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

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Abstract

The undeniable environmental ramifications of continued dependence on oil-derived jet fuel have spurred international efforts in the aviation sector towards alternative solutions. Due to the limited options for decarbonisation, the successful implementation of bio-aviation fuel is crucial in contributing to the roster of greenhouse gas emissions mitigation strategies for the aviation sector. Since fleet replacement with low-carbon technologies may not be a feasible option, due to the long lifetime and significant capital cost of aircraft, 'drop-in' alternatives, which can be used in the engines of existing aircraft in a seamless transition, may be required. This paper presents a detailed analysis of the supply chain components of bio-aviation fuel provision: feedstocks, production pathways, storage, and transport. The economic and environmental performance of different potential bio-feedstocks and technologies are investigated and compared in order to make recommendations on short- and long-term strategies that could be employed internationally. Hydroprocessed esters and fatty acids production pathway, utilising second-generation oil-seed crops and waste oils, could be an effective immediate solution with the potential for substantial greenhouse gas emissions savings. Microalgal oil could potentially offer far greater yields of bio-aviation fuel and reductions in greenhouse gas emissions, but the technology for large-scale algae cultivation is inadequately mature at present. Fischer-Tropsch production pathway using lignocellulosic biomass has the potential for the highest greenhouse gas emissions savings, which could potentially be the solution within the medium- to long-term plans of the aviation industry, but further research and optimisation are required prior to its large-scale implementation due to its limited technological maturity and high capital costs. In practice, the ‘ideal’ feedstocks and technologies of the supply chains are heavily dependent on spatial and temporal criteria. Moreover, many of the parameters investigated are interlinked to each other and the measures that are effective in greenhouse gases emissions reduction are largely associated with increased cost. Hence, policies must be streamlined across the supply chain components that could help in the cost-effective and sustainable deployment of bio-aviation fuel.

1 Introduction

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

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

To date, technological improvements have already begun contributing to the GHG emissions reduction target. Airframe and engine manufacturers have made significant technological leaps including lighter and stronger composite materials than ever before, new innovative aircraft designs with improved aerodynamics and incrementally more efficient engines (Rye et al. 2010). For example, 15 billion L of fuel, and 80 million tonnes of CO_2, were saved by retro-fitting wing tip devices to the wings of over 5000 existing aircraft (ATAG 2019). By also using weight reduction measures on cargo containers, GHG emissions decreased by 10,000 t/year (ATAG 2014). These improvements allow greater efficiency in mileage and lower fuel consumption during travel. However, the slow incremental changes in already-mature engine technology and the long lifetime (> 25 years) of existing fleets point toward AJF as a much faster and potentially more cost effective option to reduce emissions (Bauen et al. 2009). AJF can be easily utilised in existing fleets, hence avoiding large capital costs involved with buying newer models. Biofuel utilisation promises tremendous cut in GHG emissions and possible achievement of the ambitious target by 2040 as depicted in Figure 1(b). Thus, bulk of the reduction can be attained by replacing conventional jet fuel (CJF) with this alternative.

CJF produced from crude oil is a blend of various kerosene hydrocarbons. The hydrocarbon length of jet fuel is between that of gasoline and diesel. In a classical refinery, shown in Figure S1 (Supplementary Material), jet fuel (or kerosene) is the middle distillate making up to 10% of the crude oil fraction while the majority are gasoline and diesel. Table S1 shows the comparison of the physicochemical properties of gasoline, jet fuel and diesel. As fuel for aviation, jet fuel is preferred over gasoline as it less volatile and denser; while compared to diesel, jet fuel is lighter and less prone to wax at low temperatures (Yang et al. 2019). An AJF should have physical and chemical properties similar to CJF. A suitable aviation fuel must have high cold stability, for temperatures -47 to 40 °C and elevations above 30,000 feet and have sufficient energy density to supply the high energy demand of long-haul flights (The Engineering ToolBox 2003, Wilbrand 2018). The industry uses two major kerosene-based CJF, Jet A and Jet A-1. With a lower melting point of -4 ºC, Jet A-1 is the better choice for international flights. The desirable composition of a jet fuel should be 75–85 vol% consisting of paraffins, iso-paraffins and cycloparaffins and the remaining 15–25 vol% of olefins and aromatics. Other important characteristics include global availability, acceptable costs, good combustion characteristics, and good flow behaviour. Hence, AJF being a 'drop-in' fuel can be easily integrated into existing infrastructure allowing a seamless transition (Rye et al. 2010). An AJF must also have lower carbon footprints over their life cycle than CJF, which typically have a carbon footprint of roughly four tonnes per tonne of fuel (de Jong et al. 2017).

As an AJF, bio-aviation fuel (also called as bio-jet fuel, renewable jet fuel or aviation biofuel in some literature) or BAF (for short in this paper) is recognised as a short- to medium-term solution towards an overall reduction in the GHG emissions of the aviation industry. Table S2 shows the standard specifications for both CJF and BAF, which manufacturers must strictly comply (Wilbrand 2018, Yang et al. 2019). Clearly, the resulting emissions profiles of an aircraft running on BAF would be very similar to one on Jet A-1 (Rye et al. 2010). But the closed carbon cycle established by sequestering atmospheric CO_2 during biomass growth and released at the end of its life cycle as BAF, results in its significantly lower overall carbon emissions compared to CJF (Bosch et al. 2017). While this makes BAF an attractive AJF option, several issues arose in its implementation. It has not been receiving sufficient investments due to inadequate government support and industry commitment, unreliable supply of feedstocks, uncertain commerciality of the production pathways, and lack of supply chain certification (Gegg et al. 2014).

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

The focus of this review paper is on bio-aviation fuel examined holistically of its supply chain components: feedstock, production pathways, storage and transport. This review is organised into six sections. Section 2 gives an overview of bio-aviation fuel. Section 3 is a comprehensive discussion of key feedstocks, which includes their cultivation requirements, supply chain models and economic and environmental impacts. The three most prominent production technologies are compared in Section 4 in terms of their advantages and limitations, as well as their economic and environmental impacts. The storage and transport technologies for raw materials, intermediates and final jet fuel product are discussed in Section 5. Section 6 offers critical analyses, recommendations and future direction of each supply chain component. The key conclusions of this review paper are found in Section 7.

2 Bio-aviation fuel

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

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

The challenges faced by BAF are similar to those of biofuels, in general: the main one being how to ensure that the feedstocks, which come from biomass or other carbon-based sources, are secure, sustainable, economically viable and sufficiently available within both time and location of demands (Hendricks et al. 2011, Su et al. 2015). With the aviation industry along with the sectors of heating, chemicals, road transport and electricity, exerting efforts to decouple from fossil fuel dependence by shifting to biomass, their demands for the same feedstocks create a new supply competition (de Jong et al. 2017). The following sections discuss the feedstocks and critically analyse their cultivation requirements, feasibility and sustainability of their supply chains, and their economic and environmental performance. The discussions are focused specifically on feedstocks for bio-aviation fuel production but many of the issues also apply to production of biofuels in general since they share the same feedstocks.

3 Feedstocks for biomass-derived synthetic paraffinic kerosene

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

3.1 First-generation feedstocks

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

3.1.1 Oil palm

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

Globally, oil palm plantations have already expanded by about 12 million hectares between 2000 to 2012 in large portions of tropical forests in Malaysia and Indonesia (Pirker et al. 2016). When either primary or secondary forests are converted to plantations, biodiversity loss has been well associated with it (Koh and Wilcove 2008). Rich concentrations of birds and mammals are highly at risk to extinction in the vulnerable forests of Southeast Asia, South America, Mesoamerica and Africa (Vijay et al. 2016). Oil palm expansion is also well associated to the degradation of peatlands. Instead of acting as carbon sinks, peatlands become net GHG emitters after their conversion to agricultural lands. Plantations in Southeast Asia, that were once peatlands, were estimated to have surface GHG emissions of 54 to 115 $tCO_2eq/ha/yr$ (Page et al. 2011). In palm oil mills, waste management of palm oil mill effluent (POME) is the main issue. Raw POME has a high biochemical oxygen demand (> 25,000 mg/L) and large volumes are generated yearly (Madaki and Seng 2013). In 2015 alone, 60.88 and 94.76 million tonnes were generated in Malaysia and Indonesia, respectively (Choong et al. 2018). Due to high treatment costs, discharging of raw or partially treated POME to land or water bodies continues as an industry practice resulting in large-scale water pollution and ecosystem degradation (Madaki and Seng 2013).

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

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

3.2 Second-generation feedstocks

Non-edible 2-G biomass resources can circumvent the food versus fuel dilemma of 1-G feedstocks (Alalwan et al. 2019). These are classified into two main groups: energy crops and waste biomass. 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 Kaltschmitt 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 Gökalp 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

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

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

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

The high economic costs associated hinder the commercialisation of most lignocellulosic feedstocks (Correa et al. 2019). Hence, actual supply chains have yet to be fully realised. Notwithstanding, mathematical modelling and optimisation techniques have been applied to model these supply chains. Potential minimisation of costs within the agricultural, transport and industrial activities of the supply chain has been shown (Atashbar et al. 2016, Atashbar et al. 2018). To date, a few modelling studies have been published on energy crop supply chains for BAF provision. Perkis and Tyner (2018) presented a sequential start-up model, based on mixed-integer non-linear programming, with the aim of minimising the production and logistics costs of jet fuel from switch grass in Indiana, USA. 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_2 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-farsenene 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-term when CJF prices are high. LCA by Trivedi et al. (2015) confirmed that corn stover-based BAF via FT and advance fermentation have lower GHG emissions than CJF at 87% and 55%, respectively. Sugarcane bagasse, produced at 200 million tonnes annually, can be a significant feedstock for the production of biofuels for both road and air transport via established thermochemical production pathways like gasification and pyrolysis (Nicodème et al. 2018). Michailos (2018) conducted a techno-economic and life cycle analysis of BAF (farnesane) production from sugarcane bagasse via direct sugar to hydrocarbon route. With a low yield of 12.1% w/w fuel per sugarcane bagasse, the minimum jet fuel selling price (MJSP) would be USD_{2018} 2.78/L (4 times greater than CJF) suggesting government subsidies will be needed; while 49% reduction in GHG emissions against CJF would be expected indicating a favourable sustainability potential. Roda et al. (2015) assessed the available crop residues for BAF production in Malaysia, an agricultural and developing country, to a maximum of 3.8 million litres per year from the waste streams of oil palm, rubber, sugarcane, coconut and rice industries. Although the quantity of oil palm residues is highest in Malaysia, the associated environmental concerns of its cultivation constraints its sustainable availability. There are also oil-rich agro-forestry residues that can be potential BAF feedstocks. Rice bran, a by-product of rice milling and annually produced at 75 million t/year, contains 10–20% w/w oil (Sharif et al. 2014, Nguyen et al. 2019). Nguyen et al. (2019) designed a transesterification process in the presence of Ni(II)-Schiff base chelate promoter catalyst and H_2 gas environment to convert rice bran oil to a biodiesel product with even better cetane index values and lower glycerol impurities than the conventional biodiesel. The hydrotreatment of rice bran oil in the presence of $NiMo/Al_2O_3$ catalyst has also been performed yielding fuel products with similar to enhanced properties than petroleum ones (El Khatib et al. 2018). Alternatively, eucalyptus leaves can also be a source of high-octane oil, which has a potential biofuel application for road and aviation transport (Kainer and Kulheim 2016, Masimalai and Subramaniyan 2017). Due to yearlong production of forestry residues, they can be more preferable BAF feedstocks than crop residues (Richter et al. 2018). Shah et al. (2019) showed that upgraded pyrolysis oil from sawdust of eucalyptus blended with waste cooking oil has similar physico-chemical characteristics to aviation kerosene. Alves et al. (2017) also found that ethanol-to-jet production pathway is a favourable techno-economic design for BAF production from eucalyptus residues in Brazil. Ganguly et al. (2018) also conducted a well-to-wake (WTW) LCA of BAF production from mild bisulfite pretreated forestry residues via butanol-to-jet production pathway that revealed a 78% reduction in global warming impact compared to CJF.

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

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

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

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

Logistical complexity and variable availability of waste biomass are the primary challenges as BAF feedstock (Iakovou et al. 2010, Mawhood et al. 2016). The bulkiness of some can lead to high logistic operating costs and constrain the capacity of centralised processing plants (Mawhood et al. 2016). Collection, transportation and storage of large amounts of biomass wastes, like animal manure and MSW, are additional issues due to health and safety risks (Rentizelas et al. 2009, Downie and Van Zwieten 2013). Other waste management inadequate legislation, such as landfills, incineration and recycling, can potentially hinder their streamlined acquisition (Mawhood et al. 2016). The highly uncertain availability of waste biomass remains an issue for their sustainable utilisation (Roth et al. 2018). Many of the candidates as feedstocks are not available all year round and at the same location where they are needed (Staples et al. 2018). Compared to energy crops, studies on the potential and actual availability of waste biomass are limited (Roth et al. 2018). Hence, conversion technologies need to be robust in order to adapt to their variability and still produce the desired BAF product (Mawhood et al. 2016, Conrad et al. 2019).

Table 5 summarises all the supply chain models specifically for BAF provision reviewed in this paper. Studies on the supply chain of waste biomass for BAF production are still few. Most literature available are supply chain models for forest residues. Jacobson et al. (2016) developed a Forest Residue Economic Assessment Model (FREAM), a supply chain model integrated with GIS data and stakeholder engagement, for the simulation and cost estimation of harvest, transport and conversion of forest residues. A regional-scale production of BAF via ethanol-to-jet production pathway in Inland Northwest of USA was conducted revealing a total production cost of USD_{2016} 1.23/L with capital and transport accounting at 15% and 32%, respectively, of the total cost per tonne of forest residue processed. Martinkus et al. (2018) integrated multi-criteria decision analysis and a total transportation cost model for the assessment of existing industrial facilities within a forest residue-based depot-and-biorefinery supply chain. A least cost supply chain for woody biomass conversion into aviation fuel in Inland Northwest, USA was determined, which showed the capital and operational costs for disaggregated biomass pre-processing in depots are lower than an integrated biorefinery. Elia et al. (2013) developed a MILP model for the cost optimisation of a biomass-to-liquid supply chain producing diesel, gasoline and jet fuel using forest residues in the whole of USA. The BVCM by Samsatli et al. (2015) is also capable of optimising the cost and GHG emissions for a forest residue- and/or other waste biomass-based supply chain for jet fuel provision. Alves et al. (2017) performed a techno-economic assessment of co-producing renewable jet fuel and high-value platform chemicals in Brazil through a supply chain comprising of feedstock logistics, decentralised pretreatment facilities and a centralised biorefinery. Their results showed the ethanol-to-jet processing of eucalyptus residues or sugarcane residues as the most economically feasible. Contrary to studies focusing on economics, Ravi et al. (2018) studied the environmental impacts of a forest residue-based BAF supply chain in the Pacific Northwestern of USA. Using a regional air quality model with high-resolution, their results showed that the biorefineries can be a substantial local source of NO_x and CO but regionally the increase is insignificant. Moreover, the utilisation of the residues in the supply chain results in air quality and health benefits outweighing the negative effects of pile burning. On the other hand, the sequential start-up model programme by Perkis and Tyner (2018) assessed the economic performance of a corn stover- and wheat straw-based BAF supply chain in Indiana, USA. The study found that the first batch of investors would opt for corn stover and situate conversion facilities near locations of high feedstock availability. Vast quantities of rice straw and rice husk in many rice producing counties can be a potential waste stream for BAF production (Roda et al. 2015). The MILP model for efficient and sustainable rice supply chains by Doliente and Samsatli (2019) is the first to consider the biomass-based production pathways of jet fuel using rice crop residues as feedstock. Lastly on waste biomass-based supply chains for jet fuel, Lewis et al. (2019) coupled the Biomass Scenario Model, a system dynamics model, to study the supply chain evolution in the USA, with the Freight and Fuel Transportation Optimization Tool, to determine optimal transport flows and routes. Their results show that BAF production from 75 million to 4 billion litres per year is achievable with a mix of waste biomass streams and conversion technologies (HEFA leading in the short term and followed by advanced technologies in the long term). By considering the geo-spatial availability and holistically viewing the supply chain, these studies demonstrate the promising benefits of waste biomass and the respective conversion technologies in the provision of BAF (Mawhood et al. 2016, Gutiérrez-Antonio et al. 2017). Despite these efforts, the supply and demand for waste biomass-derived BAF continue to be insignificant to CJF (Mawhood et al. 2016).

3.3 Third-generation feedstocks

Algae are of high interest due to having no food value, high yields with virtually no land requirement, and relatively low cost requirements (e.g. grown in suspensions requiring only sunlight, simple nutrients, and CO_2 that can be from industrial flue gases) (Cheng and Timilsina 2011, Lee and Lavoi 2013, Atashbar et al. 2018, Richter et al. 2018). Algae are capable of growing in polluted water or water unsuitable for agriculture that can simultaneously lower operating costs and provide wastewater treatment benefit (Acheampong et al. 2017, Alalwan et al. 2019). The demand for water (regardless of quality) by algae to produce 1 L of biodiesel is about 300–1000 L that is lower than most 1-G feedstocks (e.g. 5,500 L and 15,000 L for canola and soybean, respectively).

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

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

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

Ames (2014) estimated the global potential of algal oil ranges from 350 billion L/year (limited productivity scenario) to 2 trillion L/year (high productivity scenario) with cultivation in Asia and North America to have the highest potential. However, locations having high availability of marginal lands, tropical to semi-arid climate, and close proximity to sustainable water and CO_2 sources are also favourable cultivation sites. Roth et al. (2018) reviewed the important criteria in selecting suitable sites for cultivating microalgae for BAF production. These include climatic conditions (e.g. available solar radiation and ambient temperature); terrain (commonly limited to <5% slope); sources of water (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 Pishvaee 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_2 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_2, 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_2/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_2 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_2, water and solar energy. In terms of the studies on supply chains of 4-G feedstocks, although limited to date, Mesfun et al. (2017) applied a spatio-temporal MILP model for the integration of power-to-gas (PtG) and power-to-liquid technologies in an Alpine energy supply. Depending on the pricing of fossil fuel and carbon, the study confirmed that renewable energy systems become more flexible when integrated with PtG and PtL technologies as these convert the excess intermittent renewable power to fuels and enable the utilisation of large amounts of captured CO_2 (0.20–15 million tonnes per year) via fuel production. When these technologies become commercially mature, BAF from 4-G feedstocks promise to be the most sustainable with the potential for negative carbon emissions and interlinking power, heating and aviation sectors (Mesfun et al. 2017, Richter et al. 2018).

3.5 Economic analysis

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

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

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

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

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

3.6 Environmental analysis

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

Cultivation and harvesting of 1-G and 2-G feedstocks represents significant contributions to their total GHG emissions due to the continued reliance on fossil fuels in both the direct and indirect inputs of many farming activities (Pimentel 2009, Liu et al. 2017). Direct inputs include diesel and gasoline to power machineries for land preparation and cultivation, pumps for irrigation and vehicles for transportation. While indirect inputs consist of fertilisers, pesticides, water, and seeds whose embodied energy (from production to transportation in the farm) are also from fossil fuels (Azwan et al. 2016, Elsoragaby et al. 2019). Typically, GHG emissions from fertilisers account for most of the indirect inputs since their chemical production requires large amounts of natural gas (Pimentel 2009, Liu et al. 2017). Post-harvest processing can also be a significant source of GHG emissions. For oil-bearing crops, oil mills require electricity and heat that are mostly fossil-based. Figure 4(b) depicts a relative comparison of the energy requirements for farming and oil milling of oil-seed crops for BAF production. To improve the environmental sustainability of a BAF feedstock, the use of biofuels in the machineries and bio-electricity/heat (from agro-forestry residues) in milling operations should be practiced (Sims et al. 2015). Storage and transport (to the mill and/or bio-refinery gates) of the harvested and/or pre-processed feedstocks usually account to a minor portion of the total GHG emissions. A transport process is a function of load and distance (Cefic and ECTA 2011). Greater GHG emissions result from transporting large amounts of feedstocks over large distances. Importing processed oil from the tropics to EU have been reported to result in additional GHG emissions (O'Connell et al. 2019). While some storage facilities may use minimal energy, feedstock requirements may use considerable energy and lead to GHG emissions, especially when fossil-based (Egg et al. 1993, Emery et al. 2015).

Among oil-seed food crops, O'Connell et al. (2019) demonstrated that oil palm cultivation grown in mineral soil have the least GHG emissions (Figure 4(a)). Elgowainy et al. (2012) showed that palm oil extraction energy requirement is also the least (Figure 4(b)). Hence, oil palm as BAF feedstock may be the best food crop-based option, even when considering an average of 6.0 gCO_2eq emissions associated with transporting to the EU. However, when LUC associated with cultivation happens, land-based crops like oil palm become environmentally unsustainable feedstocks. LUC can result in both direct and indirect emissions (Bauen et al. 2009). Direct LUC emissions represent activities associated with changing the land from its past condition to feedstock cultivation. While indirect LUC emissions, due to low availability of arable lands, result from land expansion at the cost of deforestation. Even without considering the indirect LUC emissions of recent land expansion of oil palm plantations, O'Connell et al. (2019) confirmed a staggering 100 to 600 times increase in GHG emissions from direct LUC of 16% and 100% peatland, respectively. The resulting life cycle GHG emissions of oil palm grown in peat land are even higher than the production of CJF at 20 gCO_2eq/MJ. In the investigation of ICAO (2009), peatland forests being repurposed into plantations have increased GHG emissions by a factor of 7.5. Large amounts of carbon stored in peatlands have not only been removed from biomass clearing, but new plants grown typically have much lower carbon storing capacities. Murdiyarso et al. (2010) quantified a 254.5 te_C/ha storing capacity for natural peatland reduces to 24.2 te_C/ha for oil palm cultivation. Hence, large-scale clearing of peatland forests would potentially result in large increases of atmospheric carbon. Although the work of O'Connell et al. (2019) focused on oil palm, other land-based crops can display the same trend of increased emissions when cultivated in peatland forests. Research conducted by Wong (2008) and ICAO (2009) showed that LUC for biomass cultivation have the potential for high GHG emissions. Page et al. (2011) recommended that the reuse of peatland for energy crop cultivation should be avoided due to its environmental consequences.

Considering that the type of land-use conversion is a vital consideration for feedstock cultivation, the use of marginal land for energy crops can ensure avoidance of LUC emissions and preservation of agricultural land (Rathmann et al. 2010, Lask et al. 2019). In the case of jatropha cultivation, direct LUC emissions of converting degraded pastureland is 42 times less than that of converting a tropical rainforest as shown in Figure 4(a). However, energy crops like jatropha have low productivity in marginal lands, which significantly improves in suitable lands (von Maltitz et al. 2014, Wani et al. 2016, Lamb et al. 2018). Hence, their possible encroachment on both agricultural land and forestland can potentially result in significant LUC emissions and their poor environmental sustainability as BAF feedstocks (Schoneveld 2010, Keles et al. 2018). If LUC emissions are to be significantly abated, waste streams and algae represent the best alternatives. Considering that algal cultivation continues be a long-term tech-economic endeavor, the utilisation of waste streams, such as UCO, agro-forestry residues, and MSW, has to be prioritised within the short- to medium-term that is attested by several initiatives and projects of BAF developers (Mawhood et al. 2016). In Figure 7, GHG emissions of waste biomass are significantly lower than all land-crop based feedstocks. Moreover, LCA of feedstocks for high-octane gasoline production by Dupuis et al. (2019) showed waste biomass to have the least cradle-to-gate GHG emissions with forest residues as most environmentally benign in both feedstock and fuel production phases. Although the utilisation of agro-forestry residues are going to be essential in meeting sustainable energy goals, they also play a significant role in maintaining soil carbon for productivity function and ecosystem services (Karlen et al. 2019). Hence, only a certain portion of these resources is truly retrievable from the plantations, which could be a limiting factor of their actual contribution in BAF production. At the current state of technology and GHG emissions, a similar conclusion by Roth et al. (2018) shows UCO as the most environmentally sustainable feedstock for BAF production.

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

4 Production pathways for synthetic paraffinic kerosene

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

4.1 HEFA

4.1.1 Process description

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).

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).

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_2 (Vásquez et al. 2017). Then, the triglycerides are broken down into three fatty acid chains and propane by further cracking with H_2. 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_2 requirement: a) hydrodeoxygenation produces H_2O molecules; b) decarboxylation produces CO_2; and c) decarbonylation produces CO and H_2O 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_2 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_2O_3 and CoMo/γ- Al_2O_3 (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.

4.1.2 Advantages

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

4.1.3 Limitations

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

4.2 FT

4.2.1 Process description

In comparison with HEFA, FT is more attractive due to a greater variety of options for feedstocks that do not compete with the food supply. Many commercially established plants use FT with fossil fuel feedstock, such as coal and natural gas, and the technology of producing liquid transportation fuels is well established (Ail and Dasappa 2016). In South Africa, Sasol, an energy and chemicals company, operate multiple synthesis plants using ‘coal-to-liquid’ process (CTL) (Ail and Dasappa 2016). A 50% blend of BAF via FT and CJF known as Sasol’s ‘Semi Synthetic Jet Fuel’ has been supplied to Johannesberg since 1999 (Lobo et al. 2011). The fuel produced using biomass is identical to CTL and very similar in composition to jet fuel but with lower net GHG emissions (Bauen et al. 2009). It is also reported that the energy efficiency of BAF via FT (77%) is higher than that of coal-based (64%) or natural gas-based (68%).

Figure S3(a) presents the major steps involved in FT. During gasification, biomass is reacted with oxidants (most commonly CO_2, steam or air) in a ratio such that partial oxidation occurs, producing CO and H_2 rich gas, also known as syngas. The ratio of H_2 to CO is determined partially by the oxidant used (Klinghoffer 2013). To produce high yields of heavier hydrocarbons that is necessary for BAF, a lower H_2 to CO ratio is ideal making CO_2 a better choice than steam (Raje and Davis 1997). Following the gasification, the syngas stream is purged of impurities and unwanted compounds including CO_2 and other gaseous impurities before the synthesis. The removal of CO_2 from syngas improves the selectivity of the downstream process. On the other hand, the removal of H_2S avoids the deactivation of the catalyst (Wei et al., 2019). Iron and cobalt are the main catalysts used. The CO to H_2 ratio is managed by water-gas-shift reaction, and subsequent CO_2 removal is made. Then the Fischer-Tropsch synthesis takes place. The basic reactions underpinning this produce alkanes or alkenes with water as a by-product as displayed in Figure S3(b) (Radich 2015). Fischer-Tropsch reactions can occur as either a high-temperature process (300-350 ºC) or a low-temperature process (200-240 °C) (Dry 2002). These reactions are extremely exothermic and, as a result, it is important that this heat is removed quickly and efficiently to prevent the catalyst deactivation due to sintering and to minimise unwanted methane production (Dry 2002). Ail and Dasappa (2016) stated that modern plants use low temperature processes for producing liquid fuels. These plants commonly use a multi-tubular reactor wherein the catalyst is placed within the tubes and the cooling medium on the shell side. Other conditions can also be altered during the reactions, such as pressure, type of catalyst and residence time, in order to specify the hydrocarbon ranges in the product (Dry 2002). Following Fischer-Tropsch synthesis, lighter hydrocarbons can be oligomerised or heavier hydrocarbons can be cracked to increase or decrease, respectively, in order to obtain bio-aviation fuel having hydrocarbon lengths within the specified range (Richter et al. 2018). The crude products are then isomerised to generate branched iso-alkanes from n-alkanes in order to produce a jet fuel product within the specified freezing point. Lastly, the bio-aviation fuel is separated from the isomerised products using distillation.

4.2.2 Advantages

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

4.2.3 Limitations

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

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

4.3 ATJ

4.3.1 Process description

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

The process diagram for ATJ depicted in Figure S4(a) are similar for all alcohol feedstock and intermediates. Due to the maturity of the technology associated with alcohols, each stage has been researched extensively. The alcohols are firstly dehydrated. The removal of water yields alkene molecules, while simultaneously removing impurities. Dehydration of ethanol for ethylene production has been in use since the 1960s, so routes with higher selectivity using heterogeneous catalysts have been developed, such as ‘Syndol’, a specialised catalyst for this process (Geleynse et al. 2018). For isobutanol, the use of strong acidic catalysts can have a two-fold effect of dehydration and commencing the oligomerisation reaction but the fuel produced has been found to be inferior in quality to that produced if the reactions were to occur separately (Taylor et al. 2010). In the oligomerisation step, the alkene monomer molecules are reacted to synthesise longer chain molecules. As presented in Figure S4(b), the larger oligomers (olefins) remain unsaturated, containing double bonds. As with the other steps, specific oligomerisation processes have been developed by a variety of companies, depending on the feedstock used, such as the Chevron Phillips ‘Ziegler’ process for ethanol. For the Ziegler ‘one-step’ process, the catalyst cannot be recycled, but must be collected and disposed of, whereas the catalyst in the ‘two-step’ reaction can be reused (Weissermel and Arpe 2008). The reaction conditions for these processes vary and must be balanced with their cost and the overall process cost. The oligomerised product consists of a wide range of carbon chain lengths. Wright et al. (2008) reported a 96% conversion of but-1-ene into C_8, C_{12}, C_{16},

C_{20} oligomers. The required carbon lengths are between C_{14} and C_{20} for jet fuel and, to maximise the yield in this desired range. The C_8 olefins can be separated then recycled or sent to a secondary dimerisation facility. This would increase the carbon chain length and produce a greater yield of jet fuel per unit of feedstock. Subsequently, the oligomers are then hydrogenated to yield a product stream containing the synthetic paraffinic kerosene. Finally, distillation separates the bio-aviation fuel product stream from the bio-naphtha and biodiesel product streams.

4.3.2 Advantages

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

A demonstration for BAF via ATJ has been proposed at a medium-scale. The process by LanzaTech utilises industrial waste gases (e.g. flue gas) from steel production containing CO, CO_2 and H_2. The process permits the recycling of carbon in the waste gas that would have been emitted to the atmosphere and takes advantage of the little to no cost of the waste gas that is likely to be cheaper than producing biogas or syngas from other feedstocks. These gases are supplemented by gasified biomass as discussed in Section 4.1.2 and fermented using microbiological species to produce alcohols (Brooks et al. 2016). In addition, this process can also use municipal waste to augment the feedstock requirement. LanzaTech, supported by Virgin Altantic Airways, are planning to develop a facility capable of producing over 13.5 million L of BAF via ATJ blended with CJF and diesel. The intention is predominantly to use waste streams from industrial and municipal sources as feedstock (Surgenor 2018). The facility is likely to proceed as it has received a USD_{2018} 520,700 grant following an application to the UK Department for Transport (LanzaTech 2018).

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

4.3.3 Limitations

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

4.4 Economic analysis

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

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

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

The production cost of the three production pathways discussed range from 3 to 7 times greater the refinery production of CJF as depicted in Figure 6. Hence, it is important to improve these processes for them to become cost-efficient and be able to compete with CJF. The price of BAF could also be lowered by subsidies and taxes though policy development. Yang et al. (2019) suggested that if BAF production via HEFA meets policy targets, it could become economically attractive by imposing a 17% subsidy on BAF and 20% tax on CJF. Anderson et al. (2012) estimated that the carbon cost for BAF that gives a 50% carbon savings should be about USD_{2012} 380/tCO_2eq, although this value is optimistic as the price of BAF might increase in the future.

4.5 Environmental analysis

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

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

5 Storage and transport of feedstocks and bio-aviation fuel

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

5.1 Raw materials and intermediates

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

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

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

5.2 Final jet fuel product

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

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

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

5.3 Economic and environmental analyses

The transport of feedstocks by truck, rail and ship are the most common, while the use of pipelines is currently the least established but may become significant in the future (Ko et al. 2018, Zafar 2018). A recent review on feedstock logistics by Ko et al. (2018) stated that interests on multimodal movement (combination of modes) will increase due to the influence of transportation costs and distances on feedstock utilisation. Figure 10(a) depicts a comparison of the cost and GHG emissions of transport by truck, rail and ship at 100-km radius of transport distance for logging residues and straw. Transportation cost consists of a fixed cost and a variable cost (dependent on distance), which is typically less for both ship and rail than for truck. Ko et al. (2018), however, added that transportation costs vary among countries due to feedstock type and composition, transport capacities and geographical differences. Shastri and Ting (2014) estimated that generally beyond the range of 150 to 200 km, transport of biomass is no longer feasible due to high transportation costs. Moreover, Zafar (2018) reported that for crop residues with low-density and high moisture content, even distances larger than a 25 to 50 km radius could be uneconomical. Similarly, transporting large quantities of feedstocks over long distances can contribute increased emissions from a life cycle standpoint (Gold and Seuring 2011). Supply chains with heavy reliance on transport by truck of feedstocks are expected to emit more GHGs than transport by ship or rail as shown in Figure 10(a). Furthermore, Figure 10(b) displays the breakdown of GHG emissions for hydro-processing, FT and sugar-to-jet production pathways for a variety of feedstocks showing the portion attributed to transportation. Although BAF produced from forest residues via FT have the lowest potential for overall WTW GHG emissions (Figure 7), over 20% of this value is due to transportation (Figure 10(b)).

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

6 Critical analysis, recommendations and future directions

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

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

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

6.1 Feedstocks

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

Other waste biomass such as MSW and agro-forestry residues also share this limitation as feedstocks to on-going commercial and technological developments of FT and ATJ . In the long-term, further research and development would enable commercial microalgae cultivation, which could provide a sustainable high oil-yielding feedstock for BAF production, superior to any 1-G and 2-G feedstocks given the low photosynthetic efficiency of land-based crops. Moreover, along with ecosystem services (wastewater treatment and CO_2 fixation), microalgae-derived BAF can provide the highest potential WTW CO_2 emissions savings. On the other hand, BAF derived from 4-G feedstocks can result in even greater negative net GHG emissions. However, these are at a very early stage of research but could be alternative solutions in the future, when they become commercially feasible.

The review on the supply chain models for BAF provision reveal that more research has to be done in this field. A supply chain analysis framework is highly needed in developing a portfolio of feedstocks for BAF provision. Particularly for land-based feedstocks, only genuinely available suitable lands should be considered in the assessment in order to minimise and/or avoid negative consequences of intensive cultivation, e.g. soil degradation, expansion to forestlands and peatlands, and depletion of water resources. GIS-based tools should be increasingly integrated in BAF supply chain models, especially for waste biomass, the spatio-temporal variability and uncertainty of which have to be resolved and captured in the planning, design and operation of their supply chains. More scenario development on various tax incentives and other legislations should be explored that could reveal strategies for economical feedstock production or extraction while avoiding food competition and additional GHG emissions. Waste valorisation and negative emissions technologies could also be integrated into the BAF feedstock supply chain development in order to potentially enhance their environmental performance.

6.2 Production pathways

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

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

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

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

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

6.3 Storage and Transport

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

7 Conclusions

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

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

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

8 Conflict of Interest

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

9 Author Contributions

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

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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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13 References

Abdullah, B., S. A. F. Syed Muhammad, Z. Shokravi, S. Ismail, K. A. Kassim, A. N. Mahmood and M. M. A. Aziz (2019). "Fourth generation biofuel: A review on risks and mitigation strategies." Renewable and Sustainable Energy Reviews: 37 - 50.

Abdurahman, N. H. and N. H. Azhari (2018). "An integrated UMAS for POME treatment." Journal of Water Reuse and Desalination **8**(1): 68 - 75.

Abideen, Z., A. Hameed, H. W. Koyro, B. Gul, R. Ansari and M. Ajmal Khan (2014). "Sustainable biofuel production from non-food sources - An overview." Emirates Journal of Food and Agriculture **26**(12): 1057 - 1066.

Acheampong, M., F. C. Ertem, B. Kappler and P. Neubauer (2017). "In pursuit of Sustainable Development Goal (SDG) number 7: Will biofuels be reliable?" Renewable and Sustainable Energy Reviews **75**: 927 - 937.

Agusdinata, D. B. and D. DeLaurentis (2015). Multi-Actor Life-Cycle Assessment of Algal Biofuels for the U.S. Airline Industry. Algal Biorefineries: Volume 2: Products and Refinery Design. A. Prokop, R. K. Bajpai and M. E. Zappi. Cham, Springer International Publishing: 537-551.

Agusdinata, D. B., F. Zhao, K. Ileleji and D. Delaurentis (2011). "Life cycle assessment of potential biojet fuel production in the United States." Environmental Science and Technology **45**(21): 9133 - 9143.

Ahorsu, R., F. Medina and M. Constantí (2018). "Significance and challenges of biomass as a suitable feedstock for bioenergy and biochemical production: A review." Energies **11**(12): 1 - 19.

Ail, S. S. and S. Dasappa (2016). "Biomass to liquid transportation fuel via Fischer Tropsch synthesis – Technology review and current scenario." Renewable and Sustainable Energy Reviews **58**: 267 - 286.

Alalwan, H. A., A. H. Alminshid and H. A. S. Aljaafari (2019). "Promising evolution of biofuel generations. Subject review." Renewable Energy Focus **28**: 127 - 139.

Alexandratos, N. (1999). "World food and agriculture: Outlook for the medium and longer term." Proceedings of the National Academy of Sciences of the United States of America **96**(11): 5908 - 5914.

Alves, C. M., M. Valk, S. de Jong, A. Bonomi, L. A. M. van der Wielen and S. I. Mussatto (2017). "Techno-economic assessment of biorefinery technologies for aviation biofuels supply chains in Brazil." Biofuels, Bioproducts and Biorefining **11**(1): 67 - 91.

Ames, J. L. (2014). Microalgae-derived HEFA jet fuel : environmental and economic impacts of scaled/integrated growth facilities and global production potential Masters thesis, Massachusetts Institute of Technology.

Anderson, S., J. Cooper, N. Gudde and J. Howes (2012). "Aviation renewable fuels: technical status and challenges for commercialisation." The Aeronautical Journal (1968) **116**(1185): 1103 - 1122.

Anderson, W. F. (2016). Feedstock Readiness Level (FSRL) evaluation: Pennisetum purpureum (napier grass), Alcohol-to-Jet, Southeast, Sept. 2016. A. D. Commons.

Arabi, M., S. Yaghoubi and J. Tajik (2019). "A mathematical model for microalgae-based biobutanol supply chain network design under harvesting and drying uncertainties." Energy: 1004 - 1016.

Asadi, E., F. Habibi, S. Nickel and H. Sahebi (2018). "A bi-objective stochastic location-inventory-routing model for microalgae-based biofuel supply chain." Applied Energy **228**: 2235 - 2261.

ASTM. (2015). "Revised ASTM Standard Expands Limit on Biofuel Contamination in Jet Fuels." Retrieved 2019-04-11, from https://www.astm.org/cms/drupal-7.51/newsroom/revised-astm-standard-expands-limit-biofuel-contamination-jet-fuels.

ASTM (2019). ASTM D7566-19b, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. Pennsylvania, USA, American Society for Testing and Materials (ASTM).

ATAG (2012). A sustainable flightpath towards reducing emissions.

ATAG (2014). Aviation benefits beyond borders: Powering global economic growth, employment, trade links, tourism and support for sustainable development through air transport. Geneva, Switzerland**:** 1 - 68.

ATAG (2017). Beginner's Guide to Sustainable Aviation Fuel, Air Transport Action Group (ATAG)**:** 1 - 22.

ATAG. (2019). "Facts and Figures." Retrieved 2019-03-25, from https://www.atag.org/facts-figures.html

Atashbar, N. Z., N. Labadie and C. Prins (2016). "Modeling and optimization of biomass supply chains: A review and a critical look." IFAC-PapersOnLine **49**(12): 604 - 615.

Atashbar, N. Z., N. Labadie and C. Prins (2018). "Modelling and optimisation of biomass supply chains: a review." International Journal of Production Research **56**(10): 3482 - 3506.

AviationPros. (2015). "Gevo's Jet Fuel to be Used in First Ever Test Flight Flown on Fuel Derived from Wood Waste." Retrieved 2019-07-29, from https://www.aviationpros.com/contact-us.

Azwan, M. B., A. L. Norasikin, A. S. Rahim, K. Norman and J. Salmah (2016). "Analysis of energy utilisation in Malaysian oil palm mechanisation operation." Journal of Oil Palm Research **28**(4): 485 - 495.

Bailis, R. E. and J. E. Baka (2010). "Greenhouse Gas Emissions and Land Use Change from Jatropha Curcas-Based Jet Fuel in Brazil." Environmental Science & Technology **44**(22): 8684-8691.

Ball, J., J. Carle and A. Del Lungo (2005). "Contribution of poplars and willows to sustainable forestry and rural development." Unasylva **56**(221): 3 - 9.

Barbosa, F. C. (2017). "Biojet Fuel - A Tool for a Sustainable Aviation Industry - A Technical Assessment." **2017-November**(November): 1 - 16.

Bauen, A., J. Howes, L. Bertuccioli and C. Chudzia (2009). Review of the potential for biofuels in aviation. London, E4Tech**:** 1 - 117.

BBC. (2012). "Who, what, why: How can an airport run out of fuel?"   Retrieved 2019-03-29, from https://www.bbc.co.uk/news/magazine-18355592.

BBI International. (2018). "US DOE grants $10.6M to produce more biodiesel, biojet fuel."   Retrieved 2019-07-22, from http://www.biodieselmagazine.com/articles/2516287/us-doe-grants-10-6m-to-produce-more-biodiesel-biojet-fuel.

Behrendt, D., C. Schreiber, C. Pfaff, A. Müller, J. Grobbelaar and L. Nedbal (2018). Algae as a Potential Source of Biokerosene and Diesel – Opportunities and Challenges. Biokerosene: Status and Prospects. M. Kaltschmitt and U. Neuling. Berlin, Heidelberg, Springer Berlin Heidelberg**:** 303 - 324.

Boakye-Boaten, N. A., L. Kurkalova, S. Xiu and A. Shahbazi (2017). "Techno-economic analysis for the biochemical conversion of *Miscanthus* x *giganteus* into bioethanol." Biomass and Bioenergy **98**: 85 - 94.

Boichenko, S., V. Oksana and I. Anna (2013). "Overview of innovative technologies for aviation fuels production." Chemistry & Chemical Technology **7**(3).

Bosch, J., S. d. Jong, R. Hoefnagels and R. Slade (2017). Aviation biofuels: strategically important, technically achievable, tough to deliver. Grantham Institute Briefing paper, Imperial College London**:** 1 - 15.

Brooks, K. P., L. J. Snowden-Swan, S. B. Jones, M. G. Butcher, G.-S. J. Lee, D. M. Anderson, J. G. Frye, J. E. Holladay, J. Owen, L. Harmon, F. Burton, I. Palou-Rivera, J. Plaza, R. Handler and D. Shonnard (2016). Low-Carbon Aviation Fuel Through the Alcohol to Jet Pathway. Biofuels for Aviation. C. J. Chuck, Academic Press**:** 109 - 150.

Buchspies, B. and M. Kaltschmitt (2018). Sustainability Aspects of Biokerosene. Biokerosene: Status and Prospects. M. Kaltschmitt and U. Neuling. Berlin, Heidelberg, Springer Berlin Heidelberg**:** 325 - 373.

Budzianowski, W. M. and K. Postawa (2016). "Total Chain Integration of sustainable biorefinery systems." Applied Energy **184**: 1432 - 1446.

Bwapwa, J. K., A. Anandraj and C. Trois (2018). "Conceptual process design and -simulation of microalgae oil -conversion to aviation fuel." Biofuels, Bioprod. Bioref **12**: 935 - 948.

Caicedo, M., J. Barros and B. Ordás (2016). "Redefining agricultural residues as bioenergy feedstocks." Materials **9**(8): 1 - 22.

Callegari, A., S. Bolognesi, D. Cecconet and A. G. Capodaglio (2019). "Production technologies, current role, and future prospects of biofuels feedstocks: A state-of-the-art review." Critical Reviews in Environmental Science and Technology: 1 - 53.

Camesasca, L., M. B. Ramírez, M. Guigou, M. D. Ferrari and C. Lareo (2015). "Evaluation of dilute acid and alkaline pretreatments, enzymatic hydrolysis and fermentation of napiergrass for fuel ethanol production." Biomass and Bioenergy **74**: 193 - 201.

Campbell, M. (2018). Camelina – An Alternative Oil Crop. Biokerosene: Status and Prospects. M. Kaltschmitt and U. Neuling. Berlin, Heidelberg, Springer Berlin Heidelberg**:** 259 - 275.

Cantarella, H., A. M. Nassar, L. A. B. Cortez and R. Baldassin (2015). "Potential feedstock for renewable aviation fuel in Brazil." Environmental Development **15**: 52 - 63.

Capaz, R. S. and J. E. A. Seabra (2016). Life Cycle Assessment of Biojet Fuels. Biofuels for Aviation. C. J. Chuck, Academic Press**:** 279 - 294.

Cefic and ECTA (2011). Guidelines for Measuring and Managing CO2 Emission from Freight Transport Operations, The European Chemical Industry Council (Cefic) and European Communities Trade Mark Association (ECTA)**:** 1 - 18.

Chang, F.-C., L.-D. Lin, C.-H. Ko, H.-C. Hsieh, B.-Y. Yang, W.-H. Chen and W.-S. Hwang (2017). "Life cycle assessment of bioethanol production from three feedstocks and two fermentation waste reutilization schemes." Journal of Cleaner Production **143**: 973 - 979.

Chen, R. X. and W. C. Wang (2019). "The production of renewable aviation fuel from waste cooking oil. Part I: Bio-alkane conversion through hydro-processing of oil." Renewable Energy: 819 - 835.

Cheng, F. and C. E. Brewer (2017). "Producing jet fuel from biomass lignin: Potential pathways to alkyl-benzenes and cycloalkanes." Renewable and Sustainable Energy Reviews **72**: 673 - 722.

Cheng, J. J. and G. R. Timilsina (2011). "Status and barriers of advanced biofuel technologies: A review." Renewable Energy **36**(12): 3541 - 3549.

Chiaramonti, D. and L. A. Horta Nogueira (2017). Aviation biofuels: Processes, opportunities, constraints, and perspectives. Biofuels Production and Processing Technology, CRC Press**:** 295 - 318.

Chiaramonti, D., M. Prussi, M. Buffi, A. M. Rizzo and L. Pari (2017). "Review and experimental study on pyrolysis and hydrothermal liquefaction of microalgae for biofuel production." Applied Energy **185**: 963-972.

Choong, Y. Y., K. W. Chou and I. Norli (2018). "Strategies for improving biogas production of palm oil mill effluent (POME) anaerobic digestion: A critical review." Renewable and Sustainable Energy Reviews **82**: 2993 - 3006.

Conrad, S., C. Blajin, T. Schulzke and G. Deerberg (2019). "Comparison of fast pyrolysis bio-oils from straw and miscanthus." Environmental Progress and Sustainable Energy: 1 - 8.

Corporan, E., T. Edwards, L. Shafer, M. J. Dewitt, C. Klingshirn, S. Zabarnick, Z. West, R. Striebich, J. Graham and J. Klein (2011). "Chemical, thermal stability, seal swell, and emissions studies of alternative jet fuels." Energy and Fuels **25**(3): 955 - 966.

Correa, D. F., H. L. Beyer, J. E. Fargione, J. D. Hill, H. P. Possingham, S. R. Thomas-Hall and P. M. Schenk (2019). "Towards the implementation of sustainable biofuel production systems." Renewable and Sustainable Energy Reviews: 250 - 263.

Couto, N. D., V. B. Silva, E. Monteiro, A. Rouboa and P. Brito (2017). "An experimental and numerical study on the Miscanthus gasification by using a pilot scale gasifier." Renewable Energy **109**: 248 - 261.

Crawford, J. T., C. W. Shan, E. Budsberg, H. Morgan, R. Bura and R. Gustafson (2016). "Hydrocarbon bio-jet fuel from bioconversion of poplar biomass: Techno-economic assessment." Biotechnology for Biofuels **9**(1): 1 - 16.

Crown Oil UK. (2019). "HVO Biodiesel (Hydrotreated Vegetable Oil)."   Retrieved 2019-04-08, from https://www.crownoiluk.com/products/hvo-biodiesel/.

Curneen, S. and L. W. Gill (2016). "Willow-based evapotranspiration systems for on-site wastewater effluent in areas of low permeability subsoils." Ecological Engineering **92**: 199 - 209.

Dabe, S. J., P. J. Prasad, A. N. Vaidya and H. J. Purohit (2019). "Technological pathways for bioenergy generation from municipal solid waste: Renewable energy option." Environmental Progress and Sustainable Energy **38**(2): 654 - 671.

Darr, M. J. and A. Shah (2012). "Biomass storage: an update on industrial solutions for baled biomass feedstocks." Biofuels **3**(3): 321 - 332.

Davidson, C., E. Newes, A. Schwab and L. Vimmerstedt (2014). An Overview of Aviation Fuel Markets for Biofuels Stakeholders, National Renewable Energy Laboratory (NREL), U.S. Department of Energy**:** 1 - 44.

Daystar, J., R. Gonzalez, C. Reeb, R. Venditti, T. Treasure, R. Abt and S. Kelley (2014). "Economics, environmental impacts, and supply chain analysis of cellulosic biomass for biofuels in the southern us: Pine, eucalyptus, unmanaged hardwoods, forest residues, switchgrass, and sweet sorghum." BioResources **9**(1): 393 - 444.

de Castro, R. E. N., R. M. de Brito Alves and C. A. O. d. N. a. R. Giudici (2018). Assessment of Sugarcane-Based Ethanol Production. Fuel Ethanol Production from Sugarcane, IntechOpen**:** 1 - 21

De Corato, U., I. De Bari, E. Viola and M. Pugliese (2018). "Assessing the main opportunities of integrated biorefining from agro-bioenergy co/by-products and agroindustrial residues into high-value added products associated to some emerging markets: A review." Renewable and Sustainable Energy Reviews **88**: 326 - 346.

de Jong, S., K. Antonissen, R. Hoefnagels, L. Lonza, M. Wang, A. Faaij and M. Junginger (2017). "Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production." Biotechnology for Biofuels **10**(1): 1 - 18.

de Jong, S., R. Hoefnagels, A. Faaij, R. Slade, R. Mawhood and M. Junginger (2015). "The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-economic comparison." Biofuels, Bioproducts and Biorefining **9**(6): 778 - 800.

de Jong, S., R. Hoefnagels, J. van Stralen, M. Londo, R. Slade, A. Faaij and M. Junginger (2017). Renewable Jet Fuel in the European Union – Scenarios and Preconditions for Renewable Jet Fuel Deployment towards 2030., Utrecht University**:** 1 - 26.

de Jong, S., R. Hoefnagels, E. Wetterlund, K. Pettersson, A. Faaij and M. Junginger (2017). "Cost optimization of biofuel production – The impact of scale, integration, transport and supply chain configurations." Applied Energy **195**: 1055 - 1070.

Dincer, I. and C. Acar (2014). "Review and evaluation of hydrogen production methods for better sustainability." International Journal of Hydrogen Energy **40**(34): 11094 - 11111.

Dodd, T., M. Orlitzky and T. Nelson (2018). "What stalls a renewable energy industry? Industry outlook of the aviation biofuels industry in Australia, Germany, and the USA." Energy Policy **123**: 92 - 103.

Doliente, S. S. and S. Samsatli (2019). Multi-objective spatio-temporal optimisation for simultaneous planning, design and operation of sustainable and efficient value chains for rice crop. Computer Aided Chemical Engineering. A. A. Kiss, E. Zondervan, R. Lakerveld and L. Özkan, Elsevier. **46:** 1453 - 1458.

Domínguez-García, S., C. Gutiérrez-Antonio, J. A. De Lira-Flores, J. M. Ponce-Ortega and M. M. El-Halwagi (2017). "Strategic Planning for the Supply Chain of Aviation Biofuel with Consideration of Hydrogen Production." Industrial and Engineering Chemistry Research **56**(46): 13812 - 13830.

Dornack, C., A. Zentner and A. Zehm (2018). Waste as Resource. Biokerosene: Status and Prospects. M. Kaltschmitt and U. Neuling. Berlin, Heidelberg, Springer Berlin Heidelberg**:** 221 - 236.

Doshi, A., S. Pascoe, L. Coglan and T. J. Rainey (2016). "Economic and policy issues in the production of algae-based biofuels: A review." Renewable and Sustainable Energy Reviews **64**: 329 - 337.

Downie, A. and L. Van Zwieten (2013). Biochar: A Coproduct to Bioenergy from Slow-Pyrolysis Technology. Advanced Biofuels and Bioproducts. J. W. Lee. New York, NY, Springer New York**:** 97-117.

Dry, M. E. (2002). "The Fischer-Tropsch process: 1950-2000." Catalysis Today **71**(3-4): 227 - 241.

Dupuis, D. P., R. G. Grim, E. Nelson, E. C. D. Tan, D. A. Ruddy, S. Hernandez, T. Westover, J. E. Hensley and D. Carpenter (2019). "High-Octane Gasoline from Biomass: Experimental, Economic, and Environmental Assessment." Applied Energy: 25 - 33.

Dzięgielewski, W., B. Gawron, U. Kaźmierczak and A. Kulczycki (2014). "Butanol/Biobutanol as a Component of an Aviation and Diesel Fuel." Journal of KONES. Powertrain and Transport **21**(2): 69 - 75.

Egg, R. P., C. G. Coble, C. R. Engler and D. H. Lewis (1993). "Feedstock storage, handling and processing." Biomass and Bioenergy **5**(1): 71 - 94.

EIA. (2018). "Biofuels: Ethanol and Biodiesel *Explained*."   Retrieved 2019-04-10, from https://www.eia.gov/energyexplained/index.php?page=biofuel_home.

EIA, U. (2020). U.S. Gulf Coast Kerosene-Type Jet Fuel Spot Price FOB (Dollars per Gallon). U. S. E. I. A. U. EIA).

El Khatib, S. A., S. A. Hanafi, Y. Barakat and E. F. Al-Amrousi (2018). "Hydrotreating rice bran oil for biofuel production." Egyptian Journal of Petroleum **27**(4): 1325 - 1331.

Elgowainy, A., M. Han, J. Wang, N. Carter, R. Stratton, J. Hileman, A. Malwitz and S. Balasubramanian (2012). Life Cycle Analysis of Alternative Aviation Fuels in GREET. Massachusetts, Energy Systems Division, Argonne National Laboratory, U.S. Department of Energy**:** 1 - 62.

Elia, J. A., R. C. Baliban, C. A. Floudas, B. Gurau, M. B. Weingarten and S. D. Klotz (2013). "Hardwood Biomass to Gasoline, Diesel, and Jet Fuel: 2. Supply Chain Optimization Framework for a Network of Thermochemical Refineries." Energy & Fuels **27**(8): 4325 - 4352.

Eller, Z., Z. Varga and J. Hancsók (2016). "Advanced production process of jet fuel components from technical grade coconut oil with special hydrocracking." Fuel **182**: 713 - 720.

Elsoragaby, S., A. Yahya, M. R. Mahadi, N. M. Nawi and M. Mairghany (2019). "Energy utilization in major crop cultivation." Energy **173**: 1285-1303.

Emery, I., J. B. Dunn, J. Han and M. Wang (2015). "Biomass Storage Options Influence Net Energy and Emissions of Cellulosic Ethanol." Bioenergy Research **8**(2): 590 - 604.

Ernsting, A. (2017). HVO Aviation biofuels: How ICAO and industry plans for 'sustainable alternative aviation fuels' could lead to planes flying on palm oil, Biofuelwatch**:** 1 - 25.

Escobar, J. C., E. S. Lora, O. J. Venturini, E. E. Yáñez, E. F. Castillo and O. Almazan (2009). "Biofuels: Environment, technology and food security." Renewable and Sustainable Energy Reviews **13**(6-7): 1275 - 1287.

Eufrade Junior, H. J., R. X. D. Melo, M. M. P. Sartori, S. P. S. Guerra and A. W. Ballarin (2016). "Sustainable use of eucalypt biomass grown on short rotation coppice for bioenergy." Biomass and Bioenergy **90**: 15 - 21.

Fabio, E. S. and L. B. Smart (2018). "Effects of nitrogen fertilization in shrub willow short rotation coppice production – a quantitative review." GCB Bioenergy **10**(8): 548 - 564.

FAO (2017). Developing sustainable food value chains -- Guiding principles. Rome, Italy, Food and Agriculture Organization of the United Nations (FAO)**:** 1 - 75.

Fazio, S. and L. Barbanti (2014). "Energy and economic assessments of bio-energy systems based on annual and perennial crops for temperate and tropical areas." Renewable Energy **69**: 233 - 241.

Ferreira, V., L. Boyero, C. Calvo, F. Correa, R. Figueroa, J. F. Gonçalves, Jr., G. Goyenola, M. A. S. Graça, L. U. Hepp, S. Kariuki, A. López-Rodríguez, N. Mazzeo, C. M'Erimba, S. Monroy, A. Peil, J. Pozo, R. Rezende and F. Teixeira-de-Mello (2019). "A Global Assessment of the Effects of Eucalyptus Plantations on Stream Ecosystem Functioning." Ecosystems **22**(3): 629 - 642.

Fischer, M., T. Zenone, M. Trnka, M. Orság, L. Montagnani, E. J. Ward, A. M. Tripathi, P. Hlavinka, G. Seufert, Z. Žalud, J. S. King and R. Ceulemans (2018). "Water requirements of short rotation poplar coppice: Experimental and modelling analyses across Europe." Agricultural and Forest Meteorology **250 - 251**: 343 - 360.

Fleming, J. S., S. Habibi and H. L. MacLean (2006). "Investigating the sustainability of lignocellulose-derived fuels for light-duty vehicles." Transportation Research Part D: Transport and Environment **11**(2): 146 - 159.

Folkedahl, B. C., A. C. Snyder, J. R. Strege and S. J. Bjorgaard (2011). "Process development and demonstration of coal and biomass indirect liquefaction to synthetic iso-paraffinic kerosene." Fuel Processing Technology **92**(10): 1939 - 1945.

Fontoura, C. F., L. E. Brandão and L. L. Gomes (2015). "Elephant grass biorefineries: Towards a cleaner Brazilian energy matrix?" Journal of Cleaner Production **96**: 85- 93.

Frederix, M., F. Mingardon, M. Hu, N. Sun, T. Pray, S. Singh, B. A. Simmons, J. D. Keasling and A. Mukhopadhyay (2016). "Development of an: E. coli strain for one-pot biofuel production from ionic liquid pretreated cellulose and switchgrass." Green Chemistry **18**(15): 4189 - 4197.

Ganguly, I., F. Pierobon, T. C. Bowers, M. Huisenga, G. Johnston and I. L. Eastin (2018). "'Woods-to-Wake' Life Cycle Assessment of residual woody biomass based jet-fuel using mild bisulfite pretreatment." Biomass and Bioenergy **108**: 207 - 216.

Gegg, P., L. Budd and S. Ison (2014). "The market development of aviation biofuel: Drivers and constraints." Journal of Air Transport Management **39**: 34 - 40.

Geleynse, S., K. Brandt, M. Garcia-Perez, M. Wolcott and X. Zhang (2018). "The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation." ChemSusChem **11**(21): 3728 - 3741.

Giudicianni, P., S. Pindozzi, C. M. Grottola, F. Stanzione, S. Faugno, M. Fagnano, N. Fiorentino and R. Ragucci (2017). "Pyrolysis for exploitation of biomasses selected for soil phytoremediation: Characterization of gaseous and solid products." Waste Management **61**: 288 - 299.

Gold, S. and S. Seuring (2011). "Supply chain and logistics issues of bio-energy production." Journal of Cleaner Production **19**(1): 32 - 42.

Gonzales, D., E. M. Searcy and S. D. Ekşioğlu (2013). "Cost analysis for high-volume and long-haul transportation of densified biomass feedstock." Transportation Research Part A: Policy and Practice **49**: 48-61.

Gonzalez, R., R. Phillips, D. Saloni, H. Jameel, R. Abt, A. Pirraglia and J. Wright (2011). "Biomass to energy in the Southern United States: Supply chain and delivered cost." BioResources **6**(3): 2954 - 2976.

Gonzalez, R., T. Treasure, R. Phillips, H. Jameel, D. Saloni, R. Abt and J. Wright (2011). "Converting Eucalyptus biomass into ethanol: Financial and sensitivity analysis in a co-current dilute acid process. Part II." Biomass and Bioenergy **35**(2): 767 - 772.

Gonzalez, R., T. Treasure, J. Wright, D. Saloni, R. Phillips, R. Abt and H. Jameel (2011). "Exploring the potential of Eucalyptus for energy production in the Southern United States: Financial analysis of delivered biomass. Part I." Biomass and Bioenergy **35**(2): 755 - 766.

Gray, D., C. White and G. Tomlinson (2007). Increasing Security and Reducing Carbon Emissions of the US Transportation Sector: A Transformational Role for Coal with Biomass, National Energy Technology Laboratory, U.S. Department of Energy**:** 1 - 69.

Green Car Congress. (2016). "ASTM ballot greenlights approval of ATJ-SPK biojet from alcohol; Gevo 1st commercial test flight with Alaska Airlines." Retrieved 2019-07-20, from https://www.greencarcongress.com/2016/03/20160329-atjspk.html.

Güell, B. M., M. Bugge, R. S. Kempegowda, A. George and S. M. Paap (2012). Benchmark of conversion and production technologies for synthetic biofuels for aviation. Norway, SINTEF Energy Research.

Gutiérrez-Antonio, C., F. I. Gómez-Castro, J. A. de Lira-Flores and S. Hernández (2017). "A review on the production processes of renewable jet fuel." Renewable and Sustainable Energy Reviews **79**(January): 709 - 729.

Gutiérrez-Antonio, C., F. Israel Gómez-Castro, J. G. Segovia-Hernández and A. Briones-Ramírez (2013). Simulation and optimization of a biojet fuel production process. Computer Aided Chemical Engineering, Elsevier B.V. **32:** 13-18.

Han, S. H., D. H. Cho, Y. H. Kim and S. J. Shin (2013). "Biobutanol production from 2-year-old willow biomass by acid hydrolysis and acetone-butanol-ethanol fermentation." Energy **61**: 13 - 17.

Harahap, F., S. Leduc, S. Mesfun, D. Khatiwada, F. Kraxner and S. Silveira (2019). "Opportunities to Optimize the Palm Oil Supply Chain in Sumatra, Indonesia." Energies **12**(3): 1 - 24.

Harsono, S. S., P. Grundmann and S. Soebronto (2014). "Anaerobic treatment of palm oil mill effluents: Potential contribution to net energy yield and reduction of greenhouse gas emissions from biodiesel production." Journal of Cleaner Production **64**: 619 - 627.

He, C. R., Y. Y. Kuo and S. Y. Li (2017). "Lignocellulosic butanol production from Napier grass using semi-simultaneous saccharification fermentation." Bioresource Technology **231**: 101 - 108.

Heinrich, G. (2018). *Jatropha curcas* L. – An Alternative Oil Crop. Biokerosene: Status and Prospects. M. Kaltschmitt and U. Neuling. Berlin, Heidelberg, Springer Berlin Heidelberg**:** 237 - 257.

Hemighaus, G., T. Boval, J. Bacha, F. Barnes, M. Franklin, L. Gibbs, N. Hogue, J. Jones, D. Lesnini, J. Lind and J. Morris (2006). Aviation Fuels Technical Review**:** 1 - 89.

Hendricks, R. C., D. M. Bushnell and D. T. Shouse (2011). "Aviation fueling: A cleaner, greener approach." International Journal of Rotating Machinery **2011**: 1 - 13.

Herr, A., D. O'Connell, D. Farine, M. Dunlop, S. Crimp and M. Poole (2012). "Watching grass grow in Australia: Is there sufficient production potential for a biofuel industry?" Biofuels, Bioproducts and Biorefining **6**(3): 257-268.

Hickman, G. C., A. Vanloocke, F. G. Dohleman and C. J. Bernacchi (2010). "A comparison of canopy evapotranspiration for maize and two perennial grasses identified as potential bioenergy crops." GCB Bioenergy **2**(4): 157 - 168.

Howe, D., T. Westover, D. Carpenter, D. Santosa, R. Emerson, S. Deutch, A. Starace, I. Kutnyakov and C. Lukins (2015). "Field-to-fuel performance testing of lignocellulosic feedstocks: An integrated study of the fast pyrolysis-hydrotreating pathway." Energy and Fuels **29**(5): 3188 - 3197.

Huber, G. W., P. O'Connor and A. Corma (2007). "Processing biomass in conventional oil refineries: Production of high quality diesel by hydrotreating vegetable oils in heavy vacuum oil mixtures." Applied Catalysis A: General **329**: 120 - 129.

Huzir, N. M., M. M. A. Aziz, S. B. Ismail, B. Abdullah, N. A. N. Mahmood, N. A. Umor and S. A. F. Syed Muhammad (2018). "Agro-industrial waste to biobutanol production: Eco-friendly biofuels for next generation." Renewable and Sustainable Energy Reviews **94**: 476 - 485.

Iakovou, E., A. Karagiannidis, D. Vlachos, A. Toka and A. Malamakis (2010). "Waste biomass-to-energy supply chain management: A critical synthesis." Waste Management **30**(10): 1860 - 1870.

IATA. (2009). "World Business Summit on Climate Change, Copenhagen." Retrieved 2019-07-24, from https://www.iata.org/pressroom/speeches/Pages/2009-05-24-01.aspx.

ICAO (2009). U.S. fuel trends analysis and comparison to GIACC/4-IP/1. Group on International Aviation and Climate Change (GIACC Fourth Meeting. Montreal, International Civil Aviation Organization (ICAO)**:** 1 - 10.

Jacobson, M. (2013). "NEWBio Energy Crop Profile: Giant Miscanthus." Retrieved 2019-07-19, from https://extension.psu.edu/newbio-energy-crop-profile-giant-miscanthus.

Jacobson, M. (2013). "NEWBio Energy Crop Profile: Switchgrass." Retrieved 2019-07-19, from https://extension.psu.edu/newbio-energy-crop-profile-switchgrass.

Jacobson, R. A., R. F. Keefe, A. M. S. Smith, S. Metlen, D. A. Saul, S. M. Newman, T. J. Laninga and D. Inman (2016). "Multi-spatial analysis of forest residue utilization for bioenergy." Biofuels, Bioproducts and Biorefining **10**(5): 560 - 575.

Jayaraman, K. and I. Gökalp (2015). "Pyrolysis, combustion and gasification characteristics of miscanthus and sewage sludge." Energy Conversion and Management **89**: 83 - 91.

Jiang, W., M. G. Jacobson and M. H. Langholtz (2019). "A sustainability framework for assessing studies about marginal lands for planting perennial energy crops." Biofuels, Bioproducts and Biorefining **13**(1): 228 - 240.

Jiménez-Díaz, L., A. Caballero, N. Pérez-Hernández and A. Segura (2017). "Microbial alkane production for jet fuel industry: motivation, state of the art and perspectives." Microbial Biotechnology **10**(1): 103 - 124.

Kaewmai, R., A. H-Kittikun and C. Musikavong (2012). "Greenhouse gas emissions of palm oil mills in Thailand." International Journal of Greenhouse Gas Control **11**: 141 - 151.

Kainer, D. and C. Kulheim. (2016). "Renewable jet fuel could be growing on Australia's iconic gum trees." Retrieved 2019-07-23, from https://theconversation.com/renewable-jet-fuel-could-be-growing-on-australias-iconic-gum-trees-59377.

Kalnes, T., M. T., D. R. Shonnard and K. P. Koers (2011). Green diesel production by hydrorefining renewable feedstocks.

Kandaramath Hari, T., Z. Yaakob and N. N. Binitha (2015). "Aviation biofuel from renewable resources: Routes, opportunities and challenges." Renewable and Sustainable Energy Reviews **42**: 1234 - 1244.

Karlen, D. L., M. R. Schmer, S. Kaffka, D. E. Clay, M. Q. Wang, W. R. Horwath, A. Kendall, A. Keller, B. J. Pieper, S. Unnasch, T. Darlington, F. Vocasek and A. G. Chute (2019). "Unraveling crop residue harvest effects on soil organic carbon." Agronomy Journal **111**(1): 93 - 98.

Karmee, S. K. (2017). "Fuel not food—towards sustainable utilization of gutter oil." Biofuels **8**(3): 339 - 346.

Keefe, Z. (2013). "Industrial Hygiene - What is Soot and Why is it Dangerous?" Retrieved 2019-04-10, from http://blog.cashins.com/blog-0/bid/191511/Industrial-Hygiene-What-is-Soot-and-Why-is-it-Dangerous.

Keles, D., J. Choumert-Nkolo, P. Combes Motel and E. Nazindigouba Kéré (2018). "Does the expansion of biofuels encroach on the forest?" Journal of Forest Economics **33**: 75 - 82.

Khatun, R., M. I. H. Reza, M. Moniruzzaman and Z. Yaakob (2017). "Sustainable oil palm industry: The possibilities." Renewable and Sustainable Energy Reviews **76**: 608 - 619.

Khezri, R., W. A. A. K. Ghani, D. R. A. Biak, R. Yunus and K. Silas (2019). "Experimental evaluation of napier grass gasification in an autothermal bubbling fluidized bed reactor." Energies **12**(8): 1 - 18.

Klein, B. C., M. F. Chagas, T. L. Junqueira, M. C. A. F. Rezende, T. D. F. Cardoso, O. Cavalett and A. Bonomi (2018). "Techno-economic and environmental assessment of renewable jet fuel production in integrated Brazilian sugarcane biorefineries." Applied Energy **209**: 290 - 305.

Klinghoffer, N. (2013). Utilization of char from biomass gasification in catalytic applications PhD Dissertation, Columbia University.

Ko, S., P. Lautala and R. M. Handler (2018). "Securing the feedstock procurement for bioenergy products: a literature review on the biomass transportation and logistics." Journal of Cleaner Production **200**: 205-218.

Koh, L. P. and D. S. Wilcove (2008). "Is oil palm agriculture really destroying tropical biodiversity?" Conservation Letters **1**(2): 60 - 64.

Kolodziej, R. and J. Scheib (2012). Bio-isobutanol: The next-generation biofuel. Hydrocarbon Processing**:** 79 - 85.

KPMG International (2013). The agricultural and food value chain: Entering a new era of cooperation**:** 1 - 39.

Lamb, M. C., W. F. Anderson, T. C. Strickland, A. W. Coffin, R. B. Sorensen, J. E. Knoll and O. Pisani (2018). "Economic Competitiveness of Napier Grass in Irrigated and Non-irrigated Georgia Coastal Plain Cropping Systems." BioEnergy Research **11**(3): 574 - 582.

LanzaTech. (2018). "UK Government Grant to Develop World First Waste Carbon to Jet Fuel Project, LanzaTech." Retrieved 2019-04-06, from http://www.lanzatech.com/lanzatech-virgin-atlantic-secure-uk-government-grant-develop-world-first-waste-carbon-jet-fuel-project-uk/.

Lask, J., M. Wagner, L. M. Trindade and I. Lewandowski (2019). "Life cycle assessment of ethanol production from miscanthus: A comparison of production pathways at two European sites." GCB Bioenergy **11**(1): 269-288.

Lee, R. A. and J.-M. Lavoi (2013). "From first- to third-generation biofuels: Challenges of producing a commodity from a biomass of increasing complexity." Animal Frontiers **3**(2): 6 - 11.

Lee, W. C. and W. C. Kuan (2015). "Miscanthus as cellulosic biomass for bioethanol production." Biotechnology Journal **10**(6): 840-854.

Lemus, R. (2009). Hay Storage: Dry Matter Losses and Quality Changes, Mississippi State University.

Lewis, K. C., E. K. Newes, S. O. Peterson, M. N. Pearlson, E. A. Lawless, K. Brandt, D. Camenzind, M. P. Wolcott, B. C. English, G. S. Latta, A. Malwitz, J. I. Hileman, N. L. Brown and Z. Haq (2019). "US alternative jet fuel deployment scenario analyses identifying key drivers and geospatial patterns for the first billion gallons." Biofuels, Bioproducts and Biorefining **13**(3): 471 - 485.

Liati, A., D. Schreiber, P. A. Alpert, Y. Liao, B. T. Brem, P. Corral Arroyo, J. Hu, H. R. Jonsdottir, M. Ammann and P. Dimopoulos Eggenschwiler (2019). "Aircraft soot from conventional fuels and biofuels during ground idle and climb-out conditions: Electron microscopy and X-ray micro-spectroscopy." Environmental Pollution: 658-667.

Liu, G., B. Yan and G. Chen (2013). "Technical review on jet fuel production." Renewable and Sustainable Energy Reviews **25**: 59 - 70.

Liu, W., J. Wu, H. Fan, H. Duan, Q. Li, Y. Yuan and H. Zhang (2017). "Estimations of evapotranspiration in an age sequence of Eucalyptus plantations in subtropical China." PLOS ONE **12**(4): 1 - 15.

Liu, X., S. Zhang and J. Bae (2017). "The nexus of renewable energy-agriculture-environment in BRICS." Applied Energy **204**: 489 - 496.

Lobo, P., D. E. Hagen and P. D. Whitefield (2011). "Comparison of PM emissions from a commercial jet engine burning conventional, biomass, and fischer-tropsch fuels." Environmental Science and Technology **45**(24): 10744-10749.

Madaki, Y. S. and L. Seng (2013). "Palm oil mill effluent (POME) from Malaysia palm oil mills: Waste or resource." International Journal of Science, Environment and Technology **2**(6): 1138 - 1155.

Mandolesi de Araújo, C. D., C. C. de Andrade, E. de Souza e Silva and F. A. Dupas (2013). "Biodiesel production from used cooking oil: A review." Renewable and Sustainable Energy Reviews **27**: 445 - 452.

Martinkus, N., G. Latta, K. Brandt and M. Wolcott (2018). "A multi-criteria decision analysis approach to facility siting in a wood-based depot-and-biorefinery supply chain model." Frontiers in Energy Research **6**(NOV): 1 - 16.

Masimalai, S. and A. Subramaniyan (2017). "An experimental assessment on the influence of high octane fuels on biofuel based dual fuel engine performance, emission, and combustion." Thermal Science **21**: 523 - 534.

Mathioudakis, V., P. W. Gerbens-Leenes, T. H. Van der Meer and A. Y. Hoekstra (2017). "The water footprint of second-generation bioenergy: A comparison of biomass feedstocks and conversion techniques." Journal of Cleaner Production **148**: 571-582.

Mawhood, R., E. Gazis, S. de Jong, R. Hoefnagels and R. Slade (2016). "Production pathways for renewable jet fuel: a review of commercialization status and future prospects." Biofuels, Bioproducts and Biorefining **10**(4): 462 - 484.

McIsaac, G. F. (2014). "Biomass Production and Water: A Brief Review of Recent Research." Current Sustainable/Renewable Energy Reports **1**(4): 157-161.

Mesfun, S., D. L. Sanchez, S. Leduc, E. Wetterlund, J. Lundgren, M. Biberacher and F. Kraxner (2017). "Power-to-gas and power-to-liquid for managing renewable electricity intermittency in the Alpine Region." Renewable Energy **107**: 361 - 372.

Michailos, S. (2018). "Process design, economic evaluation and life cycle assessment of jet fuel production from sugar cane residue." Environmental Progress and Sustainable Energy **37**(3): 1227 - 1235.

Mielke, T. (2018). World Markets for Vegetable Oils and Animal Fats. Biokerosene: Status and Prospects. M. Kaltschmitt and U. Neuling. Berlin, Heidelberg, Springer Berlin Heidelberg**:** 147 - 188.

Miettinen, I., S. Kuittinen, V. Paasikallio, M. Mäkinen, A. Pappinen and J. Jänis (2017). "Characterization of fast pyrolysis oil from short-rotation willow by high-resolution Fourier transform ion cyclotron resonance mass spectrometry." Fuel **207**: 189-197.

Millinger, M., J. Ponitka, O. Arendt and D. Thrän (2017). "Competitiveness of advanced and conventional biofuels: Results from least-cost modelling of biofuel competition in Germany." Energy Policy **107**: 394 - 402.

Mohammed, I. Y., Y. A. Abakr and R. Mokaya (2019). "Integrated biomass thermochemical conversion for clean energy production: Process design and economic analysis." Journal of Environmental Chemical Engineering **7**(3): 1 - 15.

Mohseni, S. and M. S. Pishvaee (2016). "A robust programming approach towards design and optimization of microalgae-based biofuel supply chain." Computers and Industrial Engineering **100**: 58 - 71.

Moioli, E., F. Salvati, M. Chiesa, R. T. Siecha, F. Manenti, F. Laio and M. C. Rulli (2018). "Analysis of the current world biofuel production under a water–food–energy nexus perspective." Advances in Water Resources **121**: 22 - 31.

Molefe, M., D. Nkazi and H. E. Mukaya (2019). "Method Selection for Biojet and Biogasoline Fuel Production from Castor Oil: A Review." Energy and Fuels.

MPOB (2010). Recommended Practices for Storage and Transport of Edible Oils and Fats. Washington D.C., USA, Malaysian Palm Oil Board (MPOB)**:** 1 - 13.

Murdiyarso, D., K. Hergoualc'H and L. V. Verchot (2010). "Opportunities for reducing greenhouse gas emissions in tropical peatlands." Proceedings of the National Academy of Sciences of the United States of America **107**(46): 19655-19660.

Murphy, H. T., D. A. O'Connell, R. J. Raison, A. C. Warden, T. H. Booth, A. Herr, A. L. Braid, D. F. Crawford, J. A. Hayward, T. Jovanovic, J. G. McIvor, M. H. O'Connor, M. L. Poole, D. Prestwidge, N. Raisbeck-Brown and L. Rye (2015). "Biomass production for sustainable aviation fuels: A regional case study in Queensland." Renewable and Sustainable Energy Reviews **44**: 738-750.

Neslen, A. (2016). "BA blames UK government for scrapping of £340m green fuels project." Retrieved 2019-04-04, from https://www.theguardian.com/environment/2016/jan/06/ba-blames-uk-government-for-scrapping-of-340m-green-fuels-project.

Neuling, U. and M. Kaltschmitt (2018). Biokerosene from Vegetable Oils – Technologies and Processes. Biokerosene: Status and Prospects. M. Kaltschmitt and U. Neuling. Berlin, Heidelberg, Springer Berlin Heidelberg**:** 475 - 496.

Newes, E. K., B. W. Bush, C. T. Peck and S. O. Peterson (2015). "Potential leverage points for development of the cellulosic ethanol industry supply chain." Biofuels **6**(1-2): 21 - 29.

Nguyen, D. D., J. Dharmaraja, S. Shobana, A. Sundaram, S. W. Chang, G. Kumar, H. S. Shin, R. G. Saratale and G. D. Saratale (2019). "Transesterification and fuel characterization of rice bran oil: A biorefinery path." Fuel: 975 - 987.

Nicodème, T., T. Berchem, N. Jacquet and A. Richel (2018). "Thermochemical conversion of sugar industry by-products to biofuels." Renewable and Sustainable Energy Reviews **88**: 151 - 159.

O'Connell, A., M. Kousoulidou, L. Lonza and W. Weindorf (2019). "Considerations on GHG emissions and energy balances of promising aviation biofuel pathways." Renewable and Sustainable Energy Reviews: 504 - 515.

Oladosu, G. and S. Msangi (2013). "Biofuel-Food Market Interactions: A Review of Modeling Approaches and Findings." Agriculture **3**(1): 53 - 71.

Ondrey, G. (2012). "Chementator: Demo plant for high-yield biomass-to-gasoline process under construction." Chemical Engineering **119**(1): 9.

Page, S. E., R. Morrison, C. Malins, A. Hooijer, J. O. Rieley and J. Jauhiainen (2011). Review of Peat Surface GHG Emissions from oil palm plantations in Southeast Asia. International Council on Clean Transportation: Indirect Effects of Biofuel Production Series, International Council on Clean Transportation**:** 1 - 77.

Pandey, V. C., O. Bajpai and N. Singh (2016). "Energy crops in sustainable phytoremediation." Renewable and Sustainable Energy Reviews **54**: 58 - 73.

Pandiyan, K., A. Singh, S. Singh, A. K. Saxena and L. Nain (2019). "Technological interventions for utilization of crop residues and weedy biomass for second generation bio-ethanol production." Renewable Energy **132**: 723 - 741.

Pedroli, B., B. Elbersen, P. Frederiksen, U. Grandin, R. Heikkilä, P. H. Krogh, Z. Izakovičová, A. Johansen, L. Meiresonne and J. Spijker (2013). "Is energy cropping in Europe compatible with biodiversity? - Opportunities and threats to biodiversity from land-based production of biomass for bioenergy purposes." Biomass and Bioenergy **55**: 73 - 86.

Perkis, D. F. and W. E. Tyner (2018). "Developing a cellulosic aviation biofuel industry in Indiana: A market and logistics analysis." Energy **142**: 793-802.

Pham, V., M. Holtzapple and M. El-Halwagi (2010). "Techno-economic analysis of biomass to fuel conversion via the MixAlco process." Journal of Industrial Microbiology & Biotechnology **37**(11): 1157 - 1168.

Pimentel, D. (2009). "Energy Inputs in Food Crop Production in Developing and Developed Nations." Energies **2**: 1 - 24.

Pirker, J., A. Mosnier, F. Kraxner, P. Havlík and M. Obersteiner (2016). "What are the limits to oil palm expansion?" Global Environmental Change **40**: 73 - 81.

Popov, S. and S. Kumar (2013). "Renewable fuels via catalytic hydrodeoxygenation of lipid-based feedstocks." Biofuels **4**(2): 219 - 239.

Popov, S. and S. Kumar (2013). "Renewable Fuels via Catalytic Hydrodeoxygenation of Lipid-based Feedstocks." Biofuels **4**: 219-239.

Popp, J., Z. Lakner, M. Harangi-Rákos and M. Fári (2014). "The effect of bioenergy expansion: Food, energy, and environment." Renewable and Sustainable Energy Reviews **32**: 559-578.

Radich, T. (2015). The flight paths for biofuel. Working Paper Series. Washington D.C, U.S. Energy Information Administration**:** 1 - 17.

Raje, A. P. and B. H. Davis (1997). "Fischer-Tropsch synthesis over iron-based catalysts in a slurry reactor. Reaction rates, selectivities and implications for improving hydrocarbon productivity." Catalysis Today **36**(3): 335 - 345.

Rathmann, R., A. Szklo and R. Schaeffer (2010). "Land use competition for production of food and liquid biofuels: An analysis of the arguments in the current debate." Renewable Energy **35**(1): 14-22.

Ravi, V., A. H. Gao, N. B. Martinkus, M. P. Wolcott and B. K. Lamb (2018). "Air Quality and Health Impacts of an Aviation Biofuel Supply Chain Using Forest Residue in the Northwestern United States." Environmental Science and Technology **52**(7): 4154 - 4162.

Reimer, J. J. and X. Zheng (2017). "Economic analysis of an aviation bioenergy supply chain." Renewable and Sustainable Energy Reviews **77**: 945 - 954.

Rentizelas, A. A., A. J. Tolis and I. P. Tatsiopoulos (2009). "Logistics issues of biomass: The storage problem and the multi-biomass supply chain." Renewable and Sustainable Energy Reviews **13**(4): 887-894.

Richter, S., M. Braun-Unkhoff, C. Naumann and U. Riedel (2018). "Paths to alternative fuels for aviation." CEAS Aeronautical Journal **9**(3): 389 - 403.

Rocca, S., A. Agostini, J. Giuntoli and L. Marelli (2015). Biofuels from algae: technology options, energy balance and GHG emissions: Insights from a literature review, Publications Office of the European Union**:** 83.

Roda, J.-M., M. Goralski, A. Benoist, A. Baptiste, V. Boudjema, T. Galanos, M. Georget, J.-E. Hévin, S. Lavergne, F. Eychenne, K. E. Liew, C. Schwob, M. Djama and P. M. Tahir (2015). Sustainability of bio-jetfuel in Malaysia. Paris, France, Centre of International Cooperation in Agronomy Research for Development (CIRAD).

Rödl, A. (2018). Lignocellulosic Biomass. Biokerosene: Status and Prospects. M. Kaltschmitt and U. Neuling. Berlin, Heidelberg, Springer Berlin Heidelberg**:** 189 - 220.

Roth, A., F. Riegel and V. Batteiger (2018). Potentials of Biomass and Renewable Energy: The Question of Sustainable Availability. Biokerosene: Status and Prospects. M. Kaltschmitt and U. Neuling. Berlin, Heidelberg, Springer Berlin Heidelberg**:** 95 - 122.

Ruttens, A., J. Boulet, N. Weyens, K. Smeets, K. Adriaensen, E. Meers, S. van Slycken, F. Tack, L. Meiresonne, T. Thewys, N. Witters, R. Carleer, J. Dupae and J. Vangronsveld (2011). "Short rotation coppice culture of willows and poplars as energy crops on metal contaminated agricultural soils." International Journal of Phytoremediation **13**(SUPPL.1): 194 - 207.

Rye, L., S. Blakey and C. W. Wilson (2010). "Sustainability of supply or the planet: A review of potential drop-in alternative aviation fuels." Energy and Environmental Science **3**(1): 17 - 27.

Samsatli, S., N. J. Samsatli and N. Shah (2015). "BVCM: A comprehensive and flexible toolkit for whole system biomass value chain analysis and optimisation – Mathematical formulation." Applied Energy **147**: 131-160.

Sannan, S., K. Jordal, S. Roussanaly, C. Giraldi and A. Clapis (2017). Understanding the Cost of Retrofitting CO_2 Capture in an Integrated Oil Refinery, Reference Base Case Plants: Economic Evaluation. Norway**:** 1 - 16.

Sassner, P., M. Galbe and G. Zacchi (2006). "Bioethanol production based on simultaneous saccharification and fermentation of steam-pretreated Salix at high dry-matter content." Enzyme and Microbial Technology **39**(4): 756 - 762.

Scagline-Mellor, S., T. Griggs, J. Skousen, E. Wolfrum and I. Holásková (2018). "Switchgrass and Giant Miscanthus Biomass and Theoretical Ethanol Production from Reclaimed Mine Lands." Bioenergy Research **11**(3): 562 - 573.

Schmidt, P., V. Batteiger, A. Roth, W. Weindorf and T. Raksha (2018). "Power-to-Liquids as Renewable Fuel Option for Aviation: A Review." Chemie Ingenieur Technik **90**(1-2): 127 - 140.

Schmitt, N., A. Apfelbacher, N. Jäger, R. Daschner, F. Stenzel and A. Hornung (2019). "Thermo-chemical conversion of biomass and upgrading to biofuel: The Thermo-Catalytic Reforming process – A review." Biofuels, Bioproducts and Biorefining **13**(3): 822 - 837.

Schoneveld, G. C. (2010). Potential land use competition from first-generation biofuel expansion in developing countries. Bogor, Indonesia, Center for International Forestry Research (CIFOR)**:** 1 - 21.

Searle, S. Y. and C. J. Malins (2014). "Will energy crop yields meet expectations?" Biomass and Bioenergy **65**: 3 - 12.

Seber, G., R. Malina, M. N. Pearlson, H. Olcay, J. I. Hileman and S. R. H. Barrett (2014). "Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow." Biomass and Bioenergy **67**: 108 - 118.

Shah, Z., R. C. Veses, J. C. P. Vaghetti, V. D. A. Amorim and R. D. Silva (2019). "Preparation of jet engine range fuel from biomass pyrolysis oil through hydrogenation and its comparison with aviation kerosene." International Journal of Green Energy **16**(4): 350 - 360.

Shahare, V. V., B. Kumar and P. Singh (2017). Biofuels for sustainable development: A global perspective. Green Technologies and Environmental Sustainability, Springer International Publishing**:** 67-89.

Sharif, M. K., M. S. Butt, F. M. Anjum and S. H. Khan (2014). "Rice Bran: A Novel Functional Ingredient." Critical Reviews in Food Science and Nutrition **54**(6): 807 - 816.

Shastri, Y. and K. C. Ting (2014). Biomass Feedstock Production and Provision: Overview, Current Status, and Challenges. Engineering and Science of Biomass Feedstock Production and Provision. Y. Shastri, A. Hansen, L. Rodríguez and K. C. Ting. New York, NY, Springer New York**:** 1 - 15.

Silva Braz, D. and A. Pinto Mariano (2018). "Jet fuel production in eucalyptus pulp mills: Economics and carbon footprint of ethanol vs. butanol pathway." Bioresource Technology **268**: 9 - 19.

Sims, J. T. and R. O. Maguire (2005). MANURE MANAGEMENT. Encyclopedia of Soils in the Environment. D. Hillel. Oxford, Elsevier**:** 402 - 410.

Sims, R., A. Flammini, S. Puri and S. Bracco (2015). Opportunities for agri-food chains to become energy-smart, Food and Agriculture Organization & United States Agency for International Development.

Sinha, M., A. Sørensen, A. Ahamed and B. K. Ahring (2015). "Production of hydrocarbons by Aspergillus carbonarius ITEM 5010." Fungal Biology **119**(4): 274-282.

Staples, M. D., R. Malina, P. Suresh, J. I. Hileman and S. R. H. Barrett (2018). "Aviation CO2 emissions reductions from the use of alternative jet fuels." Energy Policy **114**: 342-354.

Stratton, R. W., H. M. Wong and J. I. Hileman (2010). Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels. Partnership for Air Transportation Noise and Emissions Reduction Project 28. Cambrige, Massachussets, USA, Massachusetts Institute of Technology.

Su, Y., K. Song, P. Zhang, Y. Su, J. Cheng and X. Chen (2017). "Progress of microalgae biofuel's commercialization." Renewable and Sustainable Energy Reviews **74**: 402 - 411.

Su, Y., P. Zhang and Y. Su (2015). "An overview of biofuels policies and industrialization in the major biofuel producing countries." Renewable and Sustainable Energy Reviews **50**: 991 - 1003.

Sun, A., R. Davis, M. Starbuck, A. Ben-Amotz, R. Pate and P. T. Pienkos (2011). "Comparative cost analysis of algal oil production for biofuels." Energy **36**(8): 5169 - 5179.

Suntivarakorn, R., W. Treedet, P. Singbua and N. Teeramaetawat (2018). "Fast pyrolysis from Napier grass for pyrolysis oil production by using circulating Fluidized Bed Reactor: Improvement of pyrolysis system and production cost." Energy Reports **4**: 565 - 575.

Suresh, P., R. Malina, M. D. Staples, S. Lizin, H. Olcay, D. Blazy, M. N. Pearlson and S. R. H. Barrett (2018). "Life Cycle Greenhouse Gas Emissions and Costs of Production of Diesel and Jet Fuel from Municipal Solid Waste." Environmental Science & Technology **52**(21): 12055 - 12065.

Surgenor, C. (2018). "ASTM approval of ethanol-based renewable jet fuels a green light for LanzaTech and Byogy."   Retrieved 2019-04-06, from https://www.greenaironline.com/news.php?viewStory=2469.

Surian Ganba, O., K. C. Tonello, H. García-Leite, M. Burguet, E. V. Taguas and H. C. Teixeira-Dias (2016). "Hydrological Balance in a Eucalyptus Plantation Watershed in Minas Gerais (Brazil)." Soil Science **181**(7): 347-357.

Susila, W. R. (2004). "Contribution of oil palm industry to economic growth and poverty alleviation in Indonesia." Jurnal Penelitian dan Pengembangan Pertanian **23**(3): 107 - 113

Tao, L., A. Milbrandt, Y. Zhang and W. C. Wang (2017). "Techno-economic and resource analysis of hydroprocessed renewable jet fuel." Biotechnology for Biofuels **10**(1): 1 - 16.

Tao, L., E. C. D. Tan, R. McCormick, M. Zhang, A. Aden, X. He and B. T. Zigler (2014). "Techno-economic analysis and life-cycle assessment of cellulosic isobutanol and comparison with cellulosic ethanol and n-butanol." Biofuels, Bioproducts and Biorefining **8**(1): 30 - 48.

Tapia, J. F. D., S. Samsatli, S. S. Doliente, E. Martinez-Hernandez, W. A. B. W. A. K. Ghani, K. L. Lim, H. Z. M. Shafri and N. S. N. B. Shaharum (2019). "Design of biomass value chains that are synergistic with the food–energy–water nexus: Strategies and opportunities." Food and Bioproducts Processing **116**: 170 - 185.

Taylor, J. D., M. M. Jenni and M. W. Peters (2010). "Dehydration of fermented isobutanol for the production of renewable chemicals and fuels." Topics in Catalysis **53**(15 - 18): 1224 - 1230.

The Engineering ToolBox. (2003). "U.S. Standard Atmosphere."   Retrieved 2019-03-31, from https://www.engineeringtoolbox.com/standard-atmosphere-d_604.html.

Trivedi, P., R. Malina and S. R. H. Barrett (2015). "Environmental and economic tradeoffs of using corn stover for liquid fuels and power production." Energy and Environmental Science **8**(5): 1428 - 1437.

Ubando, A. T., J. L. Cuello, M. M. El-Halwagi, A. B. Culaba and R. R. Tan (2014). Multi-Regional Multi-Objective Optimization of an Algal Biofuel Polygeneration Supply Chain With Fuzzy Mathematical Programming. ASME 2014 8th International Conference on Energy Sustainability, Boston, Massachusetts, USA, The American Society of Mechanical Engineers (ASME).

USDA. (2012). "Napiergrass: A potential biofuel crop for the sunny Southeast." Retrieved 2019-07-23, from https://www.sciencedaily.com/releases/2012/09/120927142524.htm.

Vásquez, M. C., E. E. Silva and E. F. Castillo (2017). "Hydrotreatment of vegetable oils: A review of the technologies and its developments for jet biofuel production." Biomass and Bioenergy **105**: 197 - 206.

Velazquez Abad, A., T. Cherrett and P. Holdsworth (2015). "Waste-to-fuel opportunities for British quick service restaurants: A case study." Resources, Conservation and Recycling **104**: 239 - 253.

Vijay, V., S. L. Pimm, C. N. Jenkins and S. J. Smith (2016). "The Impacts of Oil Palm on Recent Deforestation and Biodiversity Loss." PloS one **11**(7): 1 - 19.

von Maltitz, G., A. Gasparatos and C. Fabricius (2014). "The rise, fall and potential resilience benefits of Jatropha in Southern Africa." Sustainability (Switzerland) **6**(6): 3615 - 3643.

Wang, M., J. Han, J. B. Dunn, H. Cai and A. Elgowainy (2012). "Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use." Environmental Research Letters **7**(4): 1 - 13.

Wang, W.-C. and L. Tao (2016). "Bio-jet fuel conversion technologies." Renewable and Sustainable Energy Reviews **53**: 801 - 822.

Wang, W. C. and A. C. Lee (2019). "The study of producing “drop-in” fuels from agricultural waste through fast pyrolysis and catalytic hydro-processing." Renewable Energy: 1 - 10.

Wani, S. P., K. K. Garg and G. Chander (2016). "Water needs and productivity of Jatropha curcas in India: Myths and facts." Biofuels, Bioproducts and Biorefining **10**(3): 240 - 254.

Warshay, B., J. Pan and S. Sgouridis (2011). "Aviation industry's quest for a sustainable fuel: Considerations of scale and modal opportunity carbon benefit." Biofuels **2**(1): 33 - 58.

Wei, H., W. Liu, X. Chen, Q. Yang, J. Li and H. Chen (2019). "Renewable bio-jet fuel production for aviation: A review." Fuel **254**: 1 - 16.

Weissermel, K. and H.-J. Arpe (2008). Industrial Organic Chemistry. New York, John Wiley & Sons.

Wenger, J. and T. Stern (2019). "Reflection on the research on and implementation of biorefinery systems – a systematic literature review with a focus on feedstock." Biofuels, Bioproducts and Biorefining: 1 - 18.

Wilbrand, K. (2018). Potential of Fossil Kerosene. Biokerosene: Status and Prospects. M. Kaltschmitt and U. Neuling. Berlin, Heidelberg, Springer Berlin Heidelberg**:** 43 - 57.

Wong, H. M. (2008). Life-cycle Assessment of Greenhouse Gas Emissions from Alternative Jet Fuels. Master of Science in Technology and Policy Massachusetts Institute of Technology.

Woytiuk, K., W. Campbell, R. Gerspacher, R. W. Evitts and A. Phoenix (2017). "The effect of torrefaction on syngas quality metrics from fluidized bed gasification of SRC willow." Renewable Energy **101**: 409 - 416.

Wright, M. E., B. G. Harvey and R. L. Quintana (2008). "Highly efficient zirconium-catalyzed batch conversion on 1-butene: A new route to jet fuels." Energy and Fuels **22**(5): 3299-3302.

Wu, T. Y., A. W. Mohammad, J. M. Jahim and N. Anuar (2009). "A holistic approach to managing palm oil mill effluent (POME): Biotechnological advances in the sustainable reuse of POME." Biotechnology Advances **27**(1): 40 - 52.

Xue, C., M. Liu, X. Guo, E. P. Hudson, L. Chen, F. Bai, F. Liu and S. T. Yang (2017). "Bridging chemical- and bio-catalysis: High-value liquid transportation fuel production from renewable agricultural residues." Green Chemistry **19**(3): 660 - 669.

Yan, X., D. Jiang, J. Fu and M. Hao (2018). "Assessment of sweet sorghum-based ethanol potential in China within the Water-Energy-Food nexus framework." Sustainability (Switzerland) **10**(4): 1 - 17.

Yang, J., Z. Xin, Q. S. He, K. Corscadden and H. Niu (2019). "An overview on performance characteristics of bio-jet fuels." Fuel **237**: 916 - 936.

Yao, G., M. D. Staples, R. Malina and W. E. Tyner (2017). "Stochastic techno-economic analysis of alcohol-to-jet fuel production." Biotechnology for Biofuels **10**(1).

Zafar, S. (2018). "How is Biomass Transported?" Retrieved 2019-04-06, from https://www.bioenergyconsult.com/biomass-transportation/.

Zaher, F. A., A. E. S. Hussein, B. H. Hassan and S. F. Hamed (2015). "Potential of Castor Oil as a Feedstock for the Production of Bio-fuel via Catalytic Hydro- Cracking." Current Science International **4**(3): 443 - 449.

Zalesny, R. S., Jr., G. Berndes, I. Dimitriou, U. Fritsche, C. Miller, M. Eisenbies, S. Ghezehei, D. Hazel, W. L. Headlee, B. Mola-Yudego, M. C. Negri, E. G. Nichols, J. Quinn, S. D. Shifflett, O. Therasme, T. A. Volk and C. R. Zumpf (2019). "Positive water linkages of producing short rotation poplars and willows for bioenergy and phytotechnologies." Wiley Interdisciplinary Reviews: Energy and Environment: 1- 20.

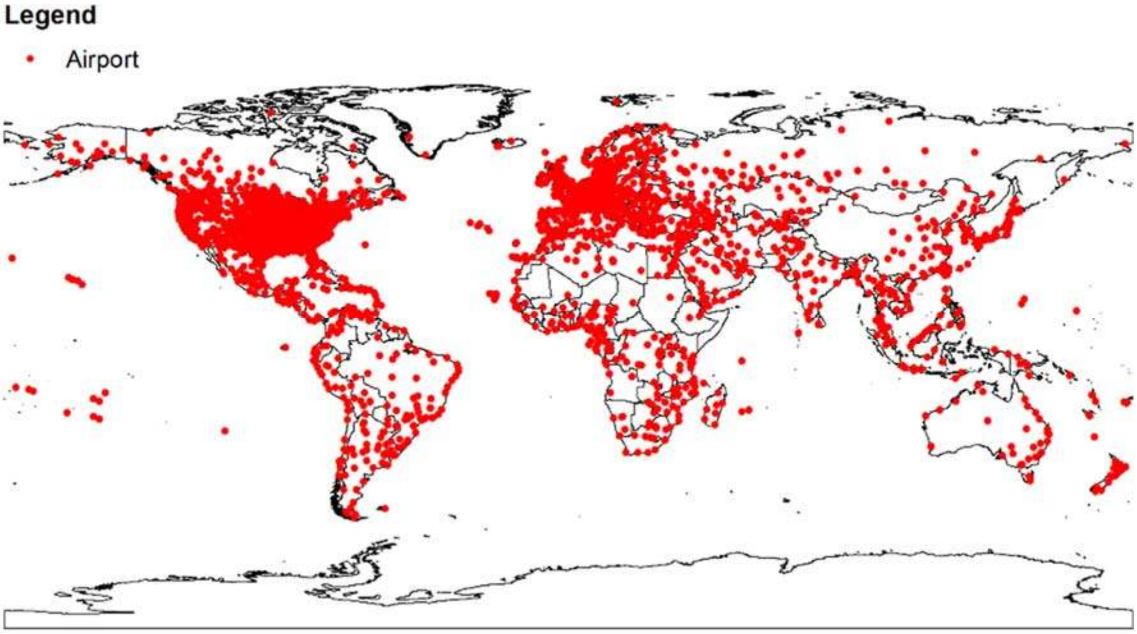
Zhang, B., J. Wu, C. Yang, Q. Qiu, Q. Yan, R. Li, B. Wang, J. Wu and Y. Ding (2018). "Recent Developments in Commercial Processes for Refining Bio-Feedstocks to Renewable Diesel." Bioenergy Research **11**(3): 689 - 702.

Zhang, X., H. Lei, L. Zhu, M. Qian, J. C. Chan, X. Zhu, Y. Liu, G. Yadavalli, D. Yan, L. Wang, Q. Bu, Y. Wei, J. Wu and S. Chen (2016). "Development of a catalytically green route from diverse lignocellulosic biomasses to high-density cycloalkanes for jet fuels." Catalysis Science and Technology **6**(12): 4210 - 4220.

Zhang, Z., Q. Wang, H. Chen and X. Zhang (2018). "Hydroconversion of Waste Cooking Oil into Bio-Jet Fuel over a Hierarchical NiMo/USY@Al-SBA-15 Zeolite." Chemical Engineering and Technology **41**(3): 590 - 597.

Zhu, Z., F. Chu, A. Dolgui, C. Chu, W. Zhou and S. Piramuthu (2018). "Recent advances and opportunities in sustainable food supply chain: a model-oriented review." International Journal of Production Research **56**(17): 5700 - 5722.

14 Figures



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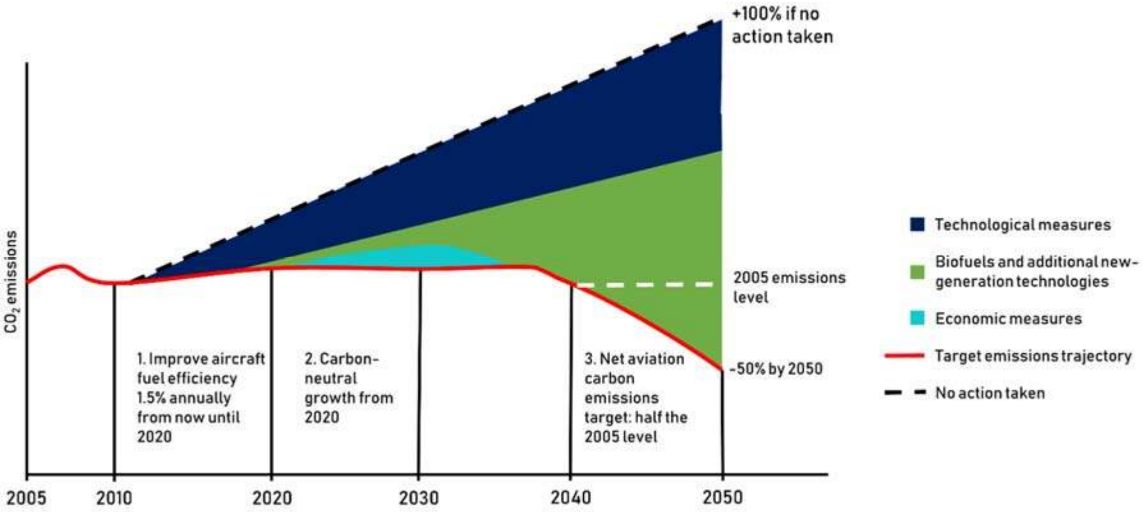

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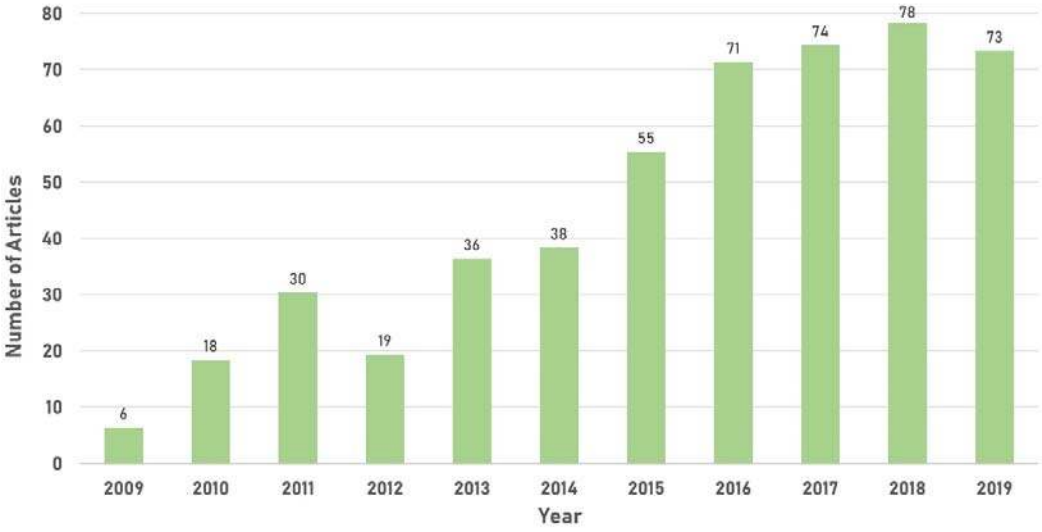

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Figure 1: Recent trends for the the aviation industry: (a) Global Airport Distribution (Plotted using data from www.arcgis.com, 2019); (b) Potential global atmospheric CO_2 emissions released by the aviation sector under various development conditions (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).

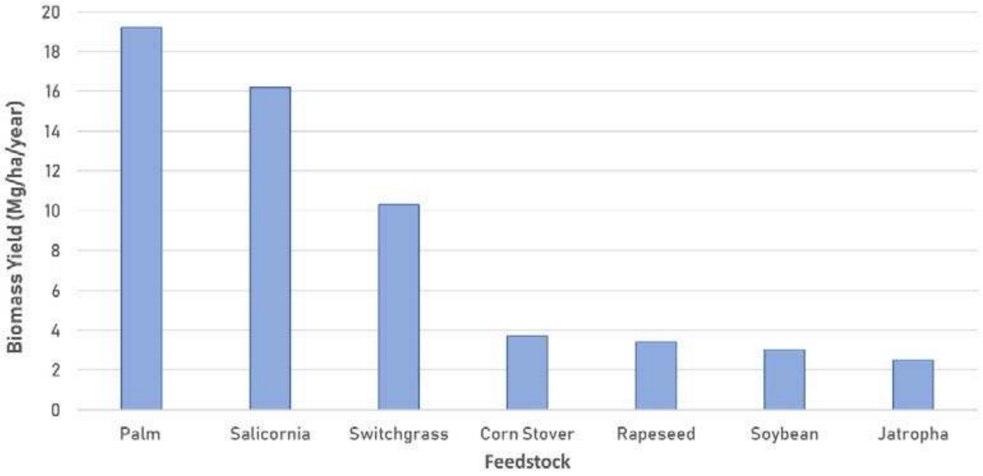

Figure 2: Typical potential yields of some 1-G and 2-G feedstocks for BAF production (Plotted using data from Stratton et al. (2010)).

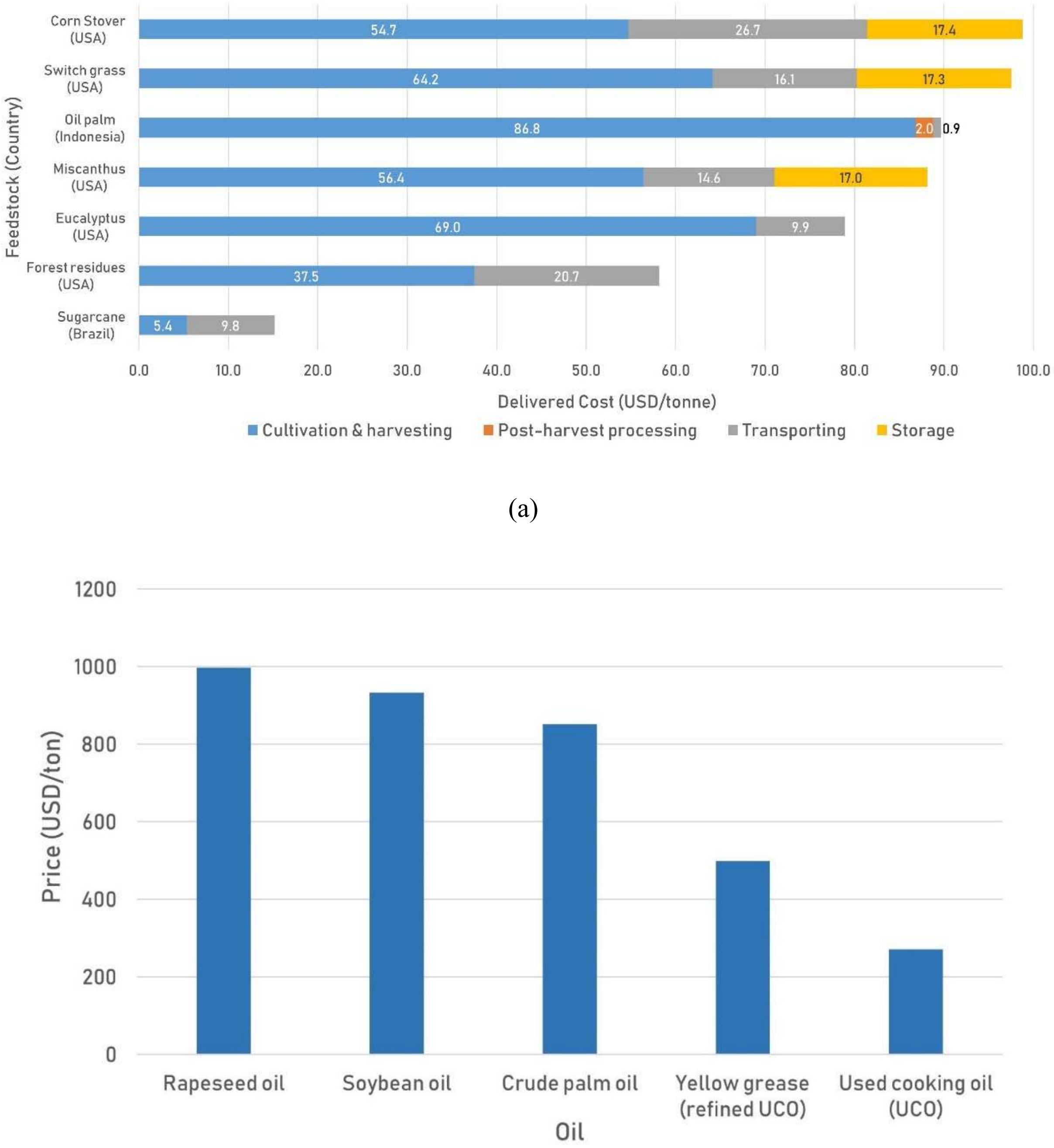

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Figure 3: Typical economic impacts (adjusted to 2019 levels) of some 1-G and 2-G feedstocks for BAF production: a) Delivered (farm-to-gate) cost (Plotted using data from Gonzalez et al. (2011), Gonzales et al. (2013), Harahap et al. (2019) and de Castro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

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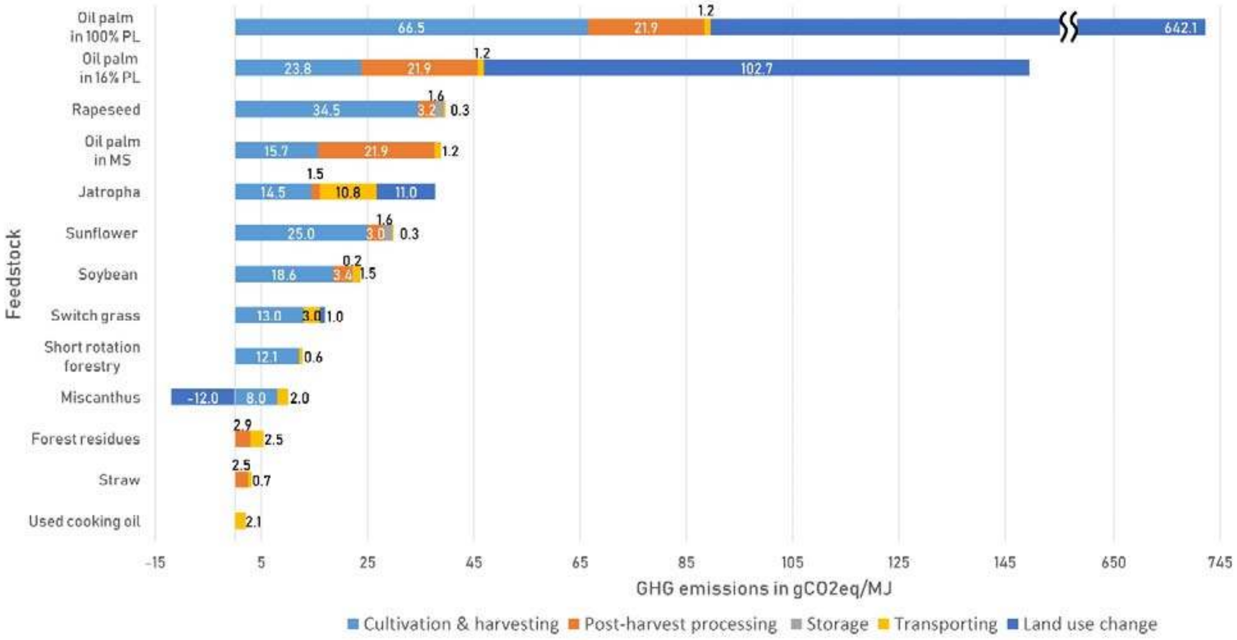

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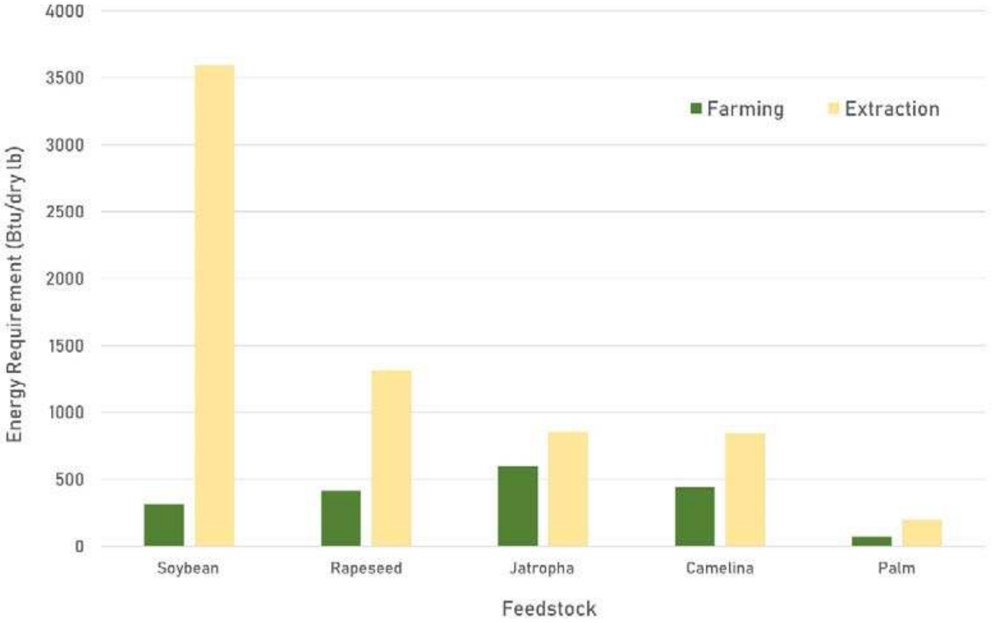

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Figure 4: Typical environmental impacts of some 1-G and 2-G feedstocks for BAF production: a) Farm-to-gate GHG emissions (Plotted using data from Bailis and Baka (2010), O'Connell et al. (2019), Velazquez Abad et al. (2015) and Wang et al. (2012));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

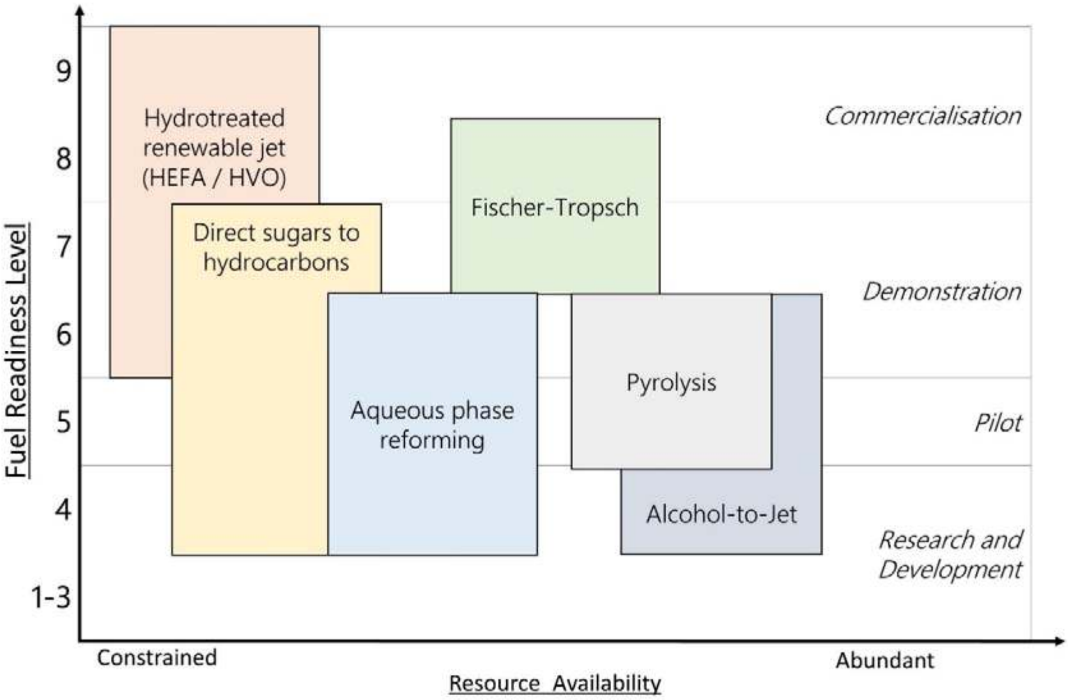

Figure 5: Future scope for adapting processes to a commercial level based on resource availability and technology maturity (Drawn using data from Bosch et al. (2017) and Mawhood et al. (2016)).

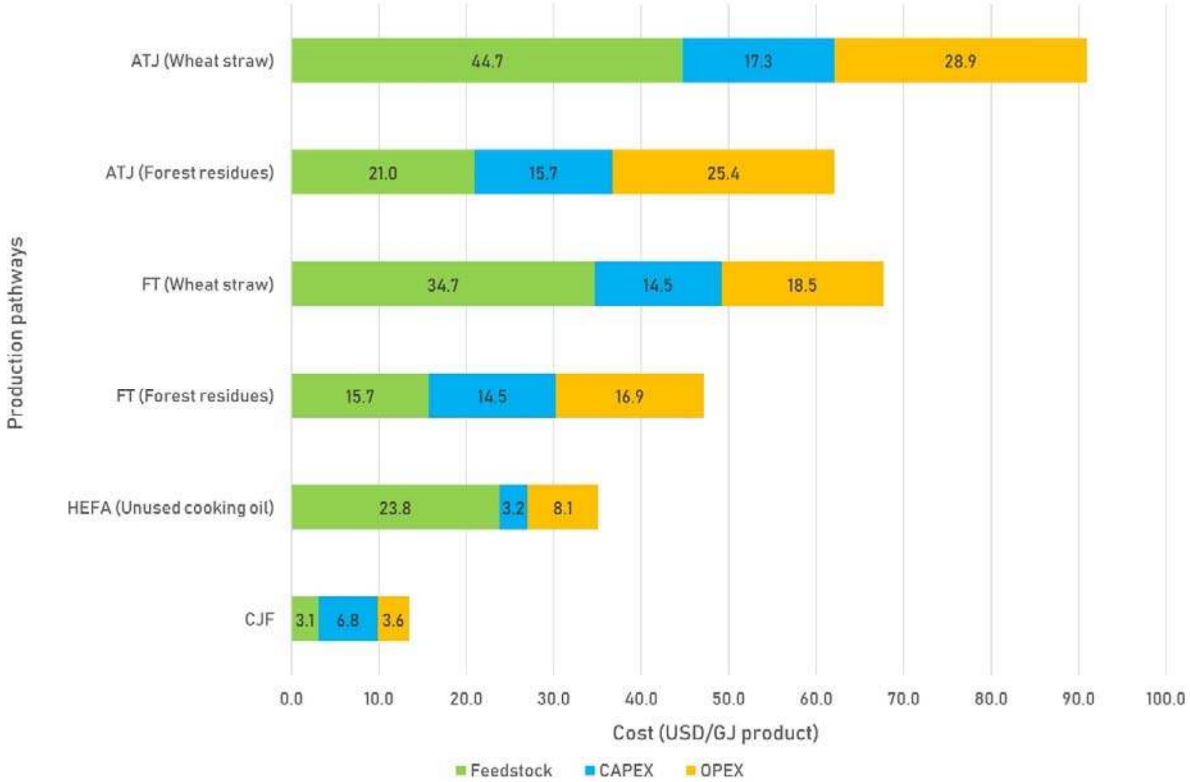

Figure 6: Breakdown of cost (adjusted to 2019 levels) producing bio-aviation fuel by HEFA, FT and ATJ (Plotted using production cost of the production pathways from de Jong et al. (2015). Production cost of conventional fuel by crude oil refinery (CJF), which was calculated and adjusted to 2019 levels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

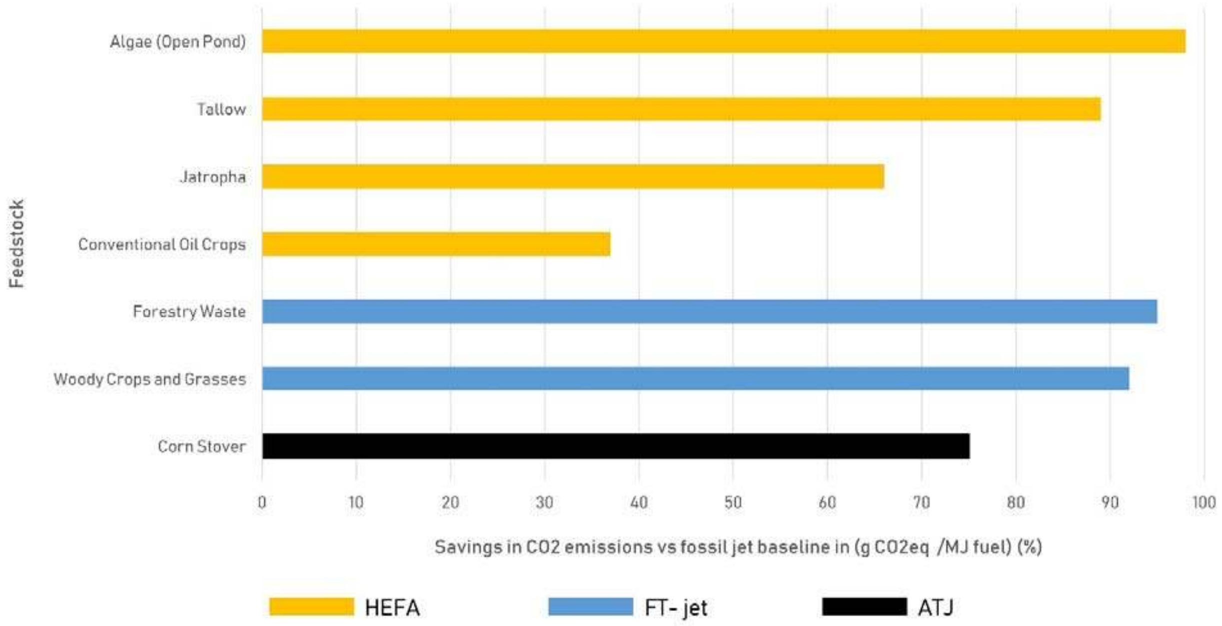

Figure 7: Potential well-to-wake GHG emissions savings from using different BAF feedstocks and production pathways (Plotted using data from Bauen et al. (2009) and de Jong et al. (2017)).

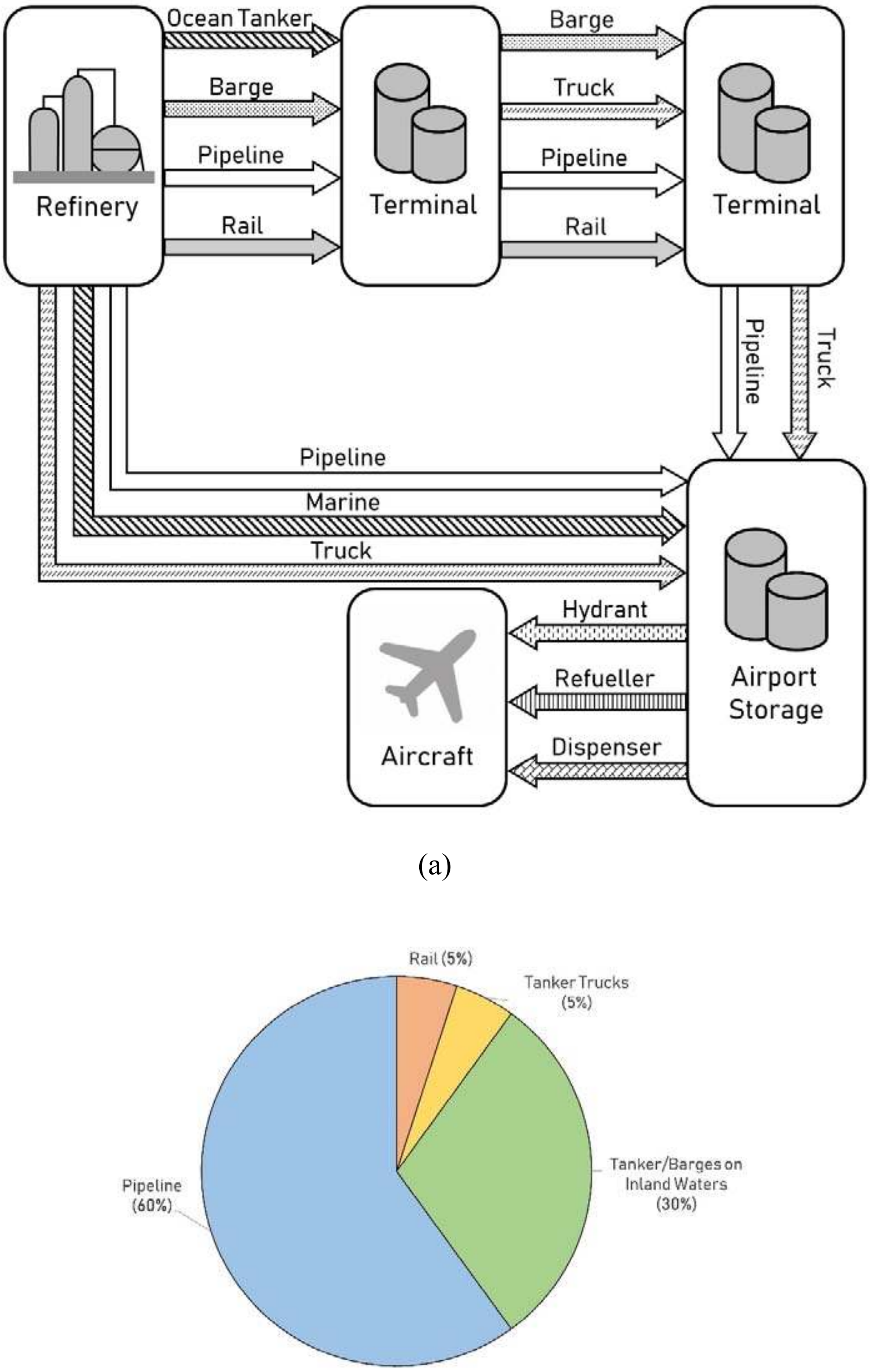

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Figure 8: Storage and transport of jet fuel: a) Typical jet fuel distribution chains (Drawn using data from Hemighaus et al. (2006)); and b) Breakdown of major transport mechanisms for all refined fuel products in the U.S. (Plotted using data from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

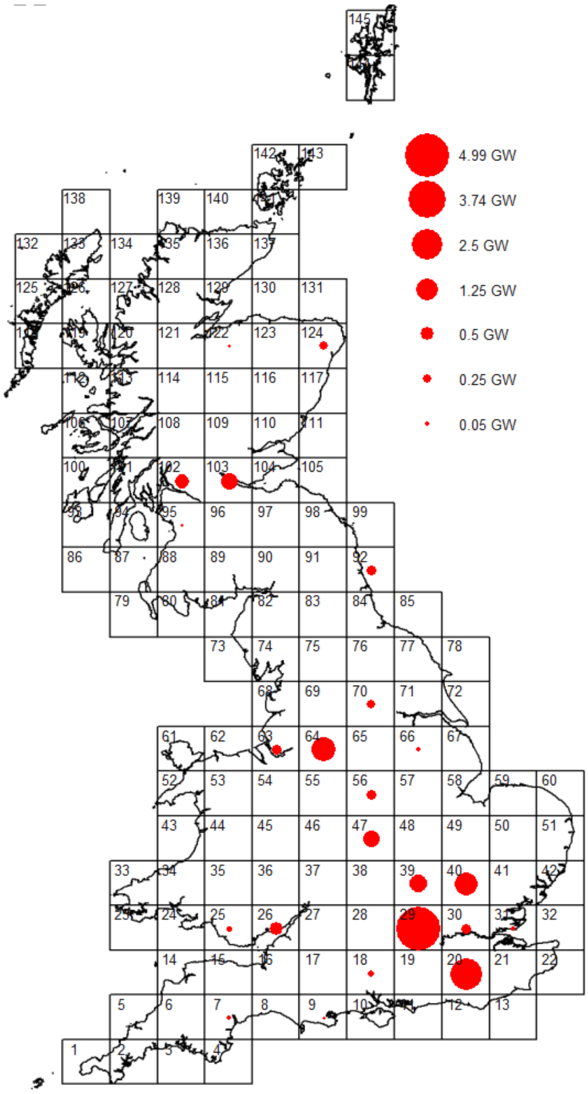
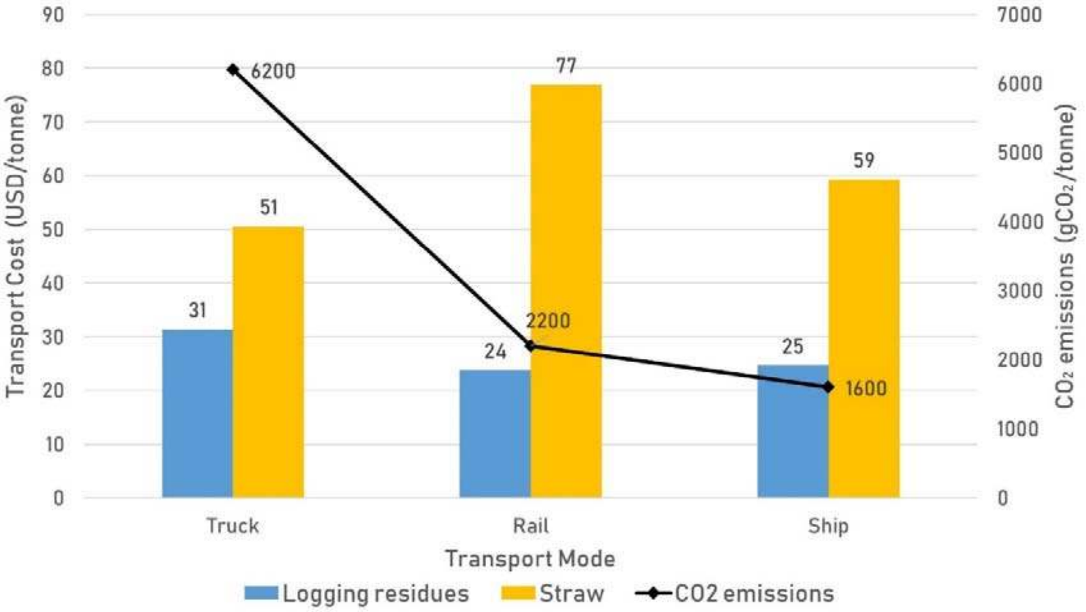


Figure 9: Jet fuel demands for Great Britain at 50 km resolution.



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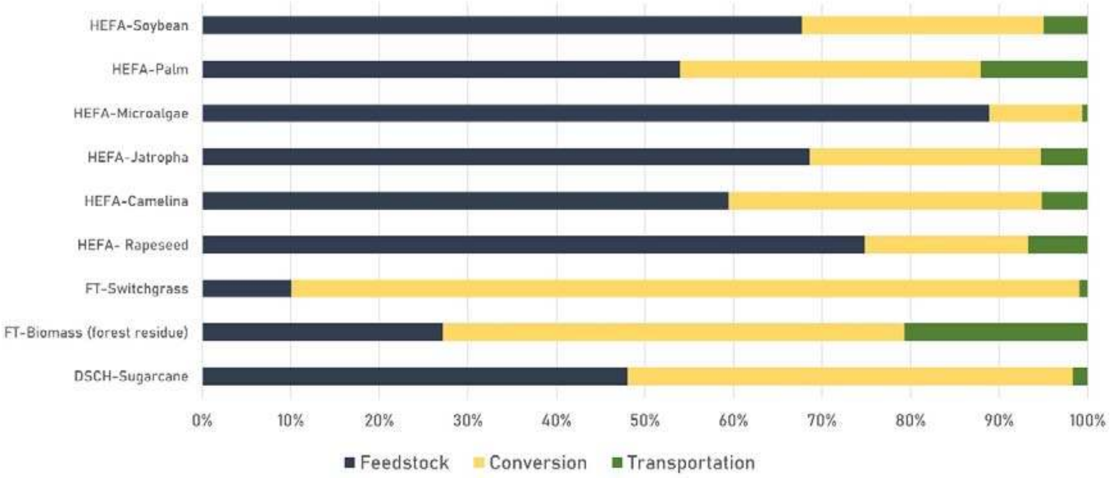

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Figure 10: Economic and environmental impacts of transporting BAF feedstocks: a) Average cost and GHG emissions of transport modes used in delivering feedstocks from farm to processing facilities (Plotted using cost data from Ko et al. (2018) and GHG 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)).

15 Tables

Table 1. Five types of synthetic paraffinic kerosene based on the production platform (Data from 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

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

Advantages	Disadvantages
Theoretically unlimited feedstock supply	Problems associated with monocultures, e.g. lack of biodiversity and susceptibility to pests.
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.
Capable of reduced net CO_2 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.
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
Generally lower in contaminants, e.g. sulphur	-

Table 3: Feedstocks for bio-aviation fuel production (Data from Rye et al. 2010, Warshay et al. 2011, Kandaramath Hari et al. 2015, ATAG 2017, Chiaramonti and Horta Nogueira 2017, Rödl 2018, Roth 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)
• Oil-seed crops: camelina, oil palm, rapeseed, soybeans, sunflower, salicornia • Sugar and starchy crops: corn, wheat, sugarcane sugar beets	• Oil-seed energy crops: jatropha, castor bean • Grass energy crops: switch grass, miscanthus, Napier grass • Wood energy crops: poplar, eucalyptus • Agricultural and forestry residues: corn stover, sugarcane bagasse, wood harvesting/processing residues • Food and municipal waste: used cooking oil, animal fats, biogenic fraction of municipal solid waste (MSW)	• Algae: microalgae	• Genetically modified organisms • Non-biological feedstocks: CO_2, renewable electricity, water

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

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
	Wheat	Moderate climates (Subtropical with rainy winters to mountainous tropical regions)	High demand	High water demand
2-G	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_N/ha)	Moderate demand (800 mm/year)
Miscanthus	Tropical to temperate; cold resistant	Moderate demand (50–75 kg_N/ha)	Moderate to high demand (1000 mm/year)
Napier grass	Tropical	High demand (150–300 kg_N/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_N/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)

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

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