneous  
111 implementation of taxes on CJF and incentives for BAF utilisation. The possibility of BAF  
112 production from different feedstocks, such as microalgae (Bwapwa et al. 2018), lignocellulosic  
113 biomass (Cheng and Brewer 2017), urban and agricultural wastes (Jiménez-Díaz et al. 2017) and  
114 vegetable oils (Vásquez et al. 2017) have also been discussed in recent review papers. Kandaramath  
115 Hari et al. (2015) presented production pathways utilizing second- and third-generation feedstocks  
116 with qualitative discussion on the feedstock. These studies provided insights on the status and future  
117 direction of the bio-aviation fuel industry. However, existing review papers are limited to individual  
118 components of the supply chain for BAF provision (e.g. raw materials, pretreatment and conversion  
119 technologies) and there are currently no reviews discussing logistics strategies (e.g. storage and  
120 transportation of resources) or the economic and environmental analysis of the whole supply chain.  
121 Therefore, this review paper addresses this gap by being the first to provide a critical review of bio-  
122 aviation fuel from a whole-system supply chain perspective.

123 The focus of this review paper is on bio-aviation fuel examined holistically of its supply chain  
124 components: feedstock, production pathways, storage and transport. This review is organised into six  
125 sections. Section 2 gives an overview of bio-aviation fuel. Section 3 is a comprehensive discussion

126 of key feedstocks, which includes their cultivation requirements, supply chain models and economic  
127 and environmental impacts. The three most prominent production technologies are compared in  
128 Section 4 in terms of their advantages and limitations, as well as their economic and environmental  
129 impacts. The storage and transport technologies for raw materials, intermediates and final jet fuel  
130 product are discussed in Section 5. Section 6 offers critical analyses, recommendations and future  
131 direction of each supply chain component. The key conclusions of this review paper are found in  
132 Section 7.

133 **2 Bio-aviation fuel**

134 Bio-aviation fuel is a biomass-derived synthesised paraffinic kerosene (SPK) that is blended into  
135 conventionally petroleum-derived jet fuel (Yang et al. 2019). Table 1 presents the five types of SPK  
136 for blending (in specified volume fraction) with CJF as certified in ASTM D7566-19a (Table S2).  
137 The production platforms with their brief process description under which these SPK are classified is  
138 also presented in Table 1. The hydroprocessed esters and fatty acids production pathway (HEFA), an  
139 oil-to-jet production platform, produces HEFA-SPK via the deoxygenation of oils and fats followed  
140 by hydroprocessing (Yang et al. 2019). Hydrothermal liquefaction of plant or algal oil and fast  
141 pyrolysis of cellulose followed by jet fuel upgrading are also other oil-to-jet platforms (Wang and  
142 Tao 2016). Gas-to-jet platform involves the gasification of biomass to produce syngas, which is  
143 converted to paraffinic and olefinic hydrocarbons by Fischer-Tropsch production pathway (FT) and,  
144 subsequently, hydroprocessed to produce FT-SPK. FT-SPK/A can also be produced by gas-to-jet  
145 platform but with the addition of alkylated and bio-based aromatics (Yang et al. 2019). In alcohol-to-  
146 jet production platform or pathway (ATJ), biomass are hydrolysed to produce fermentable sugars, the  
147 sugars are fermented to produce alcohols, and then they are dehydrated, oligomerised, hydrogenated  
148 and fractionated to produce ATJ-SPK (Yang et al. 2019). Sugar-to-jet production platform or direct  
149 sugar-to-hydrocarbon jet fuel synthesis (DSCH) involves the hydrolysis of fermentable sugars from  
150 biomass, the fermentation of these sugars to farnesene the hydroprocessing of farnesene and  
151 fractionation to produce SIP-SPK (Yang et al. 2019). Catalytic reforming of sugar or sugar  
152 intermediates via chemical or biochemical process followed by upgrading to jet fuel via aqueous  
153 phase reforming and direct sugar to hydrocarbons are other sugar-to-jet platforms (Wang and Tao  
154 2016).

155 A summary of the advantages and disadvantages of BAF are presented in Table 2, but to ensure that  
156 it is truly an environmentally friendly alternative, emissions savings are required in over all phases of  
157 production: extraction, refining and transport. Energy security, price stability and job creation are  
158 added potential gains that can be reaped. Rural development in terms of augmented employment in  
159 farming and production and increased productivity of non-arable marginal land can be expected with  
160 the deployment of bio-aviation fuel. Despite its economic benefits, deployment has been not  
161 receiving sufficient investment (Gegg et al. 2014). Hendricks et al. (2011) added that investments in  
162 the form of subsidies and legislative support are needed by the production pathways in order for them  
163 to become economically competitive against crude refinery production.

164 The challenges faced by BAF are similar to those of biofuels, in general: the main one being how to  
165 ensure that the feedstocks, which come from biomass or other carbon-based sources, are secure,  
166 sustainable, economically viable and sufficiently available within both time and location of demands  
167 (Hendricks et al. 2011, Su et al. 2015). With the aviation industry along with the sectors of heating,  
168 chemicals, road transport and electricity, exerting efforts to decouple from fossil fuel dependence by  
169 shifting to biomass, their demands for the same feedstocks create a new supply competition (de Jong  
170 et al. 2017). The following sections discuss the feedstocks and critically analyse their cultivation

171 requirements, feasibility and sustainability of their supply chains, and their economic and  
172 environmental performance. The discussions are focused specifically on feedstocks for bio-aviation  
173 fuel production but many of the issues also apply to production of biofuels in general since they share  
174 the same feedstocks.

175 **3 Feedstocks for biomass-derived synthetic paraffinic kerosene**

176 Feedstocks can be categorised as follows: first-generation (1-G), second-generation (2-G), third-  
177 generation (3-G) and fourth-generation (4-G). Table 4 presents some examples for BAF production  
178 in each category. An important factor in choosing a feedstock is its availability. For cultivated  
179 feedstocks, their availability and potential yield are interrelated. Figure 2 shows the potential yields  
180 for a number of 1-G and 2-G feedstocks. Oil palm has the highest yield at 19.2 t/ha/year among  
181 these feedstocks. For 3-G feedstocks, the potential yield for microalgae has been reported to be  
182 much higher at 91 t/ha/year but there is uncertainty in this value due to algae cultivation being mostly  
183 from lab- to pilot-scale (Bwapwa et al. 2018).

184 **3.1 First-generation feedstocks**

185 Edible food crops, such as oil palm, corn, sugarcane, sugar beets and wheat, belong to 1-G category  
186 (Lee and Lavoie 2013). Sugar, starch, fat and/or oil contents are extracted from these crops. Fats or  
187 oils can be easily converted to jet fuel through the well-established HEFA. Sugar or starch can be  
188 processed by the emerging DSCH technology. ATJ is another emerging technology, which is of high  
189 interest to the USA for their excess supply of 1-G ethanol from corn (Radich 2015). While corn uses  
190 water efficiently, the sheer volume to be cultivated will result in high water demand and increased  
191 fertiliser use. Ramping up cultivation can strain a country's water resources and cause water-related  
192 issues like shortages and eutrophication. These are the main drawbacks in choosing 1-G feedstocks  
193 since most food crops typically have high water and nutrient demands (Table 4). Another main  
194 challenge of 1-G feedstock production is competition for land, water and energy inputs with food  
195 production (Moioli et al. 2018). To circumvent scarcity of land resources, expansion to forestland  
196 has been the convenient option but at the expense of deforestation and biodiversity loss (Keles et al.  
197 2018). Oil palm cultivation, a well-established food crop and promising BAF feedstock, has been  
198 linked to these adverse consequences (Vijay et al. 2016, Khatun et al. 2017).

199 **3.1.1 Oil palm**

200 To date, HEFA is the only renewable jet fuel technology implemented industrially (Roth et al. 2018).  
201 Feedstock cost accounts for a significant fraction in the total production costs (Bosch et al. 2017).  
202 Palm oil can potentially offset the high cost of hydrogen in the HEFA being the least cost vegetable  
203 oil. Thus, there is a growing interest for oil palm as feedstock for bio-aviation fuel production  
204 (Schoneveld 2010, Ernsting 2017). Oil palm cultivation is an attractive business with relatively low  
205 nutrient demand as shown in Table 4. Natural precipitation can also substantially satisfy the high-  
206 water requirements of plantations, which are mostly located in tropical and subtropical countries.  
207 Currently, Malaysia and Indonesia are at the forefront of palm oil production that supply more than  
208 80% of the global demand driven mainly by food industries (Schoneveld 2010). As the competing  
209 industry, biodiesel production is a recent growing demand for palm oil due to its higher energy  
210 output per unit energy input compared to other edible oils (Ail and Dasappa 2016, Pirker et al. 2016).

211 Globally, oil palm plantations have already expanded by about 12 million hectares between 2000 to  
212 2012 in large portions of tropical forests in Malaysia and Indonesia (Pirker et al. 2016). When either  
213 primary or secondary forests are converted to plantations, biodiversity loss has been well associated

214 with it (Koh and Wilcove 2008). Rich concentrations of birds and mammals are highly at risk to  
215 extinction in the vulnerable forests of Southeast Asia, South America, Mesoamerica and Africa  
216 (Vijay et al. 2016). Oil palm expansion is also well associated to the degradation of peatlands.  
217 Instead of acting as carbon sinks, peatlands become net GHG emitters after their conversion to  
218 agricultural lands. Plantations in Southeast Asia, that were once peatlands, were estimated to have  
219 surface GHG emissions of 54 to 115 tCO<sub>2</sub>eq/ha/yr (Page et al. 2011). In palm oil mills, waste  
220 management of palm oil mill effluent (POME) is the main issue. Raw POME has a high biochemical  
221 oxygen demand (> 25,000 mg/L) and large volumes are generated yearly (Madaki and Seng 2013).  
222 In 2015 alone, 60.88 and 94.76 million tonnes were generated in Malaysia and Indonesia,  
223 respectively (Choong et al. 2018). Due to high treatment costs, discharging of raw or partially  
224 treated POME to land or water bodies continues as an industry practice resulting in large-scale water  
225 pollution and ecosystem degradation (Madaki and Seng 2013).

226 For oil palm to become a ‘good’ feedstock option for bio-aviation fuel production, sustainable  
227 practices in the cultivation and processing phases must be implemented. Selection of suitable  
228 available land through ecosystem service mapping can improve plantation sustainability as expansion  
229 to forestlands, land-use conversion of peatlands, and/or disruption to the environment can all be  
230 avoided. Optimal agronomic practices to maximise oil yield and minimise resource inputs can also  
231 reduce the negative impacts of plantations (Khatun et al. 2017). Improvements in sustainability of  
232 palm oil mills will need capital investments on biological treatment methods. These will not only  
233 eliminate POME but will also yield higher value products, which include fertilisers, livestock feeds,  
234 and biogas (Wu et al. 2009). To lower overall costs, the use of ultrasonic and membrane technology  
235 as an integrated system is a solution with good economic potential for biogas production  
236 (Abdurahman and Azhari 2018). It has been recommended that mills are equipped with biogas  
237 capture to reduce overall GHG emissions by about 30% and improve biofuel net energy yield  
238 (Kaewmai et al. 2012, Harsono et al. 2014).

239 Current consumption of land transport biofuels and the resulting benefits of rural development and  
240 employment has already expanded the role of supply chains of 1-G crops, like oil palm, from food  
241 feed and fibre provision to fuel provision (KPMG International 2013, Sims et al. 2015). However,  
242 the growing demand for food-based biofuels has been linked to rising global food prices and food  
243 supply imbalances (KPMG International 2013, Oladosu and Msangi 2013, Buchspies and  
244 Kaltschmitt 2018). In the case oil palm, the gap between supply and demand is expected to widen  
245 further in the future (Khatun et al. 2017). Hence, the inclusion of BAF production to the supply  
246 chain agenda of oil palm could further increase the complexity and challenges (KPMG International  
247 2013). In this arena, mathematical modelling and optimisation techniques can aid in comprehending  
248 and formulating strategies for the needed transformation of future food supply chains that can  
249 sustainably provide food and non-food commodities simultaneously (FAO 2017, Zhu et al. 2018).  
250 For example, Tapia and Samsatl (2019) developed an optimisation model for multi-product oil palm  
251 supply chains that ensure sustainable land and water use and biodiversity protection. It may be  
252 technically feasible to integrate BAF production with food production from 1-G feedstocks but the  
253 policies and management have to be systematically assessed and sustainably implemented (Sims et  
254 al. 2015).

### 255 3.2 Second-generation feedstocks

256 Non-edible 2-G biomass resources can circumvent the food versus fuel dilemma of 1-G feedstocks  
257 (Alalwan et al. 2019). These are classified into two main groups: energy crops and waste biomass.  
258 Waste biomass are further categorised into agricultural and forestry residues and food and municipal

wastes. Regardless of the classification, 2-G feedstocks are either oil- or sugar-rich materials. But in contrast to 1-G crops, the sugars of 2-G feedstocks are trapped in the tough and recalcitrant lignocellulosic matrix of plant cell walls that need pretreatment with enzymes/microorganisms and/or thermochemical transformations for biofuel conversion (Boichenko et al. 2013, Lee and Lavoi 2013). The technical barriers and high costs of these conversion technologies are the main issues of 2-G feedstocks utilisation (Alalwan et al. 2019). However, the relatively high abundance and low use competition of lignocellulosic 2-G feedstocks make them a promising alternative over 1-G crops (Rödl 2018, Correa et al. 2019). Waste biomass utilisation also offers far greater benefits, such as realisation of circular economies, waste management, and environmental protection (Ahorsu et al. 2018, Richter et al. 2018). To date, production of biodiesel and bioethanol for land transport from 2-G feedstocks still lags behind 1-G feedstocks (Su et al. 2015). For land transport, Millinger et al. (2017) predicted in the long-term that liquid biofuels from 1-G feedstocks to be more cost-competitive than those from 2-G feedstocks, while gaseous biofuels derived from 2-G feedstocks for gas-powered vehicles seen to be the more cost- and resource-effective option in the medium-term. Nevertheless, liquid biofuels from 2-G feedstocks may become more important for the aviation sector, where gaseous fuels are not feasible (Millinger et al. 2017). However, the supply of 2-G feedstocks must be proven adequate, stable and affordable. In the following subsections, various 2-G feedstocks for BAF production are reviewed in this perspective.

### 3.2.1 Energy crops

Oil-seed energy crops, like jatropha (*Jatropha curcas*) and castor bean (*Ricinus communis*), have no food value, as their oils are toxic for human consumption (Shahare et al. 2017, Molefe et al. 2019). Oil content of jatropha and castor bean are typically 30–40% and 50–60 % of the seed weight, respectively (Tao et al. 2017, Heinrich 2018). Transesterification, catalytic cracking (pyrolysis) or hydroprocessing can process castor bean oil to produce BAF (Molefe et al. 2019). The hydrocracking of oils from castor bean and jatropha for enhanced BAF production has been recommended Molefe et al. (2019). Compared to castor bean, available literature shows jatropha as the more widely studied energy crop (Rye et al. 2010, Güell et al. 2012, Roda et al. 2015, Chiaramonti and Horta Nogueira 2017, Heinrich 2018, Neuling and Kaltenschmitt 2018, Yang et al. 2019). There have been both test and commercial flights using jatropha-blended jet fuel (Su et al. 2015, Chiaramonti and Horta Nogueira 2017). Currently, markets of jatropha and castor bean as BAF feedstocks are not yet mature (Tao et al. 2017).

Several grass and wood energy crops have been proposed as 2-G feedstocks for BAF production via thermochemical and/or biochemical routes (Kandaramath Hari et al. 2015). The high lignocellulose content and readily available harvesting technologies make grass energy crops attractive for biofuel production (Herr et al. 2012). Rödl (2018) identified the following grasses:

- Switch grass is a perennial crop native to North America with an average annual yield of 12 t/ha/yr (Jacobson 2013, Rödl 2018). It has a highly promising techno-economic and environmental performance as feedstock (Warshay et al. 2011). Experimental studies have been conducted for its conversion to BAF through fast pyrolysis-hydrotreating route (Howe et al. 2015), coal- and biomass-to-liquid hydrocarbon process (Folkedahl et al. 2011); and bio-based hydrocarbons production pathways (Sinha et al. 2015, Frederix et al. 2016). Techno-economic analysis reveals a break-even price of USD 1/L (or USD 5/gal) for ATJ fuel from switch grass (Yao et al. 2017); while life cycle assessment (LCA) shows that BAF from switch grass has lower emissions than from fossil sources (Agusdinata et al. 2011). No literature can be found reporting any large-scale production and/or test flights of switch grass-derived BAF.

- Miscanthus is a family of perennial plants from its native origins in Asia and Africa brought to Europe as a garden plant (Rödl 2018). The species, *Miscanthus x giganteus*, is of great research interest due to its high productivity with an average annual yield of 25 t/ha/yr (Jacobson 2013, McIsaac 2014). Miscanthus has been shown to have greater bioenergy potential than switch grass, based on studies in USA and Europe (Scagline-Mellor et al. 2018). Despite several studies demonstrating viable production of jet fuel precursors like syngas (Jayaraman and Gökarp 2015, Couto et al. 2017, Dupuis et al. 2019), pyrolysis oil (Conrad et al. 2019, Wang and Lee 2019) and ethanol (Lee and Kuan 2015, Boakye-Boaten et al. 2017, Lask et al. 2019). There is little to no systematic literature focusing on the conversion of miscanthus to BAF. Nevertheless, there have been proposed demonstration facilities for the production of miscanthus-derived jet fuel (Ondrey 2012, BBI International 2018).
- Napier grass or elephant grass (*Pennisetum purpureum*) is a perennial grass from the tropics with reported high yields of 20-140 t/ha/yr (Fontoura et al. 2015, Chang et al. 2017, Lamb et al. 2018, Rödl 2018). It is a promising feedstock for the production of both solid and liquid biofuels (Fontoura et al. 2015, Lamb et al. 2018). However, little to no literature is available for systematic study of its conversion to BAF. Research to date has been on the production of jet fuel precursor, such as syngas (Khezri et al. 2019, Mohammed et al. 2019), pyrolysis oil (Suntivarakorn et al. 2018, Mohammed et al. 2019) and alcohols (Camesasca et al. 2015, He et al. 2017). Napier grass cultivation in Southeastern USA is highly considered as BAF feedstock via ATJ (USDA 2012, Anderson 2016).

Compared to grasses, woods have higher biomass availability per area and lower logistics costs that could make them a better feedstock option (Murphy et al. 2015). Woody energy crops for biofuel production are usually short rotation coppices. These are fast growing trees that within a cycle or rotation (< 10 years) are coppiced/planted and then harvested (Murphy et al. 2015, Rödl 2018). Moreover, short rotation coppices can supplement low supply of grass energy crops during drought periods (Murphy et al. 2015). Rödl (2018) has also identified the following short rotation coppices as BAF feedstock produced at near intensive agro-industrial scale:

- Poplar (*Populus* spp.) is a family of temperate perennial trees that is also cultivable in warmer regions (Fazio and Barbanti 2014, Searle and Malins 2014, Rödl 2018). Globally, 70 nations grow poplar, with 91% in natural forests and the remainder in plantations; with an average annual yield of 9 t/ha (Ball et al. 2005, Rödl 2018). Although mainly utilised for paper and timber production, poplar utilisation for bioenergy is gaining traction among European countries (Ball et al. 2005). With the underlying reason for product diversification and expansion, poplar is a promising BAF feedstock (Crawford et al. 2016). Recent studies confirmed that poplar-derived hydrocarbons via pyrolysis and fermentation could be upgraded to jet fuel by hydrogenation (Crawford et al. 2016, Zhang et al. 2016). No literature can be found regarding test flights running on jet fuel derived from poplar.
- Willow (*Salix* spp.) is a genus of perennial flowering trees that grow from temperate to boreal regions with annual yields ranging in 4–10 t/ha (Searle and Malins 2014, Rödl 2018). About 94%, 6% and 1% of willows worldwide grow in natural forests, plantations and agro-forestry systems, respectively. Wood production is the main application of willows (Ball et al. 2005). Its application for heat and electricity production is a growing trend among Northern hemisphere nations (Sassner et al. 2006, Woytiuk et al. 2017). Several experimental studies demonstrated willows as viable source of jet fuel precursors, which include alcohols (Sassner et al. 2006, Han et al. 2013), syngas (Giudicianni et al. 2017, Woytiuk et al. 2017) and

350 pyrolysis oil (Giudicianni et al. 2017, Miettinen et al. 2017). Despite these, no literature can  
351 be found on systematic studies of BAF production from willows.

352 • Eucalyptus (*Eucalyptus* spp.) is a group of fast-growing trees originating from Australia  
353 (Gonzalez et al. 2011, Searle and Malins 2014, Rödl 2018). Plantations cover about more  
354 than 20 million hectares worldwide with an average productivity of 10 t/ha annually (Ferreira  
355 et al. 2019). Intensive cultivation is driven primarily by paper and biomass demands  
356 (Gonzalez et al. 2011, Surian Ganba et al. 2016). Bioenergy applications of eucalyptus is a  
357 growing sector in many parts of the world (Gonzalez et al. 2011, Eufrade Junior et al. 2016).  
358 In terms of BAF production, eucalyptus has been shown to be a promising feedstock in Brazil  
359 (Cantarella et al. 2015). Techno-economic assessments show that ethanol-to-jet fuel  
360 production pathway is more favourable than the butanol-to-jet fuel route but both are  
361 currently not cost competitive alternative (Silva Braz and Pinto Mariano 2018). Initial  
362 assessment of integrating BAF production from eucalyptus in Brazilian sugarcane  
363 biorefineries also show a favourable economic and environmental performance (Klein et al.  
364 2018). No references can be found on test flights running on eucalyptus-derived jet fuel.

365 Table 4 presents resource demands for cultivating the energy crops discussed. In contrast to 1-G  
366 feedstocks, energy crops typically (except for Napier grass) have low to moderate demand for  
367 fertilisers. Thus, their cultivation in non-fertile and non-food productive marginal lands have been  
368 the main recommendation (Murphy et al. 2015, Callegari et al. 2019, Lask et al. 2019). Dependent  
369 on the type of land-use change (LUC), energy crops grown and farming practices, cultivation in  
370 degraded or abandoned land may improve biodiversity by providing opportunities for habitat (Pedroli  
371 et al. 2013). The cultivation in metal-contaminated marginal lands can also lead to phytoremediation  
372 (Rutten et al. 2011, Pandey et al. 2016, Zalesny et al. 2019). The clean-up of highly saline and  
373 polluted agricultural soils with halophyte energy crops (e.g. *Salicornia bigelovii*) is another  
374 promising ecosystem service (Abideen et al. 2014). However, there are several drawbacks of  
375 cultivation in marginal lands. Marginal lands may have poor water access and supply that may be  
376 detrimental to water-intensive energy crops (Yan et al. 2018, Jiang et al. 2019). While some energy  
377 crops, like jatropha and Napier grass, could be argued as water-use efficient or even drought  
378 resistant, their yields are better with irrigation, which is highly recommended for farming in marginal  
379 lands (von Maltitz et al. 2014, Wani et al. 2016, Lamb et al. 2018). Hence, energy crops may  
380 indirectly compete with food production via water consumption. Marginal lands typically also have  
381 low agro-economic performance. Growing energy crops in these lands may be high in cost and result  
382 in lower yields (Searle and Malins 2014, Jiang et al. 2019). Often, commercial biomass developers  
383 opt for highly productive lands that give better returns on investment. Therefore, energy crops have a  
384 high risk to compete with food production for suitable lands and to expansion in forestlands  
385 (Schoneveld 2010, Keles et al. 2018). Clearly, inclusion of energy crops in the portfolio of BAF  
386 feedstock requires optimal land-use for truly genuinely available and suitable marginal land  
387 (Schoneveld 2010, Popp et al. 2014).

388 The high economic costs associated hinder the commercialisation of most lignocellulosic feedstocks  
389 (Correa et al. 2019). Hence, actual supply chains have yet to be fully realised. Notwithstanding,  
390 mathematical modelling and optimisation techniques have been applied to model these supply chains.  
391 Potential minimisation of costs within the agricultural, transport and industrial activities of the supply  
392 chain has been shown (Atashbar et al. 2016, Atashbar et al. 2018). To date, a few modelling studies  
393 have been published on energy crop supply chains for BAF provision. Perkis and Tyner (2018)  
394 presented a sequential start-up model, based on mixed-integer non-linear programming, with the aim  
395 of minimising the production and logistics costs of jet fuel from switch grass in Indiana, USA.  
396 Domínguez-García et al. (2017) developed a multi-objective mixed-integer linear programming

(MILP) model to plan strategically a cellulosic aviation fuel industry in Mexico. The model considers bio- and fossil-resources, biomass farming sites and processing technologies (including hydrogen production) in the minimisation of cost and CO<sub>2</sub> emissions of the supply chain. Samsatli et al. (2015) formulated a novel MILP for the Biomass Value Chain Model (BVCM) for the UK, which can comprehensively model a large variety of bioenergy system pathways including BAF production from energy crops. This model is also a flexible optimisation toolkit that can account economic and environmental impacts. Samsatli and Samsatli (2018) presented an optimisation model for the combined supply chains for biomass and wind energy to meet demands for services in the heat, power and mobility sectors. A general MILP model was also proposed by Samsatli and Samsatli (2018) for designing energy supply networks of eco-towns using biomass. The cost optimisation feature in these supply chain studies is important in demonstrating the cost-competitiveness and attractiveness to investors of an energy crops-based BAF business (Martinkus et al. 2018). However, a full-scale implementation of energy crops for jet fuel production would not only entail economic impacts. Both impacts on and synergies with food (land), water, energy and environment sectors are expected that are not typically assessed and analysed holistically in most biomass supply chain models (Tapia et al. 2019).

### 3.2.2 Waste biomass

Waste biomass could be better feedstocks over energy crops as they have no land requirement (co-produced from activities in agro-forestry, domestic, commercial and industrial sectors), little to no economic value, and lower water footprints than cultivated crops (Caicedo et al. 2016, Chiaramonti and Horta Nogueira 2017, Mathioudakis et al. 2017, Rödl 2018). Given the low-cost of most waste biomass, BAF developers have been rapidly considering these as feedstock (Mawhood et al. 2016, Barbosa 2017, Wenger and Stern 2019). BAF production from waste streams could be a superior option given that the energy requirements and emissions associated with cultivation only need to be accounted for once. If the amount of resources used for purifying and upgrading wastes into jet fuel is less than that for cultivated feedstocks, wastes will prove to be a more cost-effective option for the aviation industry's emissions reduction.

The first group of waste biomass come in the form of many agricultural and forestry residues. These are typically lignocellulosic by-products resulting from cultivation, harvesting, logging and post-harvest activities (e.g. milling, crushing, wood processing etc.) (Dornack et al. 2018, Staples et al. 2018). Primary and secondary agricultural or crop residues include corn stover, sugarcane bagasse, wheat straw, rice straw, rice hull, palm kernel and empty fruit bunches. On the other hand, primary and secondary forestry residues include unprocessed portions of felled trees (e.g. leaves, stumps, branches, and treetops), wood pulp, wood chips, scrap wood, cutter shavings and saw dust (De Corato et al. 2018, Dornack et al. 2018). Technologies to convert these lignocellulosic wastes into jet fuel precursors, such as syngas, pyrolysis oil, ethanol and butanol, are already available (De Corato et al. 2018, Huzir et al. 2018, Pandiyan et al. 2019, Schmitt et al. 2019). There have been initiatives reported of BAF derived from agro-forestry residues via isobutanol-to-jet and direct sugar-to-farnesene routes (AviationPros 2015, Green Car Congress 2016, Chiaramonti and Horta Nogueira 2017)

Systematic studies focusing on the production of BAF from agricultural and forestry residues are still few. Xue et al. (2017) presented a rational process design of integrating acetone-butanol-ethanol production from corn stover and their successive catalytic conversion (76% efficiency) to long chain ketones as jet fuel precursors. The economic and environmental analysis of Agusdinata et al. (2011) showed corn stover as BAF feedstock with least total unit cost and GHG emissions in meeting the GHG emissions reduction of USA's aviation industry by 2050 but it can only compete in the short-

443 term when CJF prices are high. LCA by Trivedi et al. (2015) confirmed that corn stover-based BAF  
444 via FT and advance fermentation have lower GHG emissions than CJF at 87% and 55%,  
445 respectively. Sugarcane bagasse, produced at 200 million tonnes annually, can be a significant  
446 feedstock for the production of biofuels for both road and air transport via established  
447 thermochemical production pathways like gasification and pyrolysis (Nicodème et al. 2018).  
448 Michailos (2018) conducted a techno-economic and life cycle analysis of BAF (farnesane)  
449 production from sugarcane bagasse via direct sugar to hydrocarbon route. With a low yield of 12.1%  
450 w/w fuel per sugarcane bagasse, the minimum jet fuel selling price (MJSP) would be USD<sub>2018</sub> 2.78/L  
451 (4 times greater than CJF) suggesting government subsidies will be needed; while 49% reduction in  
452 GHG emissions against CJF would be expected indicating a favourable sustainability potential. Roda  
453 et al. (2015) assessed the available crop residues for BAF production in Malaysia, an agricultural and  
454 developing country, to a maximum of 3.8 million litres per year from the waste streams of oil palm,  
455 rubber, sugarcane, coconut and rice industries. Although the quantity of oil palm residues is highest  
456 in Malaysia, the associated environmental concerns of its cultivation constraints its sustainable  
457 availability. There are also oil-rich agro-forestry residues that can be potential BAF feedstocks. Rice  
458 bran, a by-product of rice milling and annually produced at 75 million t/year, contains 10–20% w/w  
459 oil (Sharif et al. 2014, Nguyen et al. 2019). Nguyen et al. (2019) designed a transesterification  
460 process in the presence of Ni(II)-Schiff base chelate promoter catalyst and H<sub>2</sub> gas environment to  
461 convert rice bran oil to a biodiesel product with even better cetane index values and lower glycerol  
462 impurities than the conventional biodiesel. The hydrotreatment of rice bran oil in the presence of  
463 NiMo/Al<sub>2</sub>O<sub>3</sub> catalyst has also been performed yielding fuel products with similar to enhanced  
464 properties than petroleum ones (El Khatib et al. 2018). Alternatively, eucalyptus leaves can also be a  
465 source of high-octane oil, which has a potential biofuel application for road and aviation transport  
466 (Kainer and Kulheim 2016, Masimalai and Subramaniyan 2017). Due to yearlong production of  
467 forestry residues, they can be more preferable BAF feedstocks than crop residues (Richter et al.  
468 2018). Shah et al. (2019) showed that upgraded pyrolysis oil from sawdust of eucalyptus blended  
469 with waste cooking oil has similar physico-chemical characteristics to aviation kerosene. Alves et al.  
470 (2017) also found that ethanol-to-jet production pathway is a favourable techno-economic design for  
471 BAF production from eucalyptus residues in Brazil. Ganguly et al. (2018) also conducted a well-to-  
472 wake (WTW) LCA of BAF production from mild bisulfite pretreated forestry residues via butanol-  
473 to-jet production pathway that revealed a 78% reduction in global warming impact compared to CJF.

474 Food and municipal wastes are the second group of waste biomass that can be considered as  
475 feedstocks for BAF production. According to De Corato et al. (2018) and Dornack et al. (2018), this  
476 group consists of the following:

- 477 • Animal and fish farming wastes (e.g. manure, excreta, scales, scraps);
- 478 • Food processing wastes (e.g. de-oiled seed meals/cakes, exhausted pulps, slaughterhouse  
479 wastes, feathers, animal fats);
- 480 • Industry and commercial processing wastes from beer, wine, baking, dairy and cheese  
481 industries;
- 482 • Household/urban wastes (used cooking oil or UCO, used engine oils, kitchen wastes, spent  
483 coffee grounds and tea bags);
- 484 • Spoiled (unmarketable) vegetables, fruits, meat, bread, cheese and other by-products;
- 485 • Landscape management wastes (e.g. pruning, branches, twigs, leaves, flowers);
- 486 • Biomass/organic portion of municipal solid waste (MSW); and
- 487 • Biomass/organic portion of sewage sludge.

488 In the aviation industry, low cost UCO (waste cooking oil in some literature) is currently the only  
489 waste stream of practical use due to HEFA (Roth et al. 2018). The hydrotreating process of UCO is  
490 also continually being improved, such as development of a one-pot reaction, contrary to the  
491 conventional two-step process, (Zhang et al. 2018) and screening of catalyst and process conditions  
492 for better quality jet biofuel (Chen and Wang 2019). There have been many demonstration and  
493 commercial flights running on UCO-derived or UCO-blended jet fuel (Chiaramonti and Horta  
494 Nogueira 2017, Yang et al. 2019). UCO from households and restaurants ending up in the gutter has  
495 been recently used as jet fuel blends in Boeing flights in China (Karmee 2017). Animal fats (e.g.  
496 tallow, yellow grease), is another low cost food waste stream and a promising feedstock for BAF  
497 production (Chiaramonti and Horta Nogueira 2017). Biofuels produced from animal fats potentially  
498 have better combustion quality over those produced from oil-seed crops (Popov and Kumar 2013).  
499 Tallow was reported to be an environmentally favourable feedstock for biodiesel production due to  
500 its low life cycle GHG emissions (Kalnes et al. 2011). However, the demand by the transportation  
501 sector for tallow has to compete with increasing demands from the cosmetic and biochemical  
502 industries (Ernsting 2017). World consumption of animal fat, together with vegetable fat, have also  
503 increased due to biodiesel consumption (Mielke 2018). Though animal fats can be easily converted  
504 to jet fuel by hydroprocessing (Buchspies and Kaltschmitt 2018, Zhang et al. 2018), no literature can  
505 be found on commercial or demonstration flights running on animal fat-derived jet fuel.

506 MSW has also been increasingly considered as BAF feedstock. Dabe et al. (2019) reviewed the  
507 various existing and advancing thermo- and bio-chemical production pathways of syngas and  
508 alcohols from MSW as precursors for BAF conversion. Dabe et al. (2019) added that the current  
509 technologies could already enable the utilisation of the high-energy value of MSW and alleviate  
510 problems associated with landfills. In fact, Fulcrum Bioenergy is reported to produce jet fuel via FT  
511 commercially by processing 30,000 t/year of MSW by 2020 (Richter et al. 2018). On the one hand,  
512 Swedish Biofuels is expected to complete an ATJ demonstration facility this year (2019) that will  
513 process 5,000 t/year of MSW along with other waste streams (Mawhood et al. 2016). However,  
514 systematic studies focusing in the production of BAF from MSW seem limited. This lack of data on  
515 the performance and cost of MSW conversion technologies hinders strategic decision-making. Pham  
516 et al. (2010) performed a techno-economic assessment of a mixed fermentation process that uses  
517 MSW to produce jet fuel, gasoline and diesel in the USA. MSW comes with a tipping fee that is an  
518 average price of USD<sub>2010</sub> 45/dry tonne. For a 40 t/h plant with internal production of hydrogen, the  
519 MJSP is USD<sub>2010</sub> 0.33/L. Suresh et al. (2018) conducted a techno-economic and environmental  
520 assessment with Monte Carlo uncertainty analysis of BAF from MSW via FT and ATJ in the USA.  
521 The results revealed that production costs of BAF from MSW are still more expensive than CJF  
522 production with a MJSP of USD<sub>2018</sub> 0.99/L and USD<sub>2018</sub> 1.20/L of BAF via FT and ATJ,  
523 respectively. However, both show about 93% increase in net present value due to the GHG  
524 emissions savings via implementation of carbon pricing. Compared to CJF, life cycle GHG  
525 emissions reduce by 63% and 41% with BAF from MSW via FT and ATJ, respectively. There have  
526 been no reported test flights yet with jet fuel derived from MSW.

527 Logistical complexity and variable availability of waste biomass are the primary challenges as BAF  
528 feedstock (Iakovou et al. 2010, Mawhood et al. 2016). The bulkiness of some can lead to high  
529 logistic operating costs and constrain the capacity of centralised processing plants (Mawhood et al.  
530 2016). Collection, transportation and storage of large amounts of biomass wastes, like animal  
531 manure and MSW, are additional issues due to health and safety risks (Rentizelas et al. 2009, Downie  
532 and Van Zwieten 2013). Other waste management inadequate legislation, such as landfills,  
533 incineration and recycling, can potentially hinder their streamlined acquisition (Mawhood et al.  
534 2016). The highly uncertain availability of waste biomass remains an issue for their sustainable

535 utilisation (Roth et al. 2018). Many of the candidates as feedstocks are not available all year round  
536 and at the same location where they are needed (Staples et al. 2018). Compared to energy crops,  
537 studies on the potential and actual availability of waste biomass are limited (Roth et al. 2018).  
538 Hence, conversion technologies need to be robust in order to adapt to their variability and still  
539 produce the desired BAF product (Mawhood et al. 2016, Conrad et al. 2019).

540 Table 5 summarises all the supply chain models specifically for BAF provision reviewed in this  
541 paper. Studies on the supply chain of waste biomass for BAF production are still few. Most  
542 literature available are supply chain models for forest residues. Jacobson et al. (2016) developed a  
543 Forest Residue Economic Assessment Model (FREAM), a supply chain model integrated with GIS  
544 data and stakeholder engagement, for the simulation and cost estimation of harvest, transport and  
545 conversion of forest residues. A regional-scale production of BAF via ethanol-to-jet production  
546 pathway in Inland Northwest of USA was conducted revealing a total production cost of USD<sub>2016</sub>  
547 1.23/L with capital and transport accounting at 15% and 32%, respectively, of the total cost per tonne  
548 of forest residue processed. Martinkus et al. (2018) integrated multi-criteria decision analysis and a  
549 total transportation cost model for the assessment of existing industrial facilities within a forest  
550 residue-based depot-and-biorefinery supply chain. A least cost supply chain for woody biomass  
551 conversion into aviation fuel in Inland Northwest, USA was determined, which showed the capital  
552 and operational costs for disaggregated biomass pre-processing in depots are lower than an integrated  
553 biorefinery. Elia et al. (2013) developed a MILP model for the cost optimisation of a biomass-to-  
554 liquid supply chain producing diesel, gasoline and jet fuel using forest residues in the whole of USA.  
555 The BVCM by Samsatli et al. (2015) is also capable of optimising the cost and GHG emissions for a  
556 forest residue- and/or other waste biomass-based supply chain for jet fuel provision. Alves et al.  
557 (2017) performed a techno-economic assessment of co-producing renewable jet fuel and high-value  
558 platform chemicals in Brazil through a supply chain comprising of feedstock logistics, decentralised  
559 pretreatment facilities and a centralised biorefinery. Their results showed the ethanol-to-jet  
560 processing of eucalyptus residues or sugarcane residues as the most economically feasible. Contrary  
561 to studies focusing on economics, Ravi et al. (2018) studied the environmental impacts of a forest  
562 residue-based BAF supply chain in the Pacific Northwestern of USA. Using a regional air quality  
563 model with high-resolution, their results showed that the biorefineries can be a substantial local  
564 source of NO<sub>x</sub> and CO but regionally the increase is insignificant. Moreover, the utilisation of the  
565 residues in the supply chain results in air quality and health benefits outweighing the negative effects  
566 of pile burning. On the other hand, the sequential start-up model programme by Perkis and Tyner  
567 (2018) assessed the economic performance of a corn stover- and wheat straw-based BAF supply  
568 chain in Indiana, USA. The study found that the first batch of investors would opt for corn stover  
569 and situate conversion facilities near locations of high feedstock availability. Vast quantities of rice  
570 straw and rice husk in many rice producing counties can be a potential waste stream for BAF  
571 production (Roda et al. 2015). The MILP model for efficient and sustainable rice supply chains by  
572 Doliente and Samsatli (2019) is the first to consider the biomass-based production pathways of jet  
573 fuel using rice crop residues as feedstock. Lastly on waste biomass-based supply chains for jet fuel,  
574 Lewis et al. (2019) coupled the Biomass Scenario Model, a system dynamics model, to study the  
575 supply chain evolution in the USA, with the Freight and Fuel Transportation Optimization Tool, to  
576 determine optimal transport flows and routes. Their results show that BAF production from 75  
577 million to 4 billion litres per year is achievable with a mix of waste biomass streams and conversion  
578 technologies (HEFA leading in the short term and followed by advanced technologies in the long  
579 term). By considering the geo-spatial availability and holistically viewing the supply chain, these  
580 studies demonstrate the promising benefits of waste biomass and the respective conversion  
581 technologies in the provision of BAF (Mawhood et al. 2016, Gutiérrez-Antonio et al. 2017). Despite

582 these efforts, the supply and demand for waste biomass-derived BAF continue to be insignificant to  
583 CJF (Mawhood et al. 2016).

584 **3.3 Third-generation feedstocks**

585 Algae are of high interest due to having no food value, high yields with virtually no land  
586 requirement, and relatively low cost requirements (e.g. grown in suspensions requiring only sunlight,  
587 simple nutrients, and CO<sub>2</sub> that can be from industrial flue gases) (Cheng and Timilsina 2011, Lee and  
588 Lavoie 2013, Atashbar et al. 2018, Richter et al. 2018). Algae are capable of growing in polluted  
589 water or water unsuitable for agriculture that can simultaneously lower operating costs and provide  
590 wastewater treatment benefit (Acheampong et al. 2017, Alalwan et al. 2019). The demand for water  
591 (regardless of quality) by algae to produce 1 L of biodiesel is about 300–1000 L that is lower than  
592 most 1-G feedstocks (e.g. 5,500 L and 15,000 L for canola and soybean, respectively).

593 Microalgae is the type of algae dedicated for BAF production (Warshay et al. 2011, Rocca et al.  
594 2015, ATAG 2017, Richter et al. 2018). Microalgae are unicellular organisms with excellent  
595 photosynthetic efficiency and carbon fixation capability (Rocca et al. 2015, Su et al. 2017). Popov  
596 and Kumar (2013) have summarized the many advantages of microalgae over land-based crops as  
597 follows:

- 598 • High annual growth rates, e.g. an annual potential of 91 t/ha/yr (Stratton et al. 2010);
- 599 • High lipid content, e.g. average of 2–19%w/w (dry) but with some species in excess of 50%  
600 w/w (dry) (Rocca et al. 2015, Su et al. 2017);
- 601 • No competition with food crops; and
- 602 • Production of high value co-products.

603 Microalgae as feedstock promises both high productivity and availability of fatty acids readily  
604 convertible to BAF via HEFA (Ames 2014, Tao et al. 2017). Thermochemical routes via pyrolysis  
605 and hydrothermal liquefaction technologies are also increasingly being developed to simplify and  
606 diversify the production pathways (Chiaramonti et al. 2017). Hence, microalgae is widely regarded  
607 for large-scale biofuel production (Stratton et al. 2010). While there has been significant investment  
608 into algae biofuels, a number of logistical and technological issues persists (Warshay et al. 2011,  
609 Richter et al. 2018). Issues in the cultivation, harvesting and oil extraction technologies, which are  
610 still inefficient and/or capital- and resource-intensive, along with prohibitive environmental impacts  
611 block commercialisation (Doshi et al. 2016, Su et al. 2017, Behrendt et al. 2018). There have been a  
612 number of trial and pilot microalgae production plants, and demonstration flights run on algal-  
613 derived jet fuel but to date there is still no economically feasible production (Mawhood et al. 2016,  
614 Chiaramonti and Horta Nogueira 2017, Bwapwa et al. 2018, Richter et al. 2018).

615 Ames (2014) estimated the global potential of algal oil ranges from 350 billion L/year (limited  
616 productivity scenario) to 2 trillion L/year (high productivity scenario) with cultivation in Asia and  
617 North America to have the highest potential. However, locations having high availability of marginal  
618 lands, tropical to semi-arid climate, and close proximity to sustainable water and CO<sub>2</sub> sources are also  
619 favourable cultivation sites. Roth et al. (2018) reviewed the important criteria in selecting suitable  
620 sites for cultivating microalgae for BAF production. These include climatic conditions (e.g. available  
621 solar radiation and ambient temperature); terrain (commonly limited to <5% slope); sources of water  
622 (fresh or salt water); sources of carbon dioxide (e.g. power, biogas or fermentation plants) and;

sources of nutrients (e.g. synthetic fertiliser or dissolved nutrients in wastewater). Chiaramonti et al. (2017) added that in contrast to land-based crops, it can be technically feasible to modify the suitability of a site for microalgae cultivation (e.g. temperature control, artificial lighting and long-distance gas/liquid pipelines) but the economic and ecological costs associated with the alteration can become prohibitive. In the perspective of planning a microalgae supply chain for BAF provision, both the geo-spatial and temporal aspects of microalgae cultivation must be incorporated for optimal economic and environmental performance. With butanol as a pre-cursor to jet fuel, the study of Arabi et al. (2019) presented a multi-period MILP model for the planning and design of a microalgae supply chain for biobutanol in Iran. They integrated fuzzy programming and data envelopment analysis features to deal with uncertainties and tractability of the model, respectively. Other microalgae supply chain modelling studies available focus on biodiesel provision, such as the single-objective robust MILP model for national level supply (Mohseni and Pishvaaee 2016), multi-objective fuzzy linear programming model for a multi-product supply chain (Ubando et al. 2014), and a two-objective metaheuristic model for the stochastic location-inventory-routing in a nationwide supply chain (Asadi et al. 2018). So far, only the studies of Asadi et al. (2018) and Arabi et al. (2019) considered explicitly the site suitability of microalgae cultivation. All these studies dealt with minimization of cost, while only the studies of Asadi et al. (2018) and Ubando et al. (2014) considered minimization of environmental footprints. Agusdinata and DeLaurentis (2015) integrated LCA and multi-actors (stakeholder's decisions) to assess the environmental impact of an algal-based BAF supply chain in the USA. Their study confirmed the potential of algal biofuels, showing that they could reduce the life cycle CO<sub>2</sub> emissions by 85% of the country's airline industry by 2050. While present algal technologies are still economically nonviable in the next ten years or so, research on supply chain studies and generation of robust data must continue for microalgae-based biofuels (Behrendt et al. 2018).

### 3.4 Fourth-generation feedstocks

In the portfolio of feedstocks for sustainable aviation fuels, ATAG (2017) recognised the potential of non-biological resources and genetically modified organisms that are grouped together in a separate class called fourth-generation (4-G) feedstocks (Alalwan et al. 2019). Genetically modified organisms (e.g. microalgae, cyanobacteria, fungi and yeast) have artificially enhanced oil and/or sugar yields and negative carbon capabilities, which are mostly in infancy stage of research (Alalwan et al. 2019). In spite of their promising biofuel potential, more studies are needed on the health and environmental risks that these organisms can pose, on their containment, and/or mitigating strategies when they are deployed into the world's supply chains (Abdullah et al. 2019). Non-biological feedstocks (e.g. CO<sub>2</sub>, water, renewable electricity and sunlight) can potentially be the more environmentally benign option especially when flue gases from industrial plants are utilised (ATAG 2017, Richter et al. 2018). One route is power-to-liquid (PtL) which involves the splitting of water into hydrogen and oxygen via a renewable-electricity-powered electrolyser and then hydrogen is combined with CO<sub>2</sub>/CO to produce BAF (ATAG 2017, Schmidt et al. 2018). A recent techno-economic and environmental analysis of Schmidt et al. (2018) showed that the short term costs of PtL fuels (driven mainly by the price of renewable power) are greater than CJF. However, the environmental benefits of PtL fuels (e.g. nearly carbon neutral and low requirements for water and land) along with improvements in economies of scale can potentially outweigh the economics and externalities of CJF in the long-term. Another route is the use of concentrated solar energy in splitting water and CO<sub>2</sub> to produce syngas as a precursor for BAF production (Richter et al. 2018). While both routes are still at the early stage of research, Richter et al. (2018) has identified two European initiatives, Sunfire and SOLAR-JET, that demonstrated the production of jet fuel with CO<sub>2</sub>, water and solar energy. In terms of the studies on supply chains of 4-G feedstocks, although limited

670 to date, Mesfun et al. (2017) applied a spatio-temporal MILP model for the integration of power-to-  
671 gas (PtG) and power-to-liquid technologies in an Alpine energy supply. Depending on the pricing of  
672 fossil fuel and carbon, the study confirmed that renewable energy systems become more flexible  
673 when integrated with PtG and PtL technologies as these convert the excess intermittent renewable  
674 power to fuels and enable the utilisation of large amounts of captured CO<sub>2</sub> (0.20–15 million tonnes  
675 per year) via fuel production. When these technologies become commercially mature, BAF from 4-  
676 G feedstocks promise to be the most sustainable with the potential for negative carbon emissions and  
677 interlinking power, heating and aviation sectors (Mesfun et al. 2017, Richter et al. 2018).

### 678 3.5 Economic analysis

679 The delivered cost of a feedstock accounts for the total costs of cultivation/plantation, harvesting and  
680 other post-harvest processing, storage, and transporting to the biorefinery (Gonzalez et al. 2011,  
681 Daystar et al. 2014). Figure 3(a) shows a relative comparison and breakdown of the delivered costs  
682 of some 1-G and 2-G feedstocks. Budzianowski and Postawa (2016) stated that the delivered cost at  
683 the biorefinery gates directly affects the economic feasibility of BAF, which can significantly  
684 contribute to the total production cost at about 50% or more, especially for food crops. Studies on  
685 the supply chain for BAF provision by Newes et al. (2015) and Alves et al. (2017) show that  
686 profitability is sensitive to the feedstock price. The comprehensive techno-economic assessment of  
687 Tao et al. (2017) on HEFA in USA have also revealed the price of oil as one of the main cost drivers  
688 of production. Hence, its economic success as a short- to medium-term solution lies upon the choice  
689 of oil-rich feedstocks.

690 Low-cost and/or high yielding oil-seed crops, such as oil palm and jatropha, are going to be the  
691 feedstock choices for BAF production (Ernsting 2017, Tao et al. 2017). With better productivity of  
692 these crops in tropical regions (Schoneveld 2010), countries with high jet fuel demand and low-  
693 yielding and/or expensive domestically-grown oil-rich crops would resort to importing cheaper  
694 vegetable oil from the tropics. However, importing vast quantities of oil will be costly for the  
695 environment. As the purchasing country becomes more dependent on imports, potential embargos or  
696 sanctions can also occur in the long term. Given the national burden of importation, countries should  
697 diversify their feedstocks to improve self-sufficiency (Zaher et al. 2015). Conversely, exporting  
698 countries, with favourable climatic conditions and large cultivable lands, can obtain potentially huge  
699 economic gain. In the case of Indonesian oil palm industry, Susila (2004) reported that jobs  
700 generated in the cultivation and milling sectors resulted in the country's national economic growth  
701 and regional decrease in poverty. However, exporting can also become a national burden as these  
702 countries become dependent upon the income of exports and vulnerable to market forces demanding  
703 shifts to a new feedstock. In either case, this diversification and/or shifting to other feedstocks entails  
704 land. Agusdinata et al. (2011) has highlighted that both oil price and land availability govern the  
705 viability of a feedstock. Despite of the potential economic benefits from cultivating productive  
706 feedstocks for low-income countries in the tropical region, it is vital to note that the majority of  
707 people at risk to food-insecurity that rely heavily on agricultural land for their livelihoods  
708 (Alexandratos 1999). Thus, it is important to ensure that BAF feedstocks used do not place a greater  
709 strain upon the populations by either farming 1-G feedstocks on arable lands that would have been  
710 processed and eaten or encouraging farmers to switch to 2-G feedstock cultivation that would reduce  
711 available arable land for food production. Moreover, the rapid increase in oil palm plantations in the  
712 past three decades has been linked to deforestation, biodiversity loss and increased greenhouse gas  
713 emissions (Page et al. 2011, Pirker et al. 2016, Vijay et al. 2016). These environmental concerns  
714 result in friction towards the use of biofuels, which can negate the progress of current investments on  
715 BAF (Ernsting 2017).

716 UCO and animal fats are going to be important in the choice of feedstocks for HEFA due to their  
717 relatively lower costs (Mandolesi de Araújo et al. 2013, Tao et al. 2017). Figure 3(b) presents the  
718 average market prices of fresh and waste oils for the production of biofuels. Although UCO has  
719 essentially negligible delivered cost, Mandolesi de Araújo et al. (2013) reported that UCO is usually  
720 priced about 2 and 3 times less than fresh edible oil. Roth et al. (2018) added that there is a global  
721 potential of about 6 to 7 billion L/y of bio-aviation fuel based on UCO. However, the persisting  
722 unaddressed uncertainty and variability of waste streams raises concerns of their significant  
723 contribution in the future jet fuel supply mix (Mawhood et al. 2016, Roth et al. 2018). Furthermore,  
724 the UCO demand in BAF production has to compete with established demands for biodiesel  
725 production (Roth et al. 2018). Lastly, in the view of economies of scale, Dodd et al. (2018) have  
726 recently found through a qualitative investigation of industry experts that the limited capacity of  
727 feedstocks is the major hindrance for the growth of the sustainable aviation fuels industry.

728 When proven commercially feasible, microalgae as a feedstock of HEFA is expected in the future.  
729 Its current high price bars its utilisation as biofuel feedstock (Tao et al. 2017). The pricing of algal  
730 oil is significant to the overall viability of a microalgae-based HEFA. Sun et al. (2011) carried out a  
731 rigorous comparative cost analysis that revealed no strong correlation between production scale and  
732 the cost of producing algal oil because of increased capital costs associated with the infrastructure  
733 required for algal cultivation. Sun et al. (2011) recommended that the ideal method of improving the  
734 production costs was to identify a strain of algae capable of yielding a high lipid content while  
735 sustaining a strong growth rate. The sensitivity analysis in the same paper showed that a two-fold  
736 increase in both lipid yield and algal production could improve cost structure of the business by half.

737 Given the relatively low delivered costs of MSW, agro-forestry residues and lignocellulosic energy  
738 crops, they are economically promising feedstocks for the yet commercially feasible FT and ATJ  
739 (Dupuis et al. 2019). When the more advanced technologies become commercially viable, these  
740 feedstocks are key to the medium- and long-term decarbonisation of the aviation industry (Lewis et  
741 al. 2019). A direct economic comparison of feedstocks, however, is generally difficult to carry out  
742 due to the many interdependent factors for consideration, which are for some both spatially and  
743 temporally dependent. The outlook and geographic location of aviation industries are also  
744 interdependent, which have potential implications on the policies and implementation for sustainable  
745 aviation fuels (Dodd et al. 2018). Furthermore, perspectives by the society, culture and market in a  
746 specific region results in large differences in its supply chain configuration for BAF from other parts  
747 of the world (Murphy et al. 2015).

### 748       3.6 Environmental analysis

749 The environmental impacts of the feedstock accounts for the total emissions associated with  
750 cultivation/plantation, harvesting and/or post-harvest processing, storage and transportation of the  
751 feedstock to the biorefinery gate (Gonzalez et al. 2011, Daystar et al. 2014). Daystar et al. (2014)  
752 carried out this cradle-to-gate analysis of the life cycle greenhouse gas emissions of cellulosic  
753 biomass supply chains for biofuel provision in the Southern USA. Recently, O'Connell et al. (2019)  
754 conducted a similar analysis on the feedstocks supply chains for BAF provision in the EU. Figure  
755 4(a) presents a relative comparison of the cradle-to-gate GHG emissions of feedstocks for BAF  
756 production.

757 Cultivation and harvesting of 1-G and 2-G feedstocks represents significant contributions to their  
758 total GHG emissions due to the continued reliance on fossil fuels in both the direct and indirect  
759 inputs of many farming activities (Pimentel 2009, Liu et al. 2017). Direct inputs include diesel and

760 gasoline to power machineries for land preparation and cultivation, pumps for irrigation and vehicles  
761 for transportation. While indirect inputs consist of fertilisers, pesticides, water, and seeds whose  
762 embodied energy (from production to transportation in the farm) are also from fossil fuels (Azwan et  
763 al. 2016, Elsoragaby et al. 2019). Typically, GHG emissions from fertilisers account for most of the  
764 indirect inputs since their chemical production requires large amounts of natural gas (Pimentel 2009,  
765 Liu et al. 2017). Post-harvest processing can also be a significant source of GHG emissions. For oil-  
766 bearing crops, oil mills require electricity and heat that are mostly fossil-based. Figure 4(b) depicts a  
767 relative comparison of the energy requirements for farming and oil milling of oil-seed crops for BAF  
768 production. To improve the environmental sustainability of a BAF feedstock, the use of biofuels in  
769 the machineries and bio-electricity/heat (from agro-forestry residues) in milling operations should be  
770 practiced (Sims et al. 2015). Storage and transport (to the mill and/or bio-refinery gates) of the  
771 harvested and/or pre-processed feedstocks usually account to a minor portion of the total GHG  
772 emissions. A transport process is a function of load and distance (Cefic and ECTA 2011). Greater  
773 GHG emissions result from transporting large amounts of feedstocks over large distances. Importing  
774 processed oil from the tropics to EU have been reported to result in additional GHG emissions  
775 (O'Connell et al. 2019). While some storage facilities may use minimal energy, feedstock  
776 requirements may use considerable energy and lead to GHG emissions, especially when fossil-based  
777 (Egg et al. 1993, Emery et al. 2015).

778 Among oil-seed food crops, O'Connell et al. (2019) demonstrated that oil palm cultivation grown in  
779 mineral soil have the least GHG emissions (Figure 4(a)). Elgowainy et al. (2012) showed that palm  
780 oil extraction energy requirement is also the least (Figure 4(b)). Hence, oil palm as BAF feedstock  
781 may be the best food crop-based option, even when considering an average of 6.0 gCO<sub>2</sub>eq emissions  
782 associated with transporting to the EU. However, when LUC associated with cultivation happens,  
783 land-based crops like oil palm become environmentally unsustainable feedstocks. LUC can result in  
784 both direct and indirect emissions (Bauen et al. 2009). Direct LUC emissions represent activities  
785 associated with changing the land from its past condition to feedstock cultivation. While indirect  
786 LUC emissions, due to low availability of arable lands, result from land expansion at the cost of  
787 deforestation. Even without considering the indirect LUC emissions of recent land expansion of oil  
788 palm plantations, O'Connell et al. (2019) confirmed a staggering 100 to 600 times increase in GHG  
789 emissions from direct LUC of 16% and 100% peatland, respectively. The resulting life cycle GHG  
790 emissions of oil palm grown in peat land are even higher than the production of CJF at 20  
791 gCO<sub>2</sub>eq/MJ. In the investigation of ICAO (2009), peatland forests being repurposed into plantations  
792 have increased GHG emissions by a factor of 7.5. Large amounts of carbon stored in peatlands have  
793 not only been removed from biomass clearing, but new plants grown typically have much lower  
794 carbon storing capacities. Murdiyarso et al. (2010) quantified a 254.5 tec/ha storing capacity for  
795 natural peatland reduces to 24.2 tec/ha for oil palm cultivation. Hence, large-scale clearing of  
796 peatland forests would potentially result in large increases of atmospheric carbon. Although the  
797 work of O'Connell et al. (2019) focused on oil palm, other land-based crops can display the same  
798 trend of increased emissions when cultivated in peatland forests. Research conducted by Wong  
799 (2008) and ICAO (2009) showed that LUC for biomass cultivation have the potential for high GHG  
800 emissions. Page et al. (2011) recommended that the reuse of peatland for energy crop cultivation  
801 should be avoided due to its environmental consequences.

802 Considering that the type of land-use conversion is a vital consideration for feedstock cultivation, the  
803 use of marginal land for energy crops can ensure avoidance of LUC emissions and preservation of  
804 agricultural land (Rathmann et al. 2010, Lask et al. 2019). In the case of jatropha cultivation, direct  
805 LUC emissions of converting degraded pastureland is 42 times less than that of converting a tropical  
806 rainforest as shown in Figure 4(a). However, energy crops like jatropha have low productivity in

807 marginal lands, which significantly improves in suitable lands (von Maltitz et al. 2014, Wani et al.  
808 2016, Lamb et al. 2018). Hence, their possible encroachment on both agricultural land and forestland  
809 can potentially result in significant LUC emissions and their poor environmental sustainability as  
810 BAF feedstocks (Schoneveld 2010, Keles et al. 2018). If LUC emissions are to be significantly  
811 abated, waste streams and algae represent the best alternatives. Considering that algal cultivation  
812 continues be a long-term tech-economic endeavor, the utilisation of waste streams, such as UCO,  
813 agro-forestry residues, and MSW, has to be prioritised within the short- to medium-term that is  
814 attested by several initiatives and projects of BAF developers (Mawhood et al. 2016). In Figure 7,  
815 GHG emissions of waste biomass are significantly lower than all land-crop based feedstocks.  
816 Moreover, LCA of feedstocks for high-octane gasoline production by Dupuis et al. (2019) showed  
817 waste biomass to have the least cradle-to-gate GHG emissions with forest residues as most  
818 environmentally benign in both feedstock and fuel production phases. Although the utilisation of  
819 agro-forestry residues are going to be essential in meeting sustainable energy goals, they also play a  
820 significant role in maintaining soil carbon for productivity function and ecosystem services (Karlen  
821 et al. 2019). Hence, only a certain portion of these resources is truly retrievable from the plantations,  
822 which could be a limiting factor of their actual contribution in BAF production. At the current state  
823 of technology and GHG emissions, a similar conclusion by Roth et al. (2018) shows UCO as the  
824 most environmentally sustainable feedstock for BAF production.

825 A BAF cannot be preferable over the existing solution unless the net carbon emissions of its life  
826 cycle, from feedstock production, fuel conversion and combustion, are lower than CJF. Bauen et al.  
827 (2009) found that GHG emissions savings over the life cycle of biofuel production depend heavily on  
828 the feedstock used. Table S3 summarises WTW life cycle emissions for both 2-G and 3-G  
829 feedstocks. WTW life cycle comprises both well-to-tank (WTT) and tank-to-wake (TTW) stages.  
830 Elgowainy et al. (2012) defined WTT stage as all GHG emissions resulting from feedstock  
831 production, fuel production, emissions associated with the creation of co-products and all transport  
832 processes within these elements. Whereas, TTW stage incorporates the combustion and use of the  
833 fuel in the engine. However, Table S3 do not consider emissions due to direct or indirect LUC.  
834 Nevertheless, WTW results show promising environmental sustainability of energy crops, waste  
835 biomass and algae as feedstocks.

#### 836 4 Production pathways for synthetic paraffinic kerosene

837 There have been great strides made in the research on BAF production platforms, which some have  
838 been approved for industry use. Figure 5 shows the relative maturity of these technologies in terms  
839 of fuel readiness level (FRL) against the resource availability of feedstocks. Having commercial  
840 readiness at  $FRL > 7$ , bio-aviation fuel from FT and HEFA have been approved in up to 50% blends  
841 with CJF (ASTM 2019). Fuel approval in the form of certification from a recognised authority has  
842 been achieved after laboratory tests, technical evaluations and successful pilot-scale plants.  
843 Microbial sugar-to-jet and ATJ technologies have been also approved but at lower blends. Following  
844 further research and flight tests, their efficacy with the existing engines determines the approval of  
845 higher blends in the future. Increasing the FRL would entail additional investments, studies and  
846 demonstrations but as long as a technology receives continued interests, its commercialisation could  
847 happen in the coming years. The aviation industry could potentially choose from a variety of  
848 production pathways based on available feedstock and existing infrastructure. Consequently, these  
849 can help reduce geographical dependency on feedstock and ultimately make global implementation  
850 of BAF possible. Although many emerging technologies will be important soon, this paper focuses  
851 on three prominent production methods with higher FRL and potential for implementation. The  
852 following subsections discuss and compare HEFA, FT and ATJ.

853

## 4.1 HEFA

854

### 4.1.1 Process description

855

Feedstocks for HEFA include animal fats, vegetable oils and algal oils (Seber et al. 2014). HEFA often use waste oils and fats that are more sustainable sources. Suitable and sustainable feedstocks can also be determined for individual countries based on geographical and industrial characteristics. Nevertheless, the applicability of HEFA to a wide variety of oil-rich 1-G and 2-G feedstocks allows global viability of the technology. On the other hand, bio-aviation fuel from HEFA is a specific type of HVO fuel used in aviation. Hydrotreated vegetable oil (HVO) production is a mature and established technology of the automotive industry. There are several existing companies already producing bio-aviation fuel via HEFA but at lower outputs compared to crude oil refinery production (Table S4). Most of these companies focus on producing biodiesel and/or bio-aviation fuel. These have capacities ranging from 0.1 million tons to about 100 million tons annually (Vásquez et al. 2017). A particular HVO pathway, the UOP Honeywell process or 'Ecofining', is certified to produce aviation fuel from renewable sources (Bwapwa et al. 2018). This technology primarily produced green diesel but it has been the most established technology for bio-aviation fuel production for over 10 years (Stratton et al. 2010).

869

A simplified process flow diagram of HEFA by UOP is shown in Figure S2(a). It involves four main steps, namely: refinement, deoxygenation and hydrogenation, cracking and isomerisation, and distillation (Richter et al. 2018). The extraction and refinement stages of the process can be made more or less expensive depending on the quality and type of feedstock used. The oil can be extracted using methods that include centrifugation, filtration and traditional pressing mechanisms. Depending on the oil purity required, a variety of purification and treatment processes are available such as steam injection, neutralisation, vacuum evaporation and filtration (Mandolesi de Araújo et al. 2013).

876

Figure S2(b) summarises the reaction pathways for HEFA. The building blocks that constitute vegetable oils are fatty acid carbon chains found within triglyceride molecules. Initially, the double bonds in the fatty acid carbon chains are converted to single bonds by the addition of H<sub>2</sub> (Vásquez et al. 2017). Then, the triglycerides are broken down into three fatty acid chains and propane by further cracking with H<sub>2</sub>. Through cracking, long hydrocarbon chains are reduced to specified lengths within the jet fuel range. The subsequent processing involves the removal of oxygen from the fatty acid chain (Choudhary et al., 2011). These processes differ in side products and H<sub>2</sub> requirement: a) hydrodeoxygenation produces H<sub>2</sub>O molecules; b) decarboxylation produces CO<sub>2</sub>; and c) decarbonylation produces CO and H<sub>2</sub>O in addition to the fatty acids (Boichenko et al, 2013). During deoxygenation reactions, linear hydrocarbons chains are made to contain only carbon and hydrogen atoms. Important factors in these reactions include are H<sub>2</sub> input that is used to saturate the fatty acid chains and cleave the glycerol backbone, and catalyst selection to improve the yield. The reaction occur between 250 °C and 400 °C and between 10 and 18 bar with a variety of possible catalysts like NiMo/γ-Al<sub>2</sub>O<sub>3</sub> and CoMo/γ- Al<sub>2</sub>O<sub>3</sub> (Popov and Kumar 2013). Sulfidation agents can be added to improve yields in order to maintain catalyst activity (Eller et al. 2016). Thereafter, the combustion properties of the products are improved by further processing through either isomerisation, cracking or cyclisation to obtain iso-alkanes, lighter hydrocarbons and aromatics, respectively. In isomerisation, linear hydrocarbon chains are converted into branched hydrocarbons with the same carbon number, which can result to improvements the freezing point of the bio-aviation fuel (Gutiérrez-Antonio et al. 2013). Finally, distillation separates the bio-aviation fuel from the other product streams.

897 **4.1.2 Advantages**

898 Gutiérrez-Antonio et al. (2013) outline the advantages of HEFA. The reaction is exothermic and as  
899 such, the energy generated in the first reaction can be used to decrease the energy costs for the overall  
900 process, which has positive economic and environmental implications. Notably, the quality of fuel is  
901 independent of the feedstock used whereas the quality of fatty acid methyl ester (FAME) is known to  
902 depend heavily on the choice of feedstock. BAF from HEFA has characteristics that outperform  
903 CJF. The BAF produced has a higher heating value (44 MJ/kg) and faster ignition than Jet A. It is  
904 also less susceptible to oxidation than FAME, which makes it a suitable aviation fuel (Crown Oil UK  
905 2019). Note that the limited oxygen proportion in jet fuel needs to be considered, especially to  
906 prevent contamination of the fuel supply due to oxidation. Liati et al. (2019) reported that blending  
907 Jet A-1 with 35% BAF via HEFA generates less reactive soot when aircraft are idling (on the  
908 ground) or climbing out (during take-off). This is an important factor for jet fuels as this affects air  
909 quality in regions close to the airport. Given the commercial maturity of HEFA, there have been  
910 several pilot-scale plants and demonstration (and some commercial) flights using BAF via HEFA  
911 (Mawhood et al. 2016, Chiaramonti and Horta Nogueira 2017).

912 **4.1.3 Limitations**

913 Despite being technically feasible for commercial deployment, HEFA is largely constrained by  
914 resource availability. The supply of oil required for these processes, provided by oil-rich crops and  
915 waste oils, is currently insufficient to meet projected industrial demands (Bosch et al. 2017). Rye et  
916 al. (2010) argue that HVO production is more suitable for diesel production than jet fuel. They state  
917 that the chain length of most triglycerides from plants are closer to the length of diesel oil in their  
918 unrefined state (C<sub>14</sub> to C<sub>20</sub>). Hence, the production of alkanes by cracking these triglycerides uses  
919 large amounts of hydrogen: about 10–15 moles per mole of triglycerides (Huber et al. 2007). The  
920 most commonly used method for hydrogen production is natural gas steam reforming, making up  
921 50% of global hydrogen demand; whereas, steam reforming of other fossil fuels including oil and  
922 coal make up a further 48% of the world hydrogen demand (Dincer and Acar 2014). With hydrogen  
923 used extensively across the whole spectrum of HVO jet fuel production, there is a need for alternative  
924 and sustainable sources of hydrogen. Recently, there has been increased interest regarding the use of  
925 hydrogen as a fuel in fuel cells (Samsatli et al. 2017) and as a medium for energy storage (Samsatli  
926 and Samsatli 2019, Quarton and Samsatli 2018). As a result, alternative production methods to  
927 reduce emissions and reduce cost have been gaining momentum through investment and research  
928 (Dincer and Acar 2014). Process optimisation may be able to reduce the hydrogen consumption but,  
929 of course, not to below the stoichiometric requirements and existing processes already recycle most  
930 of the unused hydrogen (Popov and Kumar 2013). Stratton et al. (2010) suggested retrofitting of  
931 existing petroleum refineries to accommodate a HVO facility, which permits access to on-site  
932 hydrogen production facilities. Moreover, the naphtha fractions after distillation can be easily  
933 reincorporated into the petroleum pipelines for further processing into valuable products.

934 **4.2 FT**

935 **4.2.1 Process description**

936 In comparison with HEFA, FT is more attractive due to a greater variety of options for feedstocks  
937 that do not compete with the food supply. Many commercially established plants use FT with fossil  
938 fuel feedstock, such as coal and natural gas, and the technology of producing liquid transportation  
939 fuels is well established (Ail and Dasappa 2016). In South Africa, Sasol, an energy and chemicals  
940 company, operate multiple synthesis plants using ‘coal-to-liquid’ process (CTL) (Ail and Dasappa  
941 2016). A 50% blend of BAF via FT and CJF known as Sasol’s ‘Semi Synthetic Jet Fuel’ has been

942 supplied to Johannesburg since 1999 (Lobo et al. 2011). The fuel produced using biomass is  
943 identical to CTL and very similar in composition to jet fuel but with lower net GHG emissions  
944 (Bauen et al. 2009). It is also reported that the energy efficiency of BAF via FT (77%) is higher than  
945 that of coal-based (64%) or natural gas-based (68%).

946 Figure S3(a) presents the major steps involved in FT. During gasification, biomass is reacted with  
947 oxidants (most commonly CO<sub>2</sub>, steam or air) in a ratio such that partial oxidation occurs, producing  
948 CO and H<sub>2</sub> rich gas, also known as syngas. The ratio of H<sub>2</sub> to CO is determined partially by the  
949 oxidant used (Klinghoffer 2013). To produce high yields of heavier hydrocarbons that is necessary  
950 for BAF, a lower H<sub>2</sub> to CO ratio is ideal making CO<sub>2</sub> a better choice than steam (Raje and Davis  
951 1997). Following the gasification, the syngas stream is purged of impurities and unwanted  
952 compounds including CO<sub>2</sub> and other gaseous impurities before the synthesis. The removal of CO<sub>2</sub>  
953 from syngas improves the selectivity of the downstream process. On the other hand, the removal of  
954 H<sub>2</sub>S avoids the deactivation of the catalyst (Wei et al., 2019). Iron and cobalt are the main catalysts  
955 used. The CO to H<sub>2</sub> ratio is managed by water-gas-shift reaction, and subsequent CO<sub>2</sub> removal is  
956 made. Then the Fischer-Tropsch synthesis takes place. The basic reactions underpinning this  
957 produce alkanes or alkenes with water as a by-product as displayed in Figure S3(b) (Radich 2015).  
958 Fischer-Tropsch reactions can occur as either a high-temperature process (300-350 °C) or a low-  
959 temperature process (200-240 °C) (Dry 2002). These reactions are extremely exothermic and, as a  
960 result, it is important that this heat is removed quickly and efficiently to prevent the catalyst  
961 deactivation due to sintering and to minimise unwanted methane production (Dry 2002). Ail and  
962 Dasappa (2016) stated that modern plants use low temperature processes for producing liquid fuels.  
963 These plants commonly use a multi-tubular reactor wherein the catalyst is placed within the tubes  
964 and the cooling medium on the shell side. Other conditions can also be altered during the reactions,  
965 such as pressure, type of catalyst and residence time, in order to specify the hydrocarbon ranges in  
966 the product (Dry 2002). Following Fischer-Tropsch synthesis, lighter hydrocarbons can be  
967 oligomerised or heavier hydrocarbons can be cracked to increase or decrease, respectively, in order to  
968 obtain bio-aviation fuel having hydrocarbon lengths within the specified range (Richter et al. 2018).  
969 The crude products are then isomerised to generate branched iso-alkanes from n-alkanes in order to  
970 produce a jet fuel product within the specified freezing point. Lastly, the bio-aviation fuel is  
971 separated from the isomerised products using distillation.

#### 972 4.2.2 Advantages

973 One advantage of BAF via FT is that the aromatics content is within the permitted range and the  
974 product is generally sulphur-free, which results to reduced emissions when burned in jet engines  
975 (Wei-Cheng Wang, 2015). Fuel production methods that contain no aromatics are unsuitable for use  
976 in an aircraft engine without blending with Jet A-1, as the aromatics content of the fuel is essential  
977 for the engine fuel seals to function properly (Corporan et al. 2011, Liu et al. 2013). However, fuels  
978 with a high aromatics content form a larger amount of carbonaceous particles which can have  
979 detrimental effects including engine failure and erosion on turbine blades after combustion  
980 (Hemighaus et al. 2006). Having aromatics within the allowable range increases the viability to gain  
981 accreditation for use as a stand-alone fuel without blending. Gray et al. (2007) found that these  
982 additional requirements in producing BAF via FT, compared to other products (e.g. biodiesel), do not  
983 add significant costs to the process. From an economic perspective, this increases the feasibility of  
984 constructing an FT facility as ratios of products can be altered easily to maximise profits.

985 **4.2.3 Limitations**

986 While FT is a very promising avenue due to nearing commercial maturity of the technology and wide  
987 variety of applicable biomass feedstocks, de Jong et al. (2017) commented that much of the current  
988 progress of FT is still based on coal and natural gas as the feedstock. Ernsting (2017) stated that even  
989 the successful coal-based Sasol FT plant would be unable to compete with CJF without heavy  
990 subsidy from the South African government as CTL is still a relatively expensive technology.  
991 Ernsting (2017) also argued that the implementation of high-volume production via FT is unlikely in  
992 the near term based on the failed efforts of companies like Choren Tech GmbH and Solena.

993 British Airways partnered with Solena in 2012 with plans to produce BAF via FT from MSW by  
994 retrofitting an unused petroleum refinery near London (Radich 2015). However, Solena filed for  
995 bankruptcy and British Airways scrapped the project in 2016. A spokesperson from British Airways  
996 attributed this to the lack of government support and record-low oil prices at the time (Neslen 2016).  
997 This validates the comments by Hendricks et al. (2011) that the large-scale development of BAF may  
998 prove difficult without the strong collaboration between the government and the aviation industry.

999 **4.3 ATJ**

1000 **4.3.1 Process description**

1001 ATJ can be used for sugar-rich or lignocellulosic biomass feedstocks (Wei et al. 2019). These  
1002 biomass raw materials can be converted to ethanol first by hydrolysis to release the sugar and then  
1003 fermentation takes place to convert it to ethanol. When ethanol is used as a feedstock, the choice of  
1004 intermediate defines the reaction pathway taken; examples of the intermediates include ethylene,  
1005 propylene, higher alcohols, and carbonyl (Brooks et al. 2016). The intermediate chosen dictates the  
1006 method of production and reaction conditions but with each method having a number of benefits and  
1007 drawbacks. Brooks et al. (2016) compared these technologies with a variety of parameters including  
1008 catalyst cost, process efficiency, level of maturity, and process complexity. Ethylene, propylene and  
1009 butene were found to perform better than the other intermediates explored with regards to these  
1010 parameters.

1011 The process diagram for ATJ depicted in Figure S4(a) are similar for all alcohol feedstock and  
1012 intermediates. Due to the maturity of the technology associated with alcohols, each stage has been  
1013 researched extensively. The alcohols are firstly dehydrated. The removal of water yields alkene  
1014 molecules, while simultaneously removing impurities. Dehydration of ethanol for ethylene  
1015 production has been in use since the 1960s, so routes with higher selectivity using heterogeneous  
1016 catalysts have been developed, such as 'Syndol', a specialised catalyst for this process (Geleynse et  
1017 al. 2018). For isobutanol, the use of strong acidic catalysts can have a two-fold effect of dehydration  
1018 and commencing the oligomerisation reaction but the fuel produced has been found to be inferior in  
1019 quality to that produced if the reactions were to occur separately (Taylor et al. 2010). In the  
1020 oligomerisation step, the alkene monomer molecules are reacted to synthesise longer chain  
1021 molecules. As presented in Figure S4(b), the larger oligomers (olefins) remain unsaturated,  
1022 containing double bonds. As with the other steps, specific oligomerisation processes have been  
1023 developed by a variety of companies, depending on the feedstock used, such as the Chevron Phillips  
1024 'Ziegler' process for ethanol. For the Ziegler 'one-step' process, the catalyst cannot be recycled, but  
1025 must be collected and disposed of, whereas the catalyst in the 'two-step' reaction can be reused  
1026 (Weisermel and Arpe 2008). The reaction conditions for these processes vary and must be balanced  
1027 with their cost and the overall process cost. The oligomerised product consists of a wide range of  
1028 carbon chain lengths. Wright et al. (2008) reported a 96% conversion of but-1-ene into C<sub>8</sub>, C<sub>12</sub>, C<sub>16</sub>,

1029 C<sub>20</sub> oligomers. The required carbon lengths are between C<sub>14</sub> and C<sub>20</sub> for jet fuel and, to maximise the  
1030 yield in this desired range. The C<sub>8</sub> olefins can be separated then recycled or sent to a secondary  
1031 dimerisation facility. This would increase the carbon chain length and produce a greater yield of jet  
1032 fuel per unit of feedstock. Subsequently, the oligomers are then hydrogenated to yield a product  
1033 stream containing the synthetic paraffinic kerosene. Finally, distillation separates the bio-aviation  
1034 fuel product stream from the bio-naphtha and biodiesel product streams.

#### 1035 **4.3.2 Advantages**

1036 A major benefit of ATJ compared to the other processes discussed can be attributed to the BAF  
1037 produced. Similar to FT, the ATJ primarily produces synthetic jet fuel with permissible aromatics  
1038 content to be used in existing engines without fuel seal concerns. As the aromatics content is a major  
1039 requirement in the current necessity to blending synthetic fuels with Jet A-1, it could be foreseen that  
1040 BAF via ATJ without blending could achieve approval for use.

1041 A demonstration for BAF via ATJ has been proposed at a medium-scale. The process by LanzaTech  
1042 utilises industrial waste gases (e.g. flue gas) from steel production containing CO, CO<sub>2</sub> and H<sub>2</sub>. The  
1043 process permits the recycling of carbon in the waste gas that would have been emitted to the  
1044 atmosphere and takes advantage of the little to no cost of the waste gas that is likely to be cheaper  
1045 than producing biogas or syngas from other feedstocks. These gases are supplemented by gasified  
1046 biomass as discussed in Section 4.1.2 and fermented using microbiological species to produce  
1047 alcohols (Brooks et al. 2016). In addition, this process can also use municipal waste to augment the  
1048 feedstock requirement. LanzaTech, supported by Virgin Atlantic Airways, are planning to develop  
1049 a facility capable of producing over 13.5 million L of BAF via ATJ blended with CJF and diesel.  
1050 The intention is predominantly to use waste streams from industrial and municipal sources as  
1051 feedstock (Surgenor 2018). The facility is likely to proceed as it has received a USD<sub>2018</sub> 520,700  
1052 grant following an application to the UK Department for Transport (LanzaTech 2018).

1053 Ethanol production is a long-established process that is already globally at commercial production  
1054 levels (Escobar et al. 2009). Using ATJ to upgrade the alcohols into jet fuel would allow the aviation  
1055 industry to take advantage of the established infrastructure and construct ‘upgrading’ facilities close  
1056 to the ethanol factories in order to decrease transportation costs. On the other hand, higher alcohols  
1057 in general have a higher energy content and lower water solubility than ethanol but are not as widely  
1058 used in fuel production (Brooks et al. 2016). In terms of GHG emissions, comparing between n-  
1059 butanol, iso-butanol and ethanol, n-butanol has the highest and ethanol has the lowest (Tao et al.  
1060 2014). Butanol has a higher calorific value of 29.2 MJ/L compared to 19.6 MJ/L for ethanol but has  
1061 lower heat of vaporisation and less corrosivity, which make it a more attractive feedstock  
1062 (Dziegielewski et al. 2014). Furthermore, butanol as feedstock could decrease production costs  
1063 further due to lower temperature and pressure requirements during alcohol dehydration and higher jet  
1064 fuel yields during oligomerisation (Brooks et al. 2016). Moreover, the wide range of alcohol-  
1065 intermediates (i.e. ethanol, n-butanol, iso-butanol) for the ATJ allows more opportunity to retrofit  
1066 existing infrastructure and facilities. For example, the capital required for infrastructure costs could  
1067 be further decreased significantly for butanol production as existing ethanol plant could be  
1068 reconfigured to produce butanol with minor changes (Kolodziej and Scheib 2012). Finally, Geleynse  
1069 et al. (2018) reported that newly developed fermentation technologies could make the production of  
1070 higher alcohols than ethanol more cost competitive in the future.

1071 **4.3.3 Limitations**

1072 Bioethanol produced through lignocellulosic biomass is currently widely used by the petrochemical  
1073 industry as a component of automobile fuel. Almost all of the gasoline sold in the USA is around 10  
1074 vol.% ethanol (EIA 2018). In effect, commercialisation of BAF via ATJ may create competition  
1075 between the air and land transport sectors in terms of feedstock availability. In addition, the main  
1076 issue with ATJ is the low yield associated with bio-alcohol production (Gutiérrez-Antonio et al.  
1077 2017). This is an important step in profitability of bio-aviation fuel. Some technical disadvantages  
1078 for ATJ include a long process route involving sugarcane and a long production cycle involving  
1079 starch crops (Wei et al. 2019). There is a need for more research and development of the ATJ in  
1080 order to reduce its high production costs and maximise its future benefits.

1081 **4.4 Economic analysis**

1082 Figure 6 displays the cost breakdown of producing BAF, in terms of the feedstock, capital  
1083 expenditures (CAPEX) and operating & maintenance expenditures (OPEX), for HEFA, FT and ATJ.  
1084 This was plotted from values (adjusted to 2019 levels) of de Jong et al. (2015) for a stand-alone  
1085 plants on a new industrial site, which the authors calculated by a harmonized techno-economic  
1086 framework using existing process modelling data. Feedstock considered for this comparison are used  
1087 cooking oil, forest residues and wheat straw (de Jong et al. 2015). The cost breakdown of producing  
1088 CJF via crude oil refining is also included for comparison. This was calculated and adjusted to 2019  
1089 levels from data of Sannan et al. (2017) and EIA (2020).

1090 Among the three production pathways, financial data exist for HEFA being on commercial scale  
1091 (Table S4). For a HEFA plant, both its CAPEX and OPEX are also cheapest among the three  
1092 pathways, which reflects the maturity of the technology. The CAPEX of a HEFA plant is even  
1093 cheaper by about half of a crude oil refinery. However, the feedstock cost of HEFA is about 8 times  
1094 greater than a crude oil refinery. Thus, the cost of sustainable feedstocks could determine the  
1095 economic performance of the HEFA (de Jong et al. 2015).

1096 ATJ and FT are yet to be on commercial scale (Figure 5). Between the two, FT is nearing  
1097 commercial maturity but its deployment could be limited due to construction challenges of  
1098 operational plants (Mawhood et al. 2016). Nevertheless, FT and ATJ require higher capital with their  
1099 CAPEX about 3 and 5 times greater than the CAPEX for crude oil refinery and HEFA, respectively.  
1100 The gasification facilities for the FT and facilities for pretreatment, hydrolysis and fermentation for  
1101 ATJ are the major costs in the CAPEX of these production pathways. The biochemical route of ATJ  
1102 results to the highest OPEX among the three production pathways as these would involve several unit  
1103 operations from alcohol synthesis to alcohol conversion to BAF (Mawhood et al. 2016). In terms of  
1104 feedstock, forest residues is more preferable over wheat straw for both FT and ATJ given its lower  
1105 delivered costs (de Jong et al. 2015).

1106 The production cost of the three production pathways discussed range from 3 to 7 times greater the  
1107 refinery production of CJF as depicted in Figure 6. Hence, it is important to improve these processes  
1108 for them to become cost-efficient and be able to compete with CJF. The price of BAF could also be  
1109 lowered by subsidies and taxes though policy development. Yang et al. (2019) suggested that if BAF  
1110 production via HEFA meets policy targets, it could become economically attractive by imposing a  
1111 17% subsidy on BAF and 20% tax on CJF. Anderson et al. (2012) estimated that the carbon cost for  
1112 BAF that gives a 50% carbon savings should be about USD<sub>2012</sub> 380/tCO<sub>2</sub>eq, although this value is  
1113 optimistic as the price of BAF might increase in the future.

1114

## 4.5 Environmental analysis

1115 Figure 7 presents the GHG emissions savings based on WTW analysis of HEFA, FT and ATJ at  
1116 different feedstocks. The use of algal oil via HEFA was found to have the highest potential GHG  
1117 emissions savings at an average of 98% relative to fossil sources (Bauen et al. 2009). Since algae  
1118 production is mostly from lab- to pilot-scale, so there is uncertainty of its actual GHG emissions  
1119 savings when the technology matures (Bwapwa et al. 2018). Of the production pathways that are at  
1120 and/or near commercial maturity, FT using 2-G feedstocks, such as woody crops, grasses and  
1121 forestry residues, have the highest potential for GHG emissions savings from 92% to 95%. Fleming  
1122 et al. (2006) corroborate this, compared to a gasoline standard, a 91% reduction in WTW GHG  
1123 emissions could be obtained from FT using 2-G feedstocks. The potential GHG emissions savings  
1124 from HEFA are generally lower than using the FT independent of the feedstock used. However,  
1125 Figure 7 clearly shows that non-food based feedstocks, such as waste tallow and jatropha, would be  
1126 more suitable than conventional oil-seed crops, such as palm oil and rapeseed.

1127 Aside from the carbon footprint, particulate matter (PM) generated from these production pathways  
1128 also needs to be considered. PM arises from the incomplete combustion of the fuel and is mainly  
1129 composed of soot and ash (Liati et al. 2019). These particulates can have an adverse effect on air  
1130 quality and cause a wide range of health, safety and environment problems, which include  
1131 exacerbating respiratory diseases, causing heart ailments, and formation of acid rain (Keefe 2013).  
1132 Lobo et al. (2011) found that PM emissions from a commercial jet engine could be decreased when  
1133 CJF is mixed with either FAME or BAF via FT. The operating points specified by the ICAO's  
1134 Landing Take-off Cycle were used to simulate the use of an engine under 30,000ft, wherein the  
1135 quality of local air would be affected. The use of a 50% blend of BAF via FT with CJF reduced PM  
1136 in terms of number and mass-based emissions by  $34\% \pm 7\%$  and  $39\% \pm 7\%$ , respectively. When this  
1137 was increased to 100% blend of BAF via FT with CJF, the reduction in PM emissions was more  
1138 pronounced at  $52\% \pm 4\%$  and  $62\% \pm 4\%$  for number and mass-based emissions, respectively. These  
1139 results could be a further incentive for stakeholders to dedicate funds in the development of BAF via  
1140 FT as an independent fuel without blending. Liati et al. (2019) also discovered that a 25% blend of  
1141 BAF via HEFA and Jet A-1 produced less soot overall than pure Jet A-1. Hence, both BAF via  
1142 HEFA and FT have a potential for soot reduction in the aviation industry. The use of 100% BAF in  
1143 engines could potentially permit the aviation sector to completely detach from Jet A-1 dependency  
1144 and to reduce its overall GHG and PM emissions.

1145

## 5 Storage and transport of feedstocks and bio-aviation fuel

1146 The storage and transport of raw materials, intermediates, and/or finals products within the supply  
1147 chain for BAF provision presents additional hurdles to their planning and implementation by the  
1148 aviation industry. Transporting feedstocks and fuels over long distances significantly increases both  
1149 costs and GHG emissions of the supply chain. Hence, the impacts associated are to be minimised in  
1150 order to make BAF more cost-effective and environmental-friendly alternative to CJF. Generally,  
1151 storage of feedstock has minimal impact on the supply chain. However, energy consuming facilities  
1152 that provide medium-to long-term drying and preservation of the feedstocks can pose additional costs  
1153 and emissions to the whole supply chain. Opportunely, storage of final BAF products becomes less  
1154 of a concern after leaving the biorefinery as sophisticated systems already exist to support these  
1155 during transport, e.g. carrier tanks equipped with particulate settlement and removal to preserve fuel  
1156 (Hemighaus et al. 2006). Nevertheless, the associated impacts of storage, if considered within a  
1157 supply chain for BAF provision, have to be included for its comprehensive planning, design and  
1158 operation.

1159

## 5.1 Raw materials and intermediates

1160 Storage and transport within the supply chain mainly facilitate the matching of supply and demand  
1161 for raw materials, intermediates and products along the sequence of activities (Gold and Seuring  
1162 2011, Ko et al. 2018). Mass and/or volume are commonly shared parameters in the choice of  
1163 transport and storage technologies (Gold and Seuring 2011). In the case of oil-seed crops, the  
1164 amount of dry biomass can be up to 4.7 times as much as the oil produced as shown in Table S5.  
1165 While the storage of oil palm fresh fruit bunches is unnecessary, their immediate transport to oils  
1166 mills is crucial in maintaining high quality oil with minimal impurities and in facilitating high oil  
1167 extraction rates (Harahap et al. 2019). Storage becomes significant for feedstocks with short  
1168 harvesting periods and widely scattered geographical distribution (Gold and Seuring 2011). For  
1169 lignocellulosic feedstocks, such as energy crops and agro-forestry residues, the prevention of  
1170 microbial activity and spontaneous combustion are additional considerations of having a storage with  
1171 drying facilities in a supply chain (Emery et al. 2015). On the other hand, distance and speed affect  
1172 transport operations (Gold and Seuring 2011). The available infrastructures also influence the  
1173 transport operations (Gold and Seuring 2011, Ko et al. 2018). Overall, the storage and/or transport of  
1174 feedstock and its corresponding intermediaries up to the production stage span from the upstream to  
1175 the midstream portion of the supply chain.

1176 The transport and storage of waste biomass is generally a difficult issue. Large quantities of  
1177 agricultural wastes are being concentrated into smaller and dispersed areas due to both improvements  
1178 in technology and intensification of the industry (Sims and Maguire 2005, Roth et al. 2018). While  
1179 BAF production facilities can be located near regions with large quantities of waste biomass to  
1180 relatively shorten the transport distance, Downie and Van Zwieten (2013) argued that the bulky and  
1181 wet nature of these feedstocks could still lead to high transport operation costs. The low-energy  
1182 density and heterogeneous composition of most waste biomass upon collection offer additional  
1183 challenges to their economic feasibility (Roth et al. 2018). Some waste biomass also have inherent  
1184 health and safety risks (Rentizelas et al. 2009). For example, Europe generally incinerates animal  
1185 waste at routine intervals. With animal wastes being wet and generated in large volumes, farms may  
1186 find difficulty in their storage and transport. Moreover, storing large quantities of this matter may  
1187 breach biosecurity legislation when regular collection cannot be achieved (Downie and Van Zwieten  
1188 2013).

1189 Bearing in mind the various consideration of storage and transport, sophisticated mathematical  
1190 models can be used to optimise supply chains, which consider the geographical distribution of  
1191 feedstock, type and siting of production facilities, applicable storage facilities, available transport  
1192 modes and routes (Gold and Seuring 2011, de Jong et al. 2017). The structure of the supply chain is  
1193 more pertinent on the transport operations from farm to refinery gate as various models can be  
1194 applied. de Jong et al. (2017) outlined three models, the centralised supply chain, and two variations  
1195 of distributed supply chains: the linear and hub and spoke models. The centralised supply chain  
1196 model is characterised by a central location in which all processing occurs including pretreatment and  
1197 upgrading. Whereas in distributed models, the feedstocks can undergo pre-processing where they are  
1198 extracted/harvested at separate facilities then transported further to an upgrading facility. This is an  
1199 important consideration as the distributed models typically have a higher CAPEX and OPEX, but  
1200 lower transportation costs overall (de Jong et al. 2017).

1201

## 5.2 Final jet fuel product

1202 The final transportation of processed jet fuel contributes to the final cost of the product and increases  
1203 overall GHG emissions. The current distribution of jet fuel from the refinery as shown in Figure 8(a)

1204 comprises a variety of modes of transport including pipelines, barges, rail and trucks. Using a variety  
1205 of modes of transport was found to decrease the cost of transporting fuel over longer distances,  
1206 thereby allowing facilities to take advantage of cheaper feedstock sources from further away (de Jong  
1207 et al. 2017). Figure 8(b) also depict pipeline transport of BAF, which makes up 60% of all refined  
1208 petroleum products in the USA. The product that leaves the refining facilities can be in excess of 1.5  
1209 million L per batch and the best form of transport suited to transporting such large volumes of fuels is  
1210 pipeline systems (Hemighaus et al. 2006).

1211 Fuels, including BAF, travelling through pipelines inevitably become contaminated with particulate  
1212 matter and water. These contaminants must be removed at their destination (Hemighaus et al. 2006).  
1213 As a result, the distance that fuels are transported should also be minimised in order to decrease the  
1214 cleaning costs required at the end of the line. Research conducted in the bioethanol supply chain also  
1215 found that the cultivation, harvesting and transportation costs of the feed made up 35 to 50% of the  
1216 final bioethanol product cost (Shastri and Ting 2014). Similarly, decreasing the feedstock  
1217 transportation costs could help make BAF become more cost competitive with CJF. Taking this in  
1218 consideration, recent specifications for bio-aviation fuel has permitted higher tolerable levels of  
1219 FAME, such that biodiesel and BAF can use the same existing transportation chains (ASTM 2015).

1220 For smaller airports or airports relying on one mode of transport, it is important to have contingency  
1221 measures to ensure fuel availability in the case of a supply disturbance, such as the fuel shortage in  
1222 Manchester Airport in June 2012 (BBC 2012). However, this could involve the airport incurring  
1223 additional costs for measures like intermediate storage facilities in the distribution chain as presented  
1224 in Figure 8(a), or large holding tanks, which are not efficient and expensive to construct. Although  
1225 airports are widely distributed around the world, due to increased population density and demand, the  
1226 concentration of airports is greater around major city hubs in the vast majority of countries. As  
1227 illustrated in Figure 9, Great Britain's jet fuel demands are in the regions of high demands for  
1228 aviation transport close to major cities that include London, Manchester, Birmingham and Newcastle.  
1229 The 30 mile pipeline in place from the Essar refinery near Ellesmere Port to Manchester Airport  
1230 transports the amount of fuel that would correspond to 79 road tankers on a daily basis (BBC 2012).  
1231 Many existing fuel-refining facilities are already in advantageous locations for fuel distribution, thus  
1232 established pathways and capital costs could be minimised by converting these to BAF refineries or  
1233 producing BAF as a secondary product.

### 1234 5.3 Economic and environmental analyses

1235 The transport of feedstocks by truck, rail and ship are the most common, while the use of pipelines is  
1236 currently the least established but may become significant in the future (Ko et al. 2018, Zafar 2018).  
1237 A recent review on feedstock logistics by Ko et al. (2018) stated that interests on multimodal  
1238 movement (combination of modes) will increase due to the influence of transportation costs and  
1239 distances on feedstock utilisation. Figure 10(a) depicts a comparison of the cost and GHG emissions  
1240 of transport by truck, rail and ship at 100-km radius of transport distance for logging residues and  
1241 straw. Transportation cost consists of a fixed cost and a variable cost (dependent on distance), which  
1242 is typically less for both ship and rail than for truck. Ko et al. (2018), however, added that  
1243 transportation costs vary among countries due to feedstock type and composition, transport capacities  
1244 and geographical differences. Shastri and Ting (2014) estimated that generally beyond the range of  
1245 150 to 200 km, transport of biomass is no longer feasible due to high transportation costs. Moreover,  
1246 Zafar (2018) reported that for crop residues with low-density and high moisture content, even  
1247 distances larger than a 25 to 50 km radius could be uneconomical. Similarly, transporting large  
1248 quantities of feedstocks over long distances can contribute increased emissions from a life cycle

1249 standpoint (Gold and Seuring 2011). Supply chains with heavy reliance on transport by truck of  
1250 feedstocks are expected to emit more GHGs than transport by ship or rail as shown in Figure 10(a).  
1251 Furthermore, Figure 10(b) displays the breakdown of GHG emissions for hydro-processing, FT and  
1252 sugar-to-jet production pathways for a variety of feedstocks showing the portion attributed to  
1253 transportation. Although BAF produced from forest residues via FT have the lowest potential for  
1254 overall WTW GHG emissions (Figure 7), over 20% of this value is due to transportation (Figure  
1255 10(b)).

1256 On feedstock storage, its primary function in a BAF supply chain is to address temporal variability of  
1257 the demand, especially during seasons of low productivity. In the case of lignocellulosic feedstocks,  
1258 the challenge of storing without significant dry matter losses (DML) must be overcome (Lemus  
1259 2009, Emery et al. 2015). Storage depends on the location and climatic conditions that influence the  
1260 quality of lignocellulosic feedstocks being stored. Different ways to store lignocellulosic feedstock  
1261 are presented by Darr and Shah (2012) in which the majority are stored in rectangular bales. Costs  
1262 for each storage infrastructure are also reported. Open storage costs around USD<sub>2014</sub> 4.13/t while  
1263 covered biomass storage costs USD<sub>2014</sub> 5.44/t. Permanent storage infrastructures, involving enclosed  
1264 structures, cost around USD<sub>2014</sub> 14–28/t. The cost for permanent storage structures is significantly  
1265 higher than the first two options but the advantage is that 2% DML can be achieved compared to  
1266 typical 6% DML in covered storage and up to 20% DML in open storage. In the case of storing  
1267 vegetable oil (e.g. palm oil) tankers (ships) are used as storage infrastructures with energy  
1268 requirements to maintain the vessel temperature (MPOB 2010). Given the different options for  
1269 feedstock storage, the studies on their GHG emissions are limited. Nevertheless, the addition of  
1270 storage facilities to a supply chain can be expected to increase both the net energy consumption and  
1271 GHG emissions (Emery et al. 2015).

## 1272 6 Critical analysis, recommendations and future directions

1273 For the successful and sustainable planning and implementation of BAF supply chains, it is vital that  
1274 international aviation bodies, such as the ICAO and IATA, continue to develop linkages across  
1275 country borders and to create agreements between the various stakeholders in the agriculture,  
1276 production and logistics sectors. This coordination will allow technology that has a high FRL  
1277 (Figure 5) to be implemented on a commercial scale in the near future. Moreover, government-  
1278 driven incentives for the use of BAF and taxes on CJF will contribute significantly to its large-scale  
1279 development. Finally, the development of an integrated and uniform conceptual framework for the  
1280 BAF industry will ensure that international stakeholders are able to share ideas with one another and  
1281 develop effectively.

1282 Developing new technologies, or scaling up existing technologies to commercial levels, will  
1283 inevitably incur higher costs than continuing to use established conventional methods and  
1284 infrastructures. This is reflected in consistently higher prices of BAF than Jet A-1. Tackling this  
1285 barrier requires funding for both research into cost optimisation of processes. Aviation companies  
1286 also need subsidies in order to encourage fuel switching from Jet A-1 to BAF. These subsidies  
1287 would offset the purchase cost of BAF over time. The financial incentives and aid that contributed to  
1288 the success of biofuel implementation in the automobile industry are not as widely distributed to the  
1289 aviation industry (Radich 2015). This would require continued dialogue between international  
1290 bodies and governments to raise the profile and accelerate the paradigm shift that the aviation  
1291 industry is undergoing.

1292 More LCA data are required on each component of the supply chain for BAF in different countries to  
1293 support its planning, design and operation. However, in order for these data to be robust and reliable  
1294 for critical assessment, the methodologies used for the LCA should also be standardised and made  
1295 open access for easier comparison. This could follow ISO 14040:2006 – the LCA principles and  
1296 framework from the International Organisation for Standardisation. It is also important for adequate  
1297 peer reviewing to take place to ensure the validity of the results provided. Overall, within each  
1298 component of the supply chain, the research conducted had a number of advantages and limitations  
1299 associated with every alternative. Due to the complex nature of this topic, the options fare differently  
1300 for each of the parameters chosen, and are often intertwined.

## 1301 6.1 Feedstocks

1302 From the review, the type of feedstocks utilised and production pathways selected are highly  
1303 interrelated. Sustainable oil-rich feedstocks are required for HEFA. Currently, the security and  
1304 availability of these feedstocks are its major limitations. Thus, a portfolio of feedstocks should be  
1305 researched and developed that can satisfy several social, economic, environmental and sustainability  
1306 dimensions. High yielding, cost-effective, and low resource-intensive oil-seed crops can potentially  
1307 serve as feedstocks for HEFA in the short term. In the case of oil palm, however, several negative  
1308 environmental consequences have to be avoided or at least minimised. Reforestation with intensive  
1309 biodiversity protection, avoidance of peatland LUC, and valorisation of POME can improve the  
1310 environmental performance of oil palm as feedstock. Competition of 1-G feedstocks, like oil palm,  
1311 for the same resources with food production is going to limit their applicability as BAF feedstocks.  
1312 Non-food oil-seed crops, like jatropha, can potentially fill some gaps in the feedstock supply and  
1313 simultaneously provide some ecosystem services. While 2-G energy crops can be grown in marginal  
1314 lands in order to avoid food competition, responsible cultivation is of paramount importance to  
1315 ensure that no encroachment on forestland and arable land occurs and no LUC of peatland happens.  
1316 Alternatively, low cost waste streams and residues are increasingly being developed as feedstocks.  
1317 To date, UCO is considered as the most economical and environmentally friendly feedstock for BAF  
1318 production. However, the variability of its supply and uncertainty of its actual contribution in  
1319 meeting GHG emissions reduction targets can limit its applicability.

1320 Other waste biomass such as MSW and agro-forestry residues also share this limitation as feedstocks  
1321 to on-going commercial and technological developments of FT and ATJ. In the long-term, further  
1322 research and development would enable commercial microalgae cultivation, which could provide a  
1323 sustainable high oil-yielding feedstock for BAF production, superior to any 1-G and 2-G feedstocks  
1324 given the low photosynthetic efficiency of land-based crops. Moreover, along with ecosystem  
1325 services (wastewater treatment and CO<sub>2</sub> fixation), microalgae-derived BAF can provide the highest  
1326 potential WTW CO<sub>2</sub> emissions savings. On the other hand, BAF derived from 4-G feedstocks can  
1327 result in even greater negative net GHG emissions. However, these are at a very early stage of  
1328 research but could be alternative solutions in the future, when they become commercially feasible.

1329 The review on the supply chain models for BAF provision reveal that more research has to be done in  
1330 this field. A supply chain analysis framework is highly needed in developing a portfolio of  
1331 feedstocks for BAF provision. Particularly for land-based feedstocks, only genuinely available  
1332 suitable lands should be considered in the assessment in order to minimise and/or avoid negative  
1333 consequences of intensive cultivation, e.g. soil degradation, expansion to forestlands and peatlands,  
1334 and depletion of water resources. GIS-based tools should be increasingly integrated in BAF supply  
1335 chain models, especially for waste biomass, the spatio-temporal variability and uncertainty of which  
1336 have to be resolved and captured in the planning, design and operation of their supply chains. More

1337 scenario development on various tax incentives and other legislations should be explored that could  
1338 reveal strategies for economical feedstock production or extraction while avoiding food competition  
1339 and additional GHG emissions. Waste valorisation and negative emissions technologies could also  
1340 be integrated into the BAF feedstock supply chain development in order to potentially enhance their  
1341 environmental performance.

## 1342 **6.2 Production pathways**

1343 Considering 2020 deployment, HEFA presents the most immediate solution. It has the lowest  
1344 CAPEX and OPEX among the three reviewed production pathways due to its commercial maturity.  
1345 Utilising 2-G feedstocks, potential GHG emissions savings of 70-90% could be realized by this  
1346 production pathway. However, the major challenges for HEFA are to obtain low cost sustainable  
1347 feedstocks and to further develop the process in order to reduce the costs of the final product.  
1348 Focusing future investments in securing a reliable and efficient supply chain could augment BAF  
1349 production via HEFA.

1350 Within the medium- to long-term goals of the aviation sector, FT presents the next best solution. It is  
1351 a technology approaching commercial maturity. Utilising agricultural and forestry residues as  
1352 feedstock, has the highest potential GHG emissions savings, at well over 90%. MSW is increasingly  
1353 being considered as feedstock, which could lessen the environmental concerns associated with  
1354 landfills. However, the high capital costs of FT make it an unattractive option at present. The  
1355 limited biomass-based application of FT could also be a major hindrance of its successful  
1356 deployment. Hence, there is a need to focus investments on more demonstration to commercial scale  
1357 projects for FT utilising biomass feedstocks along with a strong commitment from and collaboration  
1358 with the aviation industry.

1359 At present, ATJ using lignocellulosic biomass as a feedstock has the highest CAPEX and OPEX  
1360 among the three production pathways reviewed. The relatively high abundance of lignocellulosic  
1361 feedstocks and the benefit of potential GHG emissions savings (75% using corn stover as feedstock)  
1362 strongly support its potential commercial deployment in the long-term. Given the FRL of this  
1363 technology, more efforts in research and development to demonstration scale project could pave the  
1364 way of its commercial maturity. Available infrastructure and facilities of well-established alcohol  
1365 supply chains could also support the aviation industry in adopting the ATJ. However, the aviation  
1366 industry must consider that alcohol is also a fuel additive for land transport, which could give rise to  
1367 competing interests in the supply.

1368 Overall, HEFA, ATJ and FT demonstrate the capability to produce BAF for the needed  
1369 decarbonisation of the aviation industry. With the goal of bringing their costs to a comparable level  
1370 with conventional jet fuel, the implementation of all three fuels at a commercial scale could enable  
1371 increased availability of BAF and in turn, decrease the selling price to the consumers. Given the  
1372 availability of feedstock in a particular region for BAF production, it is paramount to develop  
1373 decision-making frameworks to determine what capacities of these technologies should be installed,  
1374 where the processing facilities should be deployed and when and how they should be operated.

1375 The development of other novel processes such as DSCH and hydrothermal liquefaction should be a  
1376 priority for future work. There is currently limited quantitative data available on these new  
1377 technologies, due to the lack of large-scale production facilities at present

## 1378 **6.3 Storage and Transport**

1379 The total distance that feedstock, all intermediates and refined fuel are transported, and all associated  
1380 emissions and costs can be minimised by using mathematical modelling and optimisation strategies  
1381 to tactically design supply chains. Some models have been proposed for optimising production  
1382 facilities location in BAF supply chains. However, the proposed models only considered the  
1383 transportation aspect of the supply chains. Supply chain models for BAF need to be improved more  
1384 in terms of detail, accounting for the storage that would enable to satisfy short-term future demands  
1385 and accounting for impacts to biodiversity and to food-energy-water-energy-environment nexus.  
1386 These should be carried out using as recent data as possible to ensure that the results are reliable and  
1387 relevant.

## 1388 7 Conclusions

1389 With the demand on the aviation sector projected to increase in the near future, the dilemma is how to  
1390 satisfy this demand while complying with international efforts for emissions reductions. The  
1391 implementation of alternative jet fuel is a pivotal step that will help the sector decarbonise and  
1392 simultaneously become independent from limited fossil fuel supply. In this paper, the opportunities  
1393 in the future bio-aviation fuel industry have been explored through a comprehensive analysis of the  
1394 feedstocks, production processes, storage, and transport mode options. The key conclusions are as  
1395 follows:

- 1396 1. A range of feedstocks for bio-aviation fuel production is available with different economic  
1397 potential and environmental benefits. In the short- to medium-term, low-cost and high-  
1398 yielding oil-rich feedstocks could be an effective transitional solution. The negative  
1399 environmental consequences of land-based crops, such as oil palm and jatropha, can limit  
1400 their applicability, while the uncertainty and variability of waste streams such as used cooking  
1401 oil and municipal solid waste can limit their contribution. The great potential of microalgae  
1402 as a feedstock, due to its higher yield than oil-bearing crops, still must be proven economical  
1403 in the long-term. A wide range of feedstocks are going to be needed to ensure security,  
1404 availability and sustainability of bio-aviation fuel.
- 1405 2. Production pathways are available but at different readiness levels. Being a mature  
1406 technology, HEFA could be a solution for the immediate, cost-effective implementation of  
1407 bio-aviation fuel. It is necessary to explore these production pathways further, especially  
1408 with FT having near commercial maturity and higher GHG savings than other pathways but  
1409 needing higher capital costs.
- 1410 3. The structure of biomass feedstock and refined fuel products transportation, whether  
1411 distributed or centralised, should be optimally designed to developed streamlined supply  
1412 chains. Utilising multiple transport modes in the chain was found to lower transportation  
1413 costs and GHG emissions over long distances.
- 1414 4. Optimisation models are valuable as decision-making tools for planning and designing supply  
1415 chains for bio-aviation fuel provision. Supply chain decisions are dependent on spatial and  
1416 temporal factors. Spatial factors include the yield and location of feedstocks, capacity and  
1417 location of processing and storage facilities – these determine the most appropriate modes of  
1418 transport. Temporal factors include the seasonality and availability of feedstocks and  
1419 variability of fuel demands – these affect the production and inventory levels.
- 1420 5. Evidence-based policies are essential for the successful and sustainable implementation of the  
1421 bio-aviation fuel supply chains. These policies must be streamlined across each component  
1422 of the supply chain such that their growth and expansion are coordinated while  
1423 simultaneously meeting socio-economic and environmental sustainability criteria. Given the  
1424 trans-boundary nature of the aviation industry, specific policies must be standardised

1425 internationally but with enough room for flexibility for the varying national goals of different  
1426 countries.

1427 **8 Conflict of Interest**

1428 N. J. Samsatli was employed by Process Systems Enterprise Ltd. and is co-founder of Samsatli  
1429 Solutions. The remaining authors declare that the research was conducted in the absence of any  
1430 commercial or financial relationships that could be construed as a potential conflict of interest.

1431 **9 Author Contributions**

1432 SS conceptualised the topic and scope of the paper. AR gathered the data and completed an early draft  
1433 of this work under the SS's supervision. SSD and JFT expanded the initial draft by adding more data  
1434 and discussion, with SSD significantly expanding the discussion and presentation of the feedstock  
1435 classification, supply chain models for bio-aviation fuel provision, transport, and storage, and their  
1436 economic and environmental analyses. SS and NJS provided data, ideas and feedback and wrote some  
1437 parts of the manuscript. YZ reviewed the paper and provided feedback.

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1444 respectively.

1445 **11 Nomenclature**

1-G	First-generation
2-G	Second-generation
3-G	Third-generation
4-G	Fourth-generation
AJF	Alternative jet fuel
ASTM	American Standard Testing Method
ATJ	Alcohol-to-jet production pathway
ATAG	Air Transport Action Group
BAF	Bio-aviation fuel
CAPEX	Capital expenditures
CTL	Coal-to-Liquid process

CJF	Conventional jet fuel
DSCH	Direct sugar-to-hydrocarbon jet fuel synthesis
DML	Dry matter losses
FAME	Fatty acid methyl ester
FT	Fischer-Tropsch production pathway
FRL	Fuel readiness level
GHG	Greenhouse gases
GIS	Geographic Information System
HVO	Hydrotreated vegetable oils
HEFA	Hydroprocessed esters and fatty acids production pathway
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
LUC	Land-use change
LCA	Life cycle assessment
MJSP	Minimum jet fuel selling price
MSW	Municipal solid waste
MILP	Mixed-integer linear programming
OPEX	Operating & maintenance expenditures
POME	Palm oil mill effluent
PM	Particulate matter
PtG	Power-to-Gas
PtL	Power-to-Liquid
SPK	Synthetic paraffinic kerosene
TTW	Tank-to-wake
UCO	Used cooking oil
USD	United States Dollar

WTT Well-to-tank

WTW Well-to-wake

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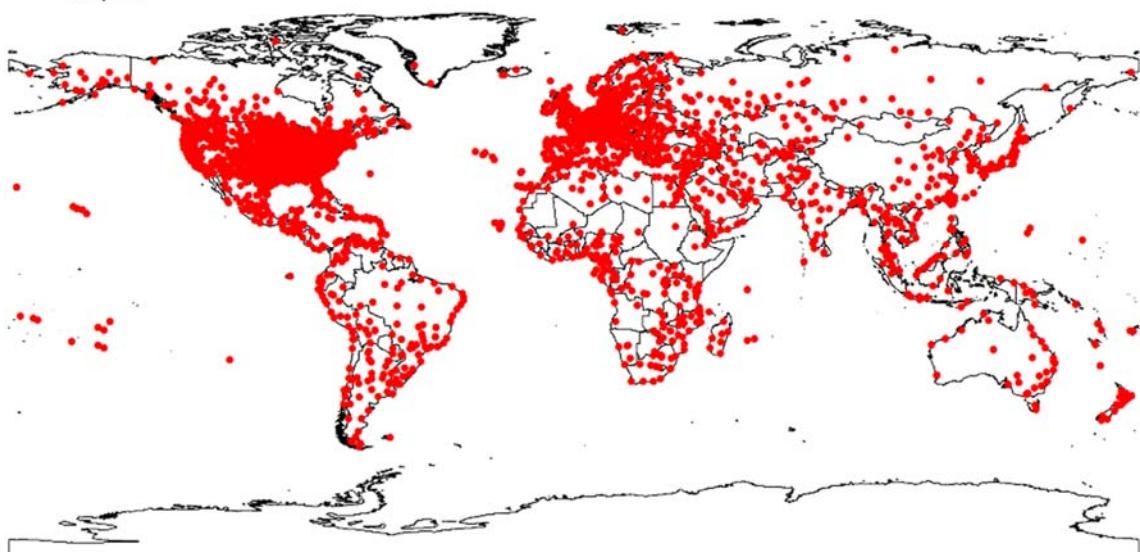
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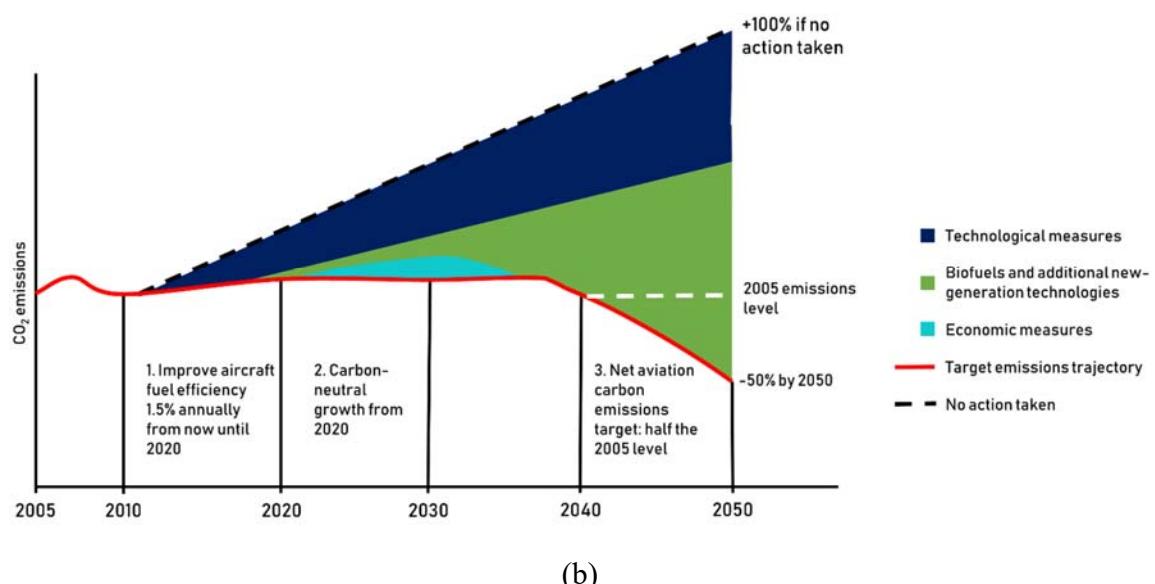
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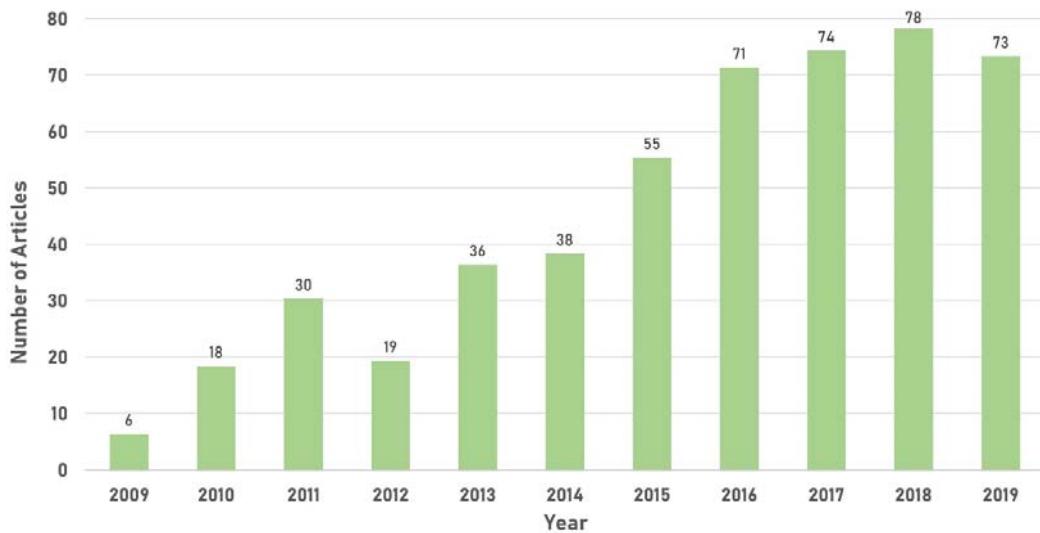
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(a)



(b)



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Figure 1: Recent trends for the the aviation industry: (a) Global Airport Distribution (Plotted using data from [www.arcgis.com](http://www.arcgis.com), 2019); (b) Potential global atmospheric CO<sub>2</sub> emissions released by the aviation sector under various development conditions (Drawn using data from IATA 2009); and (c) Publication history on bio-aviation fuel research (Plotted using data from Scopus accessed on January 17, 2020).

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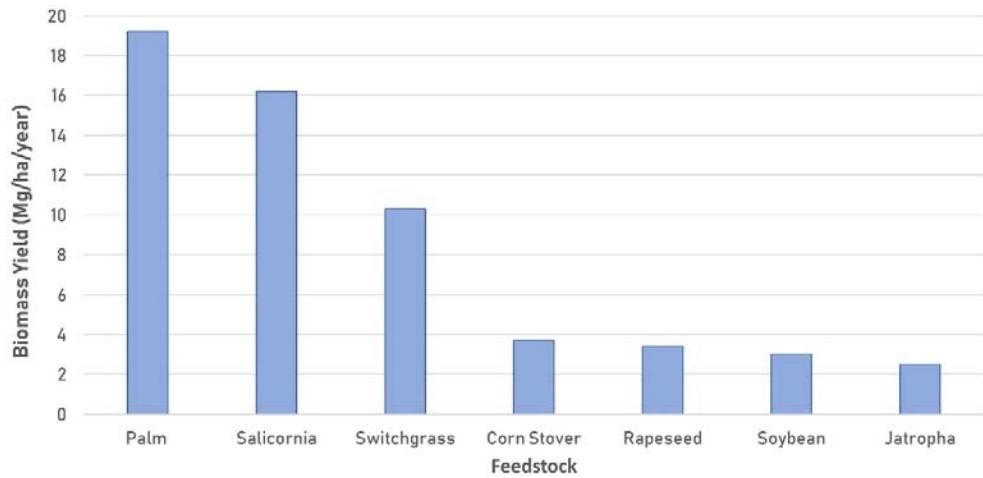
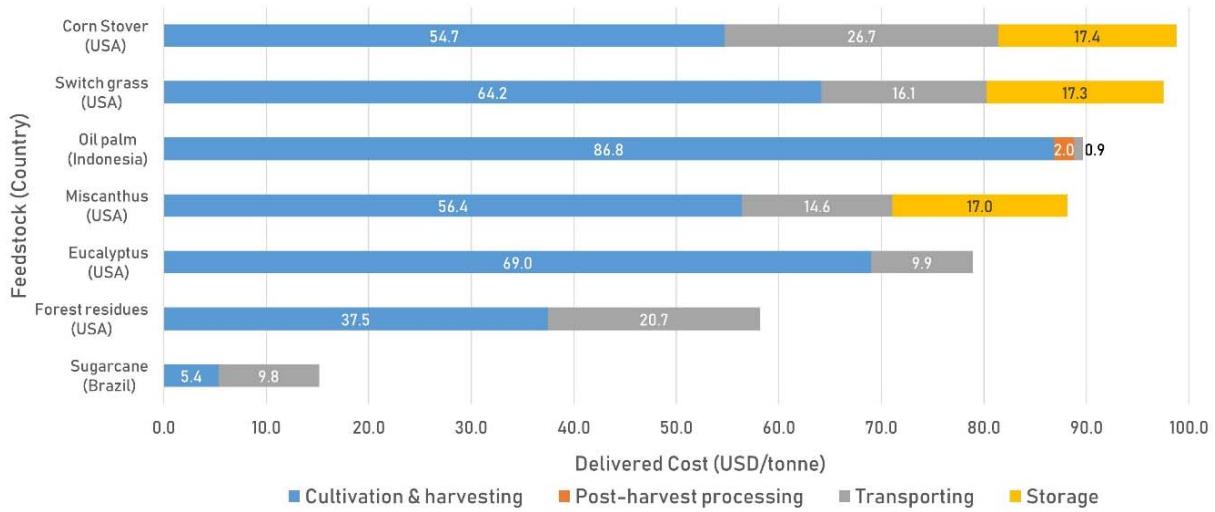


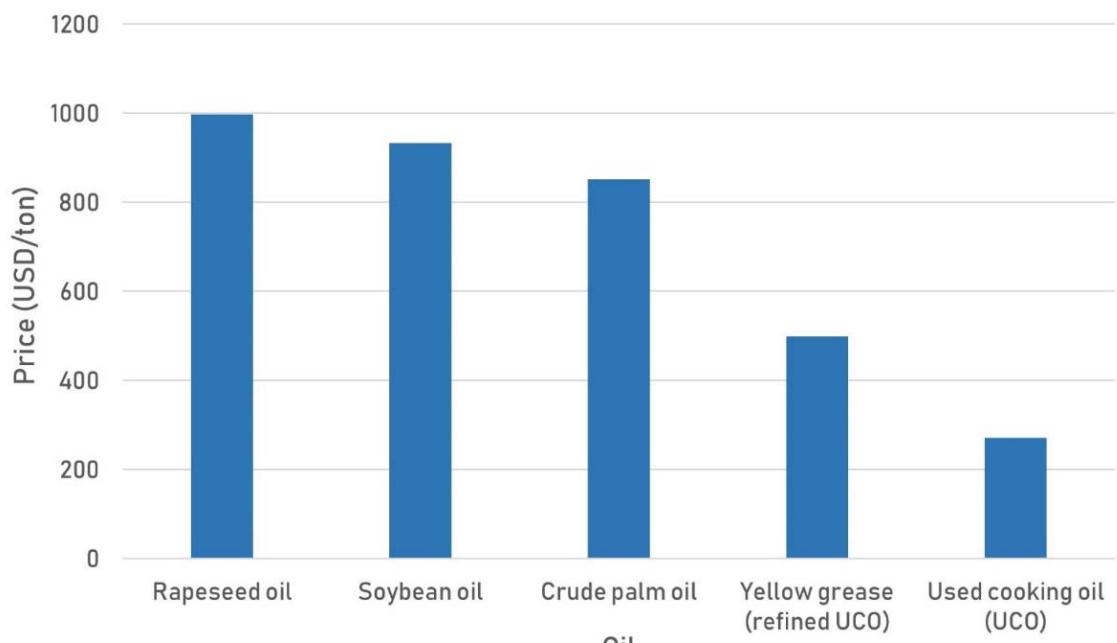
Figure 2: Typical potential yields of some 1-G and 2-G feedstocks for BAF production (Plotted using data from Stratton et al. (2010)).

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## Bio-aviation fuel: A comprehensive review and analysis of the supply chain components



(a)



(b)

Figure 3: Typical economic impacts (adjusted to 2019 levels) of some 1-G and 2-G feedstocks for BAF production: a) Delivered (farm-to-gate) cost (Plotted using data from Gonzalez et al. (2011), Gonzales et al. (2013), Harahap et al. (2019) and de Castro et al. (2018)); and b) Average market price of fresh edible and waste oils (Plotted using data from Mandolesi de Araújo et al. (2013)).

## Bio-aviation fuel: A comprehensive review and analysis of the supply chain components

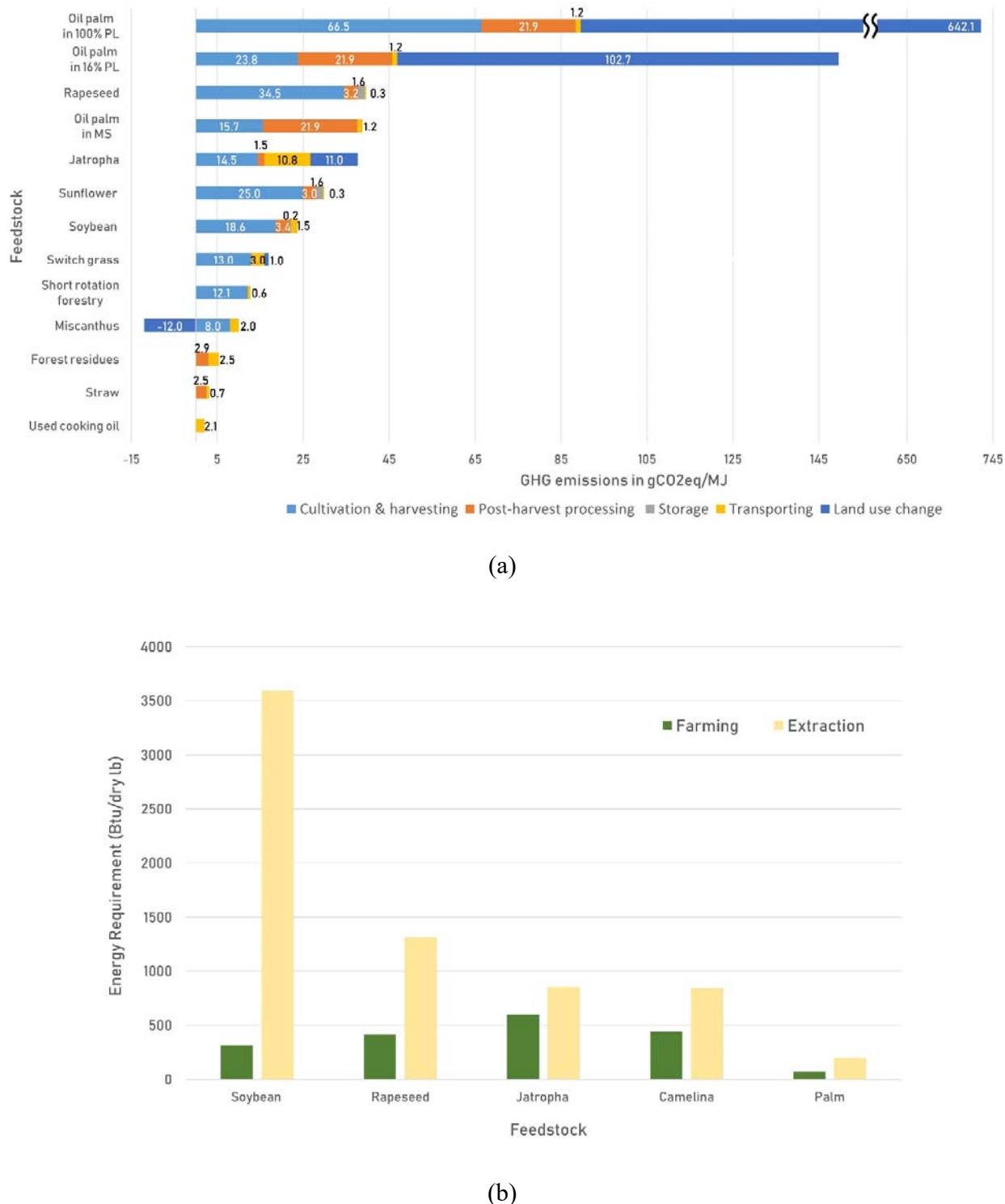


Figure 4: Typical environmental impacts of some 1-G and 2-G feedstocks for BAF production: a) Farm-to-gate GHG emissions (Plotted using data from Bailis and Baka (2010), O'Connell et al. (2019), Velazquez Abad et al. (2015) and Wang et al. (2012)); and b) Energy requirements for farming and extraction of some oil-seed crops (Plotted using data from Elgowainy et al. (2012)).

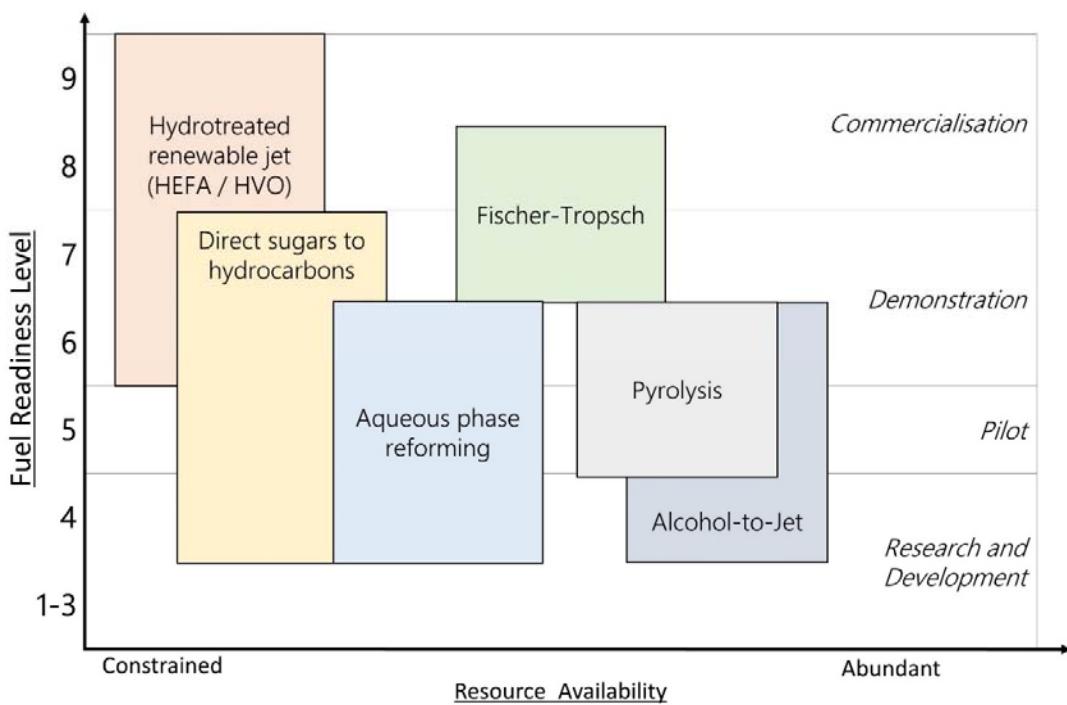


Figure 5: Future scope for adapting processes to a commercial level based on resource availability and technology maturity (Drawn using data from Bosch et al. (2017) and Mawhood et al. (2016)).

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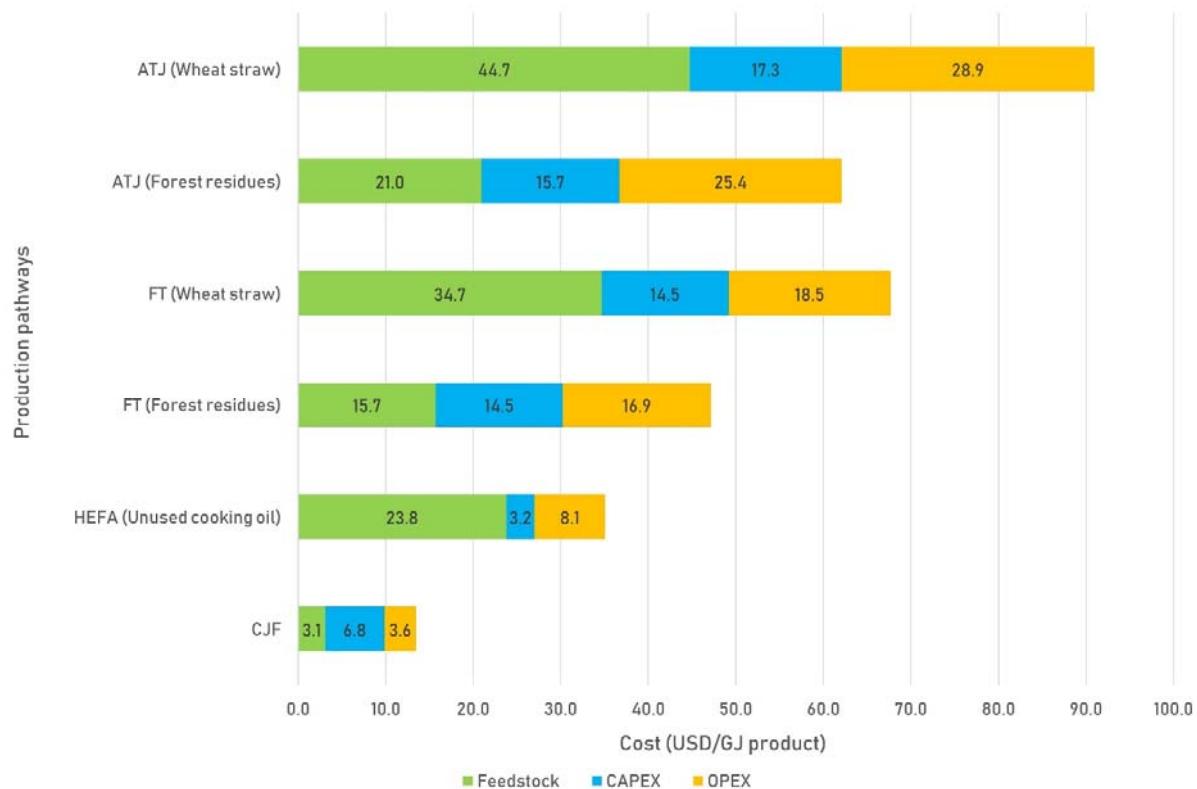


Figure 6: Breakdown of cost (adjusted to 2019 levels) producing bio-aviation fuel by HEFA, FT and ATJ (Plotted using production cost of the production pathways from de Jong et al. (2015). Production cost of conventional fuel by crude oil refinery (CJF), which was calculated and adjusted to 2019 levels from data of Sannan et al. (2017) and EIA (2020), is also plotted for comparison).

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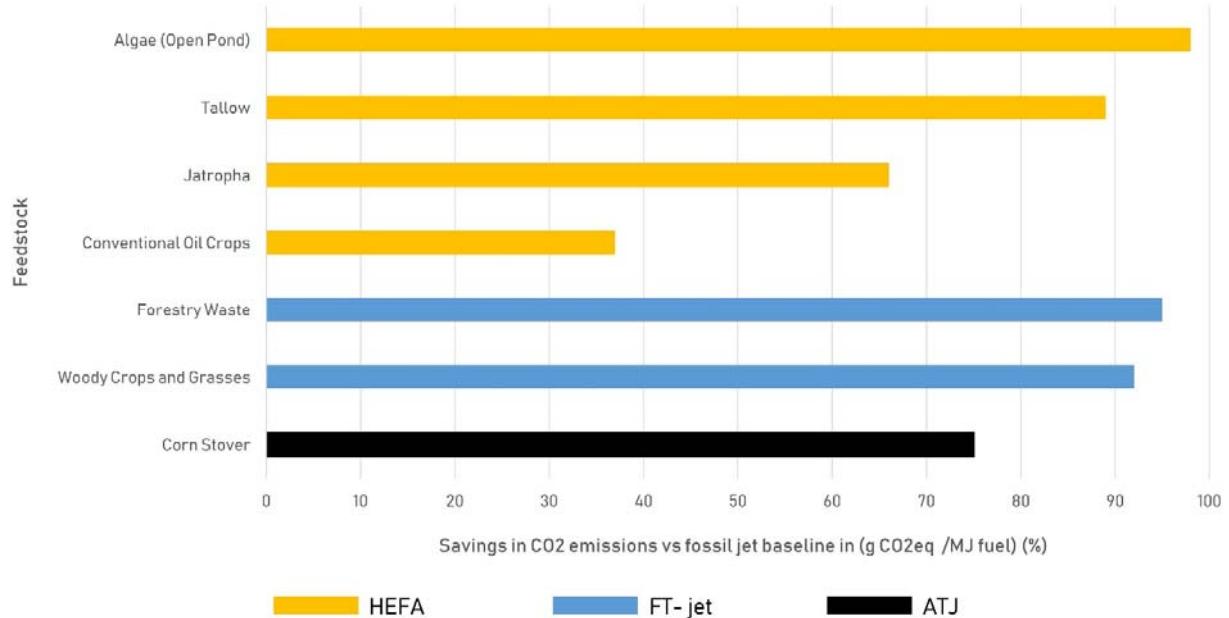


Figure 7: Potential well-to-wake GHG emissions savings from using different BAF feedstocks and production pathways (Plotted using data from Bauen et al. (2009) and de Jong et al. (2017)).

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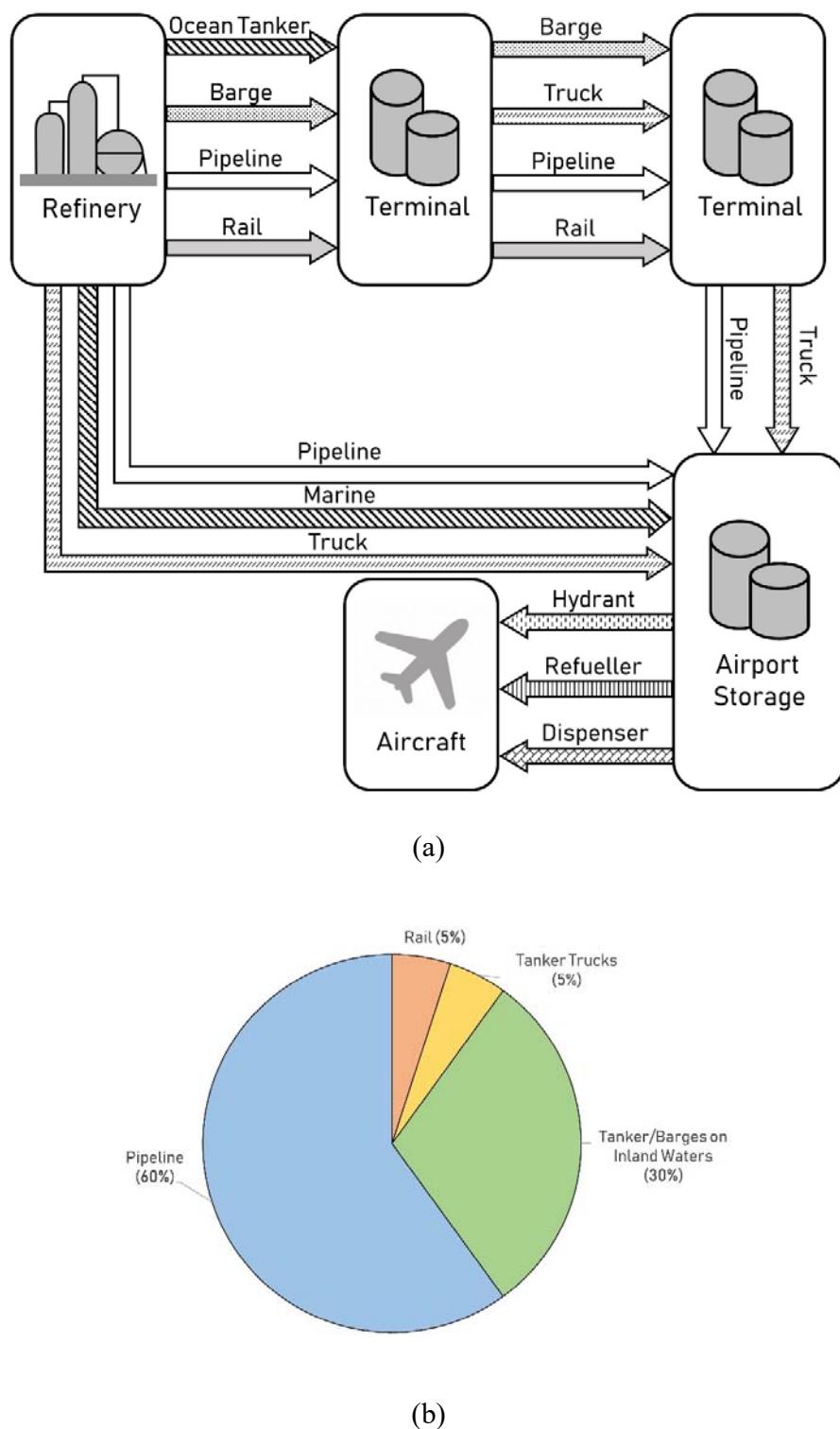


Figure 8: Storage and transport of jet fuel: a) Typical jet fuel distribution chains (Drawn using data from Hemighaus et al. (2006)); and b) Breakdown of major transport mechanisms for all refined fuel products in the U.S. (Plotted using data from Davidson et al. (2014)).

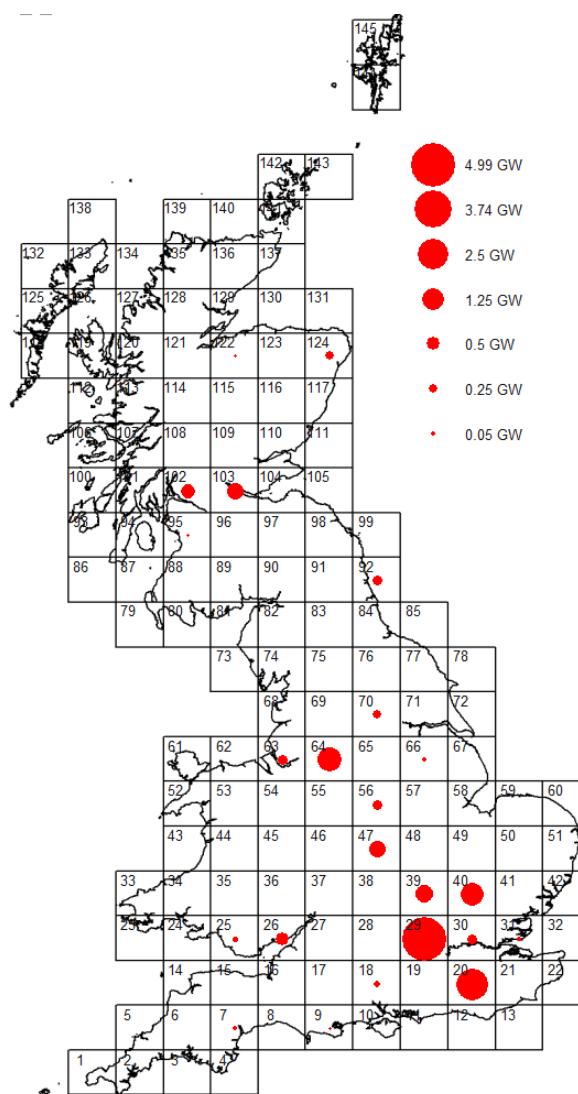


Figure 9: Jet fuel demands for Great Britain at 50 km resolution.

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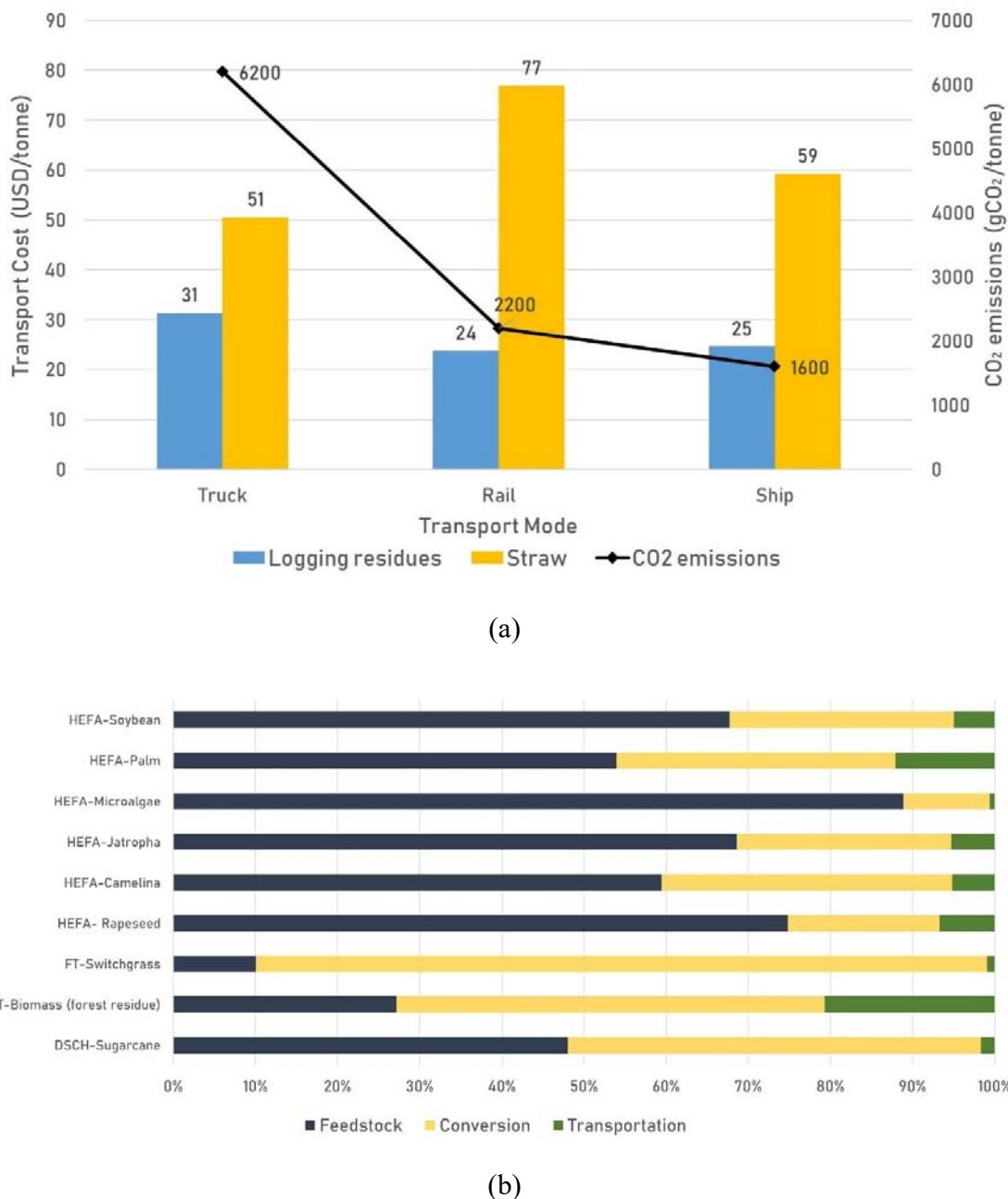


Figure 10: Economic and environmental impacts of transporting BAF feedstocks: a) Average cost and GHG emissions of transport modes used in delivering feedstocks from farm to processing facilities (Plotted using cost data from Ko et al. (2018) and GHG emissions data from Cefic and ECTA (2011) for transport by truck, rail and ship; the relative comparison assumed a transport distance of 100 km); and b) Breakdown of GHG emissions by phases for HEFA, FT and DSCH for a variety of feedstocks (Plotted using data from Capaz and Seabra (2016)).

2260 **15 Tables**

2261 Table 1. Five types of synthetic paraffinic kerosene based on the production platform (Data from  
 2262 Wang and Tao 2016, Yang et al. 2019).

SPK	Production platform	Brief process description
HEFA-SPK	Oil-to-jet	Deoxygenation of oils and fats → hydroprocessing
FT-SPK	Gas-to-jet	Gasification of biomass → Fischer-Tropsch → hydroprocessing
FT-SPK/A	Gas-to-jet	Gasification of biomass → Fischer-Tropsch → hydroprocessing → increase aromatics content
ATJ-SPK	Alcohol-to-jet	Hydrolysis of biomass → sugar fermentation to alcohol → dehydration → oligomerisation → hydrogenation → fractionation
SIP-SPK	Sugar-to-jet	Hydrolysis of biomass → sugar fermentation to farnesene → hydroprocessing → fractionation

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2277 Table 2: Advantages and disadvantages of bio-aviation fuel (Data from Rye et al. 2010, Hendricks et  
 2278 al. 2011, Gegg et al. 2014, Bosch et al. 2017, de Jong et al. 2017).

2279	Advantages	Disadvantages
2280	Theoretically unlimited feedstock supply	Problems associated with monocultures, e.g. lack of biodiversity and susceptibility to pests.
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2282	Less risk in the long term in the case of fuel spillage	Competition with food supply if energy crops become more profitable than food crops for farmers.
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2284	Capable of reduced net CO <sub>2</sub> emissions when burned depending on production methods	Detrimental land-use change, e.g. clearing existing vegetation from land, eutrophication from fertiliser use, and water/energy use during cultivation.
2285		
2286	Use as 'drop-in' alternative for existing engines	Spatial and temporal boundaries, e.g. feedstock may not be grown all year round or at all in some areas if specific conditions are required
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2288	Generally lower in contaminants, e.g. sulphur	-
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2302 Table 3: Feedstocks for bio-aviation fuel production (Data from Rye et al. 2010, Warshay et al. 2011,  
 2303 Kandaramath Hari et al. 2015, ATAG 2017, Chiaramonti and Horta Nogueira 2017, Rödl 2018, Roth  
 2304 et al. 2018, Staples et al. 2018, Alalwan et al. 2019).

First-generation (1-G)	Second-generation (2-G)	Third-generation (3-G)	Fourth-generation (4-G)
<ul style="list-style-type: none"> <li>• Oil-seed crops: camelina, oil palm, rapeseed, soybeans, sunflower, salicornia</li> <li>• Sugar and starchy crops: corn, wheat, sugarcane, sugar beets</li> </ul>	<ul style="list-style-type: none"> <li>• Oil-seed energy crops: jatropha, castor bean</li> <li>• Grass energy crops: switch grass, miscanthus, Napier grass</li> <li>• Wood energy crops: poplar, eucalyptus</li> <li>• Agricultural and forestry residues: corn stover, sugarcane bagasse, wood harvesting/processing residues</li> <li>• Food and municipal waste: used cooking oil, animal fats, biogenic fraction of municipal solid waste (MSW)</li> </ul>	<ul style="list-style-type: none"> <li>• Algae: microalgae</li> </ul>	<ul style="list-style-type: none"> <li>• Genetically modified organisms</li> <li>• Non-biological feedstocks: CO<sub>2</sub>, renewable electricity, water</li> </ul>

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2311      Table 4: Comparison of the cultivation requirements of various 1-G and 2 feedstocks (Data from  
 2312      Escobar et al. 2009, Hickman et al. 2010, Fazio and Barbanti 2014, Searle and Malins 2014, Curneen  
 2313      and Gill 2016, Surian Ganba et al. 2016, Liu et al. 2017, Campbell 2018, Fabio and Smart 2018,  
 2314      Fischer et al. 2018, Rödl 2018).

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Category	Feedstock	Climate	Nutrients	Water
1-G	Camelina	Temperate to tropical; also, in semi-arid climate zones	Low demand	Low to moderate rainfall
	Corn	Tropical	High fertility soil required	Efficient water use
	Oil Palm	Tropical and Subtropical (25–32°C)	Low demand	Higher (Uniform precipitation required all year round, 1800–5000 mm/year)
	Rapeseed	Most efficient growth at 15–20°C; sensitive to high temperatures	High demand	Low to moderate demand (600 mm/year needed)
	Sugar beet	Variety of moderate climates	High fertiliser demand	Moderate water use (550–750 mm rainfall during growth)
	Sugarcane	Tropical and Subtropical	High demand	High precipitation required all year round
	Soybeans	Subtropical to tropical	Moderate fertiliser demand	High water demand
2-G	Wheat	Moderate climates (Subtropical with rainy winters to mountainous tropical regions)	High demand	High water demand
	Jatropha	Tropical: Annual average temperature between 20–28°C	Low demand	Low demand and drought resistant (Minimum precipitation 400 mm/year needed)
	Castor bean	Tropical: 20–30°C	Moderate demand	Low demand (At least 400 mm of precipitation during seedling and blossoming)

Switch grass	Temperate	Low demand (0–50 kg <sub>N</sub> /ha)	Moderate demand (800 mm/year)
Miscanthus	Tropical to temperate; cold resistant	Moderate demand (50–75 kg <sub>N</sub> /ha)	Moderate to high demand (1000 mm/year)
Napier grass	Tropical	High demand (150–300 kg <sub>N</sub> /ha)	High demand but drought resistant (Precipitation of 1500 mm/year)
Poplar	Temperate	Low demand	Low to moderate demand (Precipitation of 400– 800 mm/year)
Willow	Temperate	Low to moderate demand (0–150 kg <sub>N</sub> /ha)	Moderate to high demand (Precipitation of 600– 1000 mm/year)
Eucalyptus	Dry tropical to subtropical zones	Low demand	Moderate to high demand (Precipitation of 600– 1000 mm/year)

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Table 5: Literature review on supply chains models for bio-aviation fuel provision.

Author (Year)	Feedstock	Model	Model capability	Location
Elia et al. (2013)	Forest residues	A nation-wide mixed-integer linear programming model for biomass-to-liquid supply chain	A supply chain cost optimisation framework that determines the best operating network	USA
Agusdinata and DeLaurentis (2015)	Microalgae	Multi-actor life cycle assessment integrated to a system dynamics model	Evaluation of the GHG emissions reduction potential of algal-based jet fuels	USA
Newes et al. (2015)	Cellulosic feedstock (Not specified)	Biomass Scenario Model	A system dynamics model for the simulation of the complex incentive-production interaction	USA
Samsatli et al. (2015)	Energy crops (miscanthus, willow) and waste biomass (waste wood, food wastes)	Biomass Value Chain Model (BVCM)	A comprehensive and flexible whole system optimisation model for biomass supply chain with spatio-temporal capabilities	UK
Jacobson et al. (2016)	Forest residues	Forest Residue Economic Assessment Model (FREAM)	Modelling platform for the analysis of the logistics of wood-based bioenergy	USA
Alves et al. (2017)	Sugar crops, oil crops, and lignocellulosic biomass	Techno-economic assessment of biorefinery technologies: feedstock logistics, pre-processing, biorefinery	Scenario development for the co-production of bio-aviation fuels and biochemicals	Brazil

Domínguez- García et al. (2017)	Jatropha, camelina	Multi-objective mixed-integer linear programming model to plan strategically an aviation biofuel supply chain with hydrogen production	Minimization of cost and GHG emissions	Mexico
Martinkus et al. (2018)	Wood residues	Integrated multi-criteria decision analysis and Total Transportation Cost Model (TTCM)	Selection of depot for biorefinery based on least cost analysis	USA
Perkis and Tyner (2018)	Corn stover, wheat straw, and switch grass	A sequential start-up model written as a mixed-integer non-linear (quadratic) program	Sequential optimisation of units cost based on selected siting and capacity of conversion facilities and feedstocks	USA
Ravi et al. (2018)	Wood residues	Regional air quality model at high resolution	Estimation of air quality impacts of forestry-based bio-aviation fuel supply chain	USA
Doliente and Samsatli (2019)	Rice straw, rice husk	A multi-objective spatio-temporal mixed-integer linear programming model for rice value chains	Simultaneously determine the planning, design and operation of efficient and sustainable rice value chains	Philippines
Lewis et al. (2019)	Waste biomass (MSW, waste oils and fats, and agro-forestry residues)	Integrated Biomass Scenario Model (BSM) and Freight and Fuel Transportation Optimization Tool (FTOT)	System dynamics model with geo-spatial capability to develop scenarios for the deployment of bio-aviation fuel based on optimal feedstock and fuel flows	USA