Aviation biofuel from renewable resources: Routes, opportunities and challenges

Thushara Kandaramath Hari a, Zahira Yaakob a,∗, Narayanan N. Binitha b

a Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi 43600, Malaysia
b Department of Chemistry, Sree Neelakanta Govt. Sanskrit College Pattambi, Kerala, India

ARTICLE INFO

Article history:
Received 16 October 2013
Received in revised form 31 July 2014
Accepted 28 October 2014
Available online 18 November 2014

Keywords:
Bio jet fuel
Aviation
Feedstock
Production route
Challenge

ABSTRACT

Air transport describes an inevitable part in the day to day life of the modern world. It is highly responsible for the worldwide social contacts and business developments. The use of petroleum fuels as energy source for air transport is not sustainable. Aviation is one of the leading contributors to the total greenhouse gas emissions. Also, the fossil fuel prices are becoming more volatile day by day. So it is very essential to introduce and industrialize alternative aviation fuels generated from renewable resources, especially biomass. A number of industrial commitments and collaborations have emerged to find alternative ways to reach bio aviation fuels. Research on the conversion of biomass based sources to bio jet fuels is of current interest. The main concern is the production of biojet fuel, from renewable resources, with relatively low greenhouse gas life cycle and sustainability with affordable price. The present paper overviews the opportunities and challenges in the development of alternative fuels for aviation. The production process, feedstock used and the most promising global projects are also reviewed.

© 2014 Elsevier Ltd. All rights reserved.

Contents

1. Introduction .................................................................................................................. 1235
2. Renewable resources .................................................................................................. 1236
   2.1. Camelina ................................................................................................................... 1236
   2.2. Jatropha .................................................................................................................... 1236
   2.3. Algae ....................................................................................................................... 1236
   2.4. Wastes ...................................................................................................................... 1236
   2.5. Halophytes ............................................................................................................. 1236
3. Alternative fuels for air transport .................................................................................. 1237
   3.1. Hydroprocessed renewable jet fuels ......................................................................... 1237
   3.2. Fischer Tropsch fuels .............................................................................................. 1237
   3.3. Biodiesel ................................................................................................................ 1237
   3.4. Liquid biohydrogen and biomethane ....................................................................... 1237
   3.5. Bio alcohols ........................................................................................................... 1237
4. Production routes ......................................................................................................... 1238
   4.1. Thermochemical process ......................................................................................... 1238
   4.1.1. Biomass to liquid process (BTL process) .............................................................. 1238
   4.1.2. Fischer Tropsch process (FT process) ................................................................. 1238
   4.2. Hydroprocessing ..................................................................................................... 1238
   4.3. Biochemical process ............................................................................................... 1238
   4.3.1. Direct sugar to hydrocarbon process (DHSC) and alcohol to jet process (ATJ) ...... 1238
   4.3.2. Bio alcohol production ....................................................................................... 1238

∗ Corresponding author. Tel.: +60 389216422; fax: +60 389216148.
E-mail address: zahirayaakob65@gmail.com (Z. Yaakob).

http://dx.doi.org/10.1016/j.rser.2014.10.095
1364-0321/© 2014 Elsevier Ltd. All rights reserved.
1. Introduction

Combustion of fossil fuels and human activities disturb the environment by the emission of greenhouse gases like nitrous oxide, carbon dioxide, methane etc. [1]. The requirement of oils for transport is growing day by day and it is expected to be increased by 1.3% per year up to 2030 [2]. There is no unique solution available for these complications and so alternative ways are to be found out such as modification in vehicle designs, development in public transport and replacement of conventional fuels with alternative advanced fuels and fuel technologies [3]. It is expected that by 2030, the carbon emission from the transport sector and the energy requirement will increase up to 80% [4]. Air transport acquired a significant role in the everyday life of modern world. The influence of air travel increased worldwide social contact, especially in improving business and marketing. The total diesel fuel and jet fuel consumption was in the range of 5 to 6 million barrels per day in between 2005 and 2010 [5]. The average cost of jet fuels was $320/t in 2004 which is increased to an average of $1005/t in 2011 [2]. According to the report from U.S. Energy Information Administration (IEA), for the next thirty years, the jet fuel cost will increase gradually and the average price in the year of 2013 was ($2.82/gal) [7].

The production of alternative fuel for aviation is mainly inspired by increased petroleum costs and environmental concern [5]. Not only the increased cost and environmental effects, some other factors such as secured working of the aircraft engine, consistency etc. should also be considered [8]. Use of biofuels are attracted by the low greenhouse gas emissions while combustion, decrease in the dependence on fossil fuel sources and availability of renewable resources [9]. The aviation transport sector requires fuels with high energy density and so it depends mainly on liquid hydrocarbon fuels. Alternative aviation fuels must possess some specific qualities such as good cold flow properties, thermal stability and low freezing point [10]. The fuel must be well suited for the present design of the aircraft engine [11]. Sustainable aviation fuels must offer low carbon emission over their lifecycles. The energy crops used as the production source should not challenge the food production and ecosystem and also do not harm the environment and do not cause deforestation [12].

The feedstock used for the production of alternative aviation fuels are biological in origin and thus are renewable. Non edible oil crops such as camellia, jatropha, algae, halophytes, municipal and sewage wastes, forest residues etc are the major available resources for the energy production process [13]. Many technologies have emerged for the production of aviation bio fuel from the biomass resources. The conversion routes include thermochemical and biochemical approaches [14]. The bright future of alternative aviation fuel can be influenced by the co-operation between national and international organizations, states and countries [15]. International Air Transport Association (IATA) expects 30% contribution of Bio jet fuel for the jet fuel use by 2030 [16]. The annual universal production of biomass is about 100 trillion kilograms. So obviously, biomass is a potential feedstock having the ability to substitute fossil fuel resource [17,18].

In addition to the reduction in the emission of greenhouse gases, alternative aviation biofuels experiences several advantages.
over conventional jet fuel. The fossil fuels are affected mainly by cost fluctuation [19]. Since the sources used for the production of bio aviation fuel are renewable and of low cost, a well suited production route can reduce the cost of the fuel. Bio aviation fuel production can offer economic profits, especially in developing countries where there is unavailable land available for the cultivation of non-food crops and thus can support the supply chain process [20]. One of the major problems that related to fossil fuels is the difficulty in supply with increasing demand. Here the attraction of bio aviation fuels is that the feedstock is available worldwide and the production process is not location limited [21]. Bio aviation fuels can satisfy the fundamental properties of conventional aviation fuels such as low temperature performance, low flash point, good thermal stability etc. [22]. In brief the aviation biofuels are ecologically, economically and socially sustainable [23].

Daggett et al. gave a well outline of the alternative aviation fuels and their feasibility [24]. Bomani et al. provided a survey on biofuels as an alternative aviation energy source in which they included application of fuel produced from palm oil, algae, halophytes and biomass for aviation and road transport purposes [25]. Nygren et al. investigated the scenarios in aviation fuel and future oil production [26]. Liu et al. investigated various jet fuel production processes and discussed each process in detail [27]. A recent review by Kallio et al. analyzed the application of microbial biotechnology for the renewable production of jet fuel [28].

Even though bio jet fuels are excellent alternatives for conventional aviation fuels; there are many difficulties and challenges to overcome in order to achieve it. Collection of feedstock, the production route, characteristic of the produced fuel and its characterization are extremely challenging. The present paper deals with the opportunities and challenges in the production of aviation biofuel from renewable feedstock. Discussions on the characteristics of feedstock, the methods used in the production process, a comparison of renewable hydrocarbon fuel with biohydrogen, biodiesel, bioalcohol and biomethane as alternative fuels, the industry commitments and collaborations and future outlook and recommendations in this field are also included.

2. Renewable resources

Renewable feedstocks are better resources for the production of biojet fuels. The important advantages of these feedstock are (1) sustainability (2) carbon dioxide recycling (3) renewability (4) eco-friendly technology and (5) less dependence on petroleum supplying countries [29]. The feedstocks generally favoured are non-food energy crops, algae, municipal and sewage wastes, waste wood, forest residues and halophytes. The characteristics of some of the renewable feedstock are mentioned below.

2.1. Camelina

Camelina is a non-food energy crop with high oil content. The average oil content of the plant is about 30–40% and the plant needs lesser amount of fertilizers for growth [30]. Camelina possesses many advantages. Camelina plant can grow on infertile soil or marginal land [31] and the plant is less susceptible to diseases and pets [20]. Camelina can be cultivated as a rotational crop for wheat and cereals and it needs minimum input [30]. The meal left after the extraction of oil can be used as animal feed. The cost of the camelina oil is very less ($0.40–$0.70/gal) and the current markets of the oil in US are Northwest US and Southern Canada; in 2012, 200 million gallons of camelina oil were produced only in US [22]. Since it can be cultivated as a rotational crop, it can solve the problems related to mono cropping which will help farmers to find additional profits from the land [32]. Otherwise the continuous mono cropping may cause decrease in the yield and can destroy the soil.

2.2. Jatropha

Jatropha is a non-edible energy crop which can grow in marginal land and so it does not compete with food crops. The jatropha plant is drought and pest resistant. The plant can grow even in unproductive soil under unfavourable climatic conditions and grows quickly [33]. The plant has a permanent pattern of high yield oil production [34]. Jatropha plant can continue yielding for 40 years once started when a small amount of moisture is available [35]. The meal left after the extraction of oil cannot be used since it is poisonous, but it is rich in N, K and P so can be used as organic manure [34]. Jatropha cultivation is currently occurring in South Africa, South and Central America and South East Asia [36]. The jatropha seed production also depends on location, management practices, varieties, etc. Information from current plantation reveals that the plant requires irrigation for better growing [37].

2.3. Algae

Algae is an attractive solution for the fuel scarcity issues because of their high lipid content, high rate of carbon dioxide absorption, low land use and faster rate of growth [38–40]. The most important benefit of algae is that algae do not affect crop cultivation since it does not require land or water to survive, which help to reduce the food-fuel competition [41]. Algae can produce large quantities of lipids and carbohydrate by using sunlight, waste water and carbon dioxide and thus can play a crucial role in wastewater treatment [42,43]. The biomass left after the extraction of algal oil can be used as animal feed, for preparing bio plastic and for nutrition and also the dried biomass can be further processed for energy production [31]. Microalgae are widely used for fuel purpose. It is easy to cultivate and can be harvested all the year [2]. Compared to other energy crops, algae can produce 30 times more yields per acre [21]. Algae can be processed into a variety of renewable fuels [44].

2.4. Wastes

Wastes from different sources are dependable feedstock for the production of alternative biofuels. Wastes of plant origin and animal origin, such as foodstuffs, wood products, paper, forest residues, industrial and agricultural residues, household wastes, bagasse, animal wastes and municipal wastes can be converted to biofuel through different potential routes [20]. These resources are of low cost and easily available. The use of waste materials for the production of energy will be an asset to the waste management technology without the generation of any harmful products. Municipal wastes and sewage sludge can contribute more since they are widely available and are rich in lipids [45]. The use of waste materials for the production of biofuels can overcome many difficulties such as need of fertilizer, irrigation, land and labour [46].

2.5. Halophytes

Halophytes are grasses that grow in salty water where plants could not grow usually [20]. Halophytes are mostly found in tropical and subtropical regions [47]. Halophytes are can grow in marshes, inland lakes, coastal shorelines, desert areas and in the sea [48]. The speciality of halophytes feedstock is that they will not compete with agricultural crops for fresh water supply and land [49].
3. Alternative fuels for air transport

Alternative aviation fuels can be produced from all of the above renewable bioresources. The properties of alternative aviation fuels are (1) reduced greenhouse gas emission (2) renewable resources (3) compatibility with conventional fuel (4) sustainability and clean burning. The currently developing alternative fuels includes the following.

3.1. Hydroprocessed renewable jet fuels

Hydroprocessed renewable jet fuels (HRJs) are produced by the hydrodeoxygenation of vegetable oils, animals fats, waste grease, algal oil and bio oil and the major side products are water and propane [50]. The hydroprocessed renewable jet fuels are high energy biofuels that can be used as such as fuel even without blending. One of the major advantages of hydroprocessed renewable jet fuels is reduction in the emission of greenhouse gas such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM) [51]. The HRJs are free of aromatics and sulphur and possess high cetane number, high thermal stability and low tailpipe emissions [52]. These fuels are stable for storage and resistant to microbial growth [53].

The hydroprocessed renewable jet fuels are suitable for conventional aircraft engines without further engine modification and do not raise any fuel quality issues. These fuels avoid the chance of deposit formation in the engine and engine corrosion [54]. The fuel combustion is completely ash free. Because of the better cold flow properties, HRJs are highly fit for higher altitude flights [51]. Complete absence of oxygen and sulphur in the fuel decreases its lubricity [55]. The higher paraffin content in the fuel somehow adversely affects the cold flow properties like cold filter plugging point and cloud point which in turn depend on the type of feedstock used [56]. The difference in the cetane numbers of hydroprocessed renewable jet fuels and conventional petroleum fuels affects the fuel ignition in the engine. These problems are better solved by blending HRJs with conventional fuels [55].

The Nest Oil Company has established plants to produce hydrodetered renewable jet fuels. UOP Honeywell, ENI and Galp Energia have plans for to construct hydrodertreating plants worldwide [57]. Aeroméxico, Air China, Air France, Finnair, Iberia and Air France KLM, Lufthansa have performed commercial passenger flights with hydroprocessed esters and fatty acids (HEFA) as fuels [58].

3.2. Fischer Tropsch fuels

Fischer Tropsch fuels (FT fuels) are hydrocarbon fuels, which are produced by catalytic conversion of syn gas (CO and H2) [59]. A wide range of biomass feedstock can be used for the generation of syn gas [60]. The FT fuels are usually clean burning, high value fuels [61]. The FT fuels are characterized by non-toxicity, no emission of nitrogen oxides, high cetane number, reduced particulate emission, low sulphur and aromatic content etc. Also the fuel combustion is free of carbon dioxide and hydrocarbons [46]. Unlike many other alternative fuels, FT fuels does not need special distribution infrastructure and because of the quality of fuel and comfortable for distribution, FT fuels can be produced 2–3 million barrels per day [61]. The characteristics of FT fuels less depend on the nature of the feedstock used and the differences in fuel properties are mainly due to the operational conditions [62]. The FT process is expensive and the efficiency of the process ranges between 25 and 50% [59]. Due to less energy density, the Fischer Tropsch fuels offer low power and low fuel economy [61]. The other problem with the fuel is low lubricity because of the absence of sulphur [62]. Solena is going to establish waste to bio jet fuel plants having a capacity of 50,000 t/year by 2017. StoraEnso and Neste Oil, UPM and Carbona have formed consortia to develop BTL plants in Europe [57]. The ASTM international standard, D7566, has approved specification for aviation fuels. FT fuels in 2009 and HRJs in 2011 [63].

3.3. Biodiesel

Biodiesel is alkyl esters of fatty acid, especially vegetable oils and animal fats and it is produced by the process of transesterification. Biodiesel fuel is biodegradable and possesses excellent lubricity [8]. Biodiesel as fuel shows the advantages of renewability in origin, high flash point, good energy balance and good miscibility with petroleum fuels. It contains no sulphur and show highly reduced greenhouse gas emissions [64]. It is also noted that the biodiesel fuels do not contain aromatic compounds, does not cause any water, soil or air pollution and it is non-toxic [65–67]. But the biodiesel fuel is not sufficient to use as an aviation fuel. The energy density of biodiesel is very low compared to conventional jet fuels [68].

Use of biodiesel as aviation fuel does not need further engine modification and infrastructure, but it does not show much efficiency [69]. The biodegradability of biodiesel may cause biological growth during storage which will affect the stability [8]. The freezing point of biodiesel is very high compared to petroleum based aviation fuel, which makes it insufficient for high altitude flights. The presence of polysaturated and unsaturated fatty acids decreases the stability of the biodiesel due to the oxidation of the unsaturated sites [46]. Because of the presence of ester groups, biodiesel is polar to some extent which will cause the formation of emulsion and therefore water separation will be difficult [8]. Inadequate feedstock supply and deprived economics are the other problems of biodiesel fuel [64].

3.4. Liquid biohydrogen and biomethane

Liquid hydrogen is being established as alternative jet fuel. Bio hydrogen is produced from a wide range of biomass resources by following both thermal and biochemical methods [70]. Liquid hydrogen produces more energy per weight compared to conventional aviation fuel, but requires high storage volume [71,72]. The combustion of liquid hydrogen fuels causes low emission of greenhouse gases compared to petroleum based jet fuels [73]. The major problem is that the liquid hydrogen fuel cannot be used as such in the conventional aircraft engine so the engine has to be modified [74]. The production cost, formation of char and tar as side products are also to be faced [70]. The other problem associated with the use of liquid hydrogen is that upon mixing with air, it can burn in low concentration which will cause safety problems and the storage of hydrogen as liquid is also difficult since it need low temperature [75]. The emission of comparatively high amount of water vapour is a problem associated with hydrogen aircrafts [46]. Liquid methane can be used as fuel in cryogenic aircrafts. The use of carbon dioxide emission can be decreased about 25% by the use of liquid methane fuel. Engine design is a difficulty that has to be faced for the commercialization of the liquid methane fuels. The combustion of liquid methane fuel emits methane, which is a major greenhouse gas [46].

3.5. Bio alcohols

Bio alcohols are produced by the fermentation of starch and sugar or catalytic conversion of biogas. Ethanol and butanol are generally used as alternative fuels. Ethanol cannot be used for
aviation purposes because of its high volatility, low flash point, and low energy density [52]. The case of butanol is almost similar. Alcohol as aviation fuel needs special delivery infrastructure and storage system [8]. Use of alcohol as jet fuel needs engine modifications [59]. The high volatility of ethanol causes safety problems during high altitude travels [52]. Blending of alcohol with conventional fuels is not feasible because of its poor fuel properties which will cause aviation issues.

4. Production routes

The fuel production routes have much importance in determining the fuel characters. The method adopted to produce the fuel will influence the product composition, fuel cost, fuel properties, availability and environmental impact. The generally used methods for the production of hydrocarbon fuels involve two types. One is thermochemical process and the other is biochemical process [14]. The other methods used for the production of alternative fuels are also discussed below.

4.1. Thermochemical process

Thermochemical process is the conversion of biomass to fuel by pyrolysis, gasification and upgrading. Pyrolysis is the process of thermal decomposition of biomass in the absence of air, which results in the formation of bio oil and methane with other side products [76]. Gasification involves the treatment of pyrolysis products with air or steam to produce syngas, which is a mixture of hydrogen and carbon monoxide. Syngas can be upgraded by the FT process instead gasification and the FT process bio oil can be subjected to hydropyrolysis or hydrodeoxygenation which will result in hydrocarbon fuel same as that from the FT process [77].

4.1.1. Biomass to liquid process (BTL process)

Biomass to liquid process comprises the conversion of biomass to liquid hydrocarbon fuel. A wide range of feedstock can be subjected to this process, including municipal and agricultural wastes, cellulose, wood, and algae [23]. The process involves the following steps, namely pretreatment of biomass, gasification, syngas purification and FT synthesis or pyrolysis followed by hydropyrolysis [78,79]. The method takes the advantages of sustainability, reduced greenhouse gas emissions and no food to fuel competition [80].

4.1.2. Fischer Tropsch process (FT process)

The Fischer Tropsch process comprises the catalytic conversion of syngas (CO and H₂) which is produced by the gasification of biomass to liquid straight chain hydrocarbon fuels [81]. The range of hydrocarbons produced depends on the catalyst, pressure and temperature conditions of the process [82]. Jet fuel produced by the FT process from different feedstock exhibits similar properties and they are characterized by zero sulphur and aromatics [52]. The resulted FT fuels show clean burning. FT fuels are now recommended to use in blending with conventional fuel to meet requirement of specific lubricity in the absence of sulphur [81]. The method takes the advantage of the production of total negative greenhouse gas fuels [62]. Since the fuel is free of aromatic compounds, it makes some fuel leakage problems in the engine due to shrinkage of the engine while blending and it can be better minimized by the use of additives [8]. Even though a wide range of feedstock like waste wood and agricultural residues can be upgraded using the FT process to fuel, the method is quite expensive [23,68].

4.2. Hydropyrolysis

The method of hydropyrolysis involves treatment of fats and oils (vegetable oils and bio oils) in the presence of hydrogen for the removal of oxygen from the feedstock. The hydrodeoxygenation step is followed by isomerization and cracking to get fuel of desired specifications like low temperature properties [83]. Hydro-processing results in the formation of clean paraffinic fuels with high thermal stability, no aromatics and sulphur and they are generally mentioned as hydropyrolysed renewable jet fuels (HRJs) [84]. In the hydrodeoxygenation method, oxygen is most preferably removed as water and propane is one of the byproducts [85]. The most promising feedstock used for the production of HRJs are plant oils like jatropha oil, camellina oil, algal oil, bio oil, animal fats and waste grease that can be made available in plenty [52]. The method is efficient and it can produce hydrocarbon fuel with improved cold flow behaviours and high cetane number [78]. Hydropyrolysed renewable jet fuels are comparatively economical [23]. The low lubricity of HRJs can be improved by blending with conventional jet fuel or by the use of additives [52].

4.3. Biochemical process

Biochemical process is the conversion of biomass to carbohydrates that can be further transformed into alcohol by the method of fermentation using enzymes or micro-organisms [86]. Studies are going on to decrease the cost of the pretreatment and hydrolysis process by enzymes, and also trying to develop new microorganisms to carry out the process. The current processes used are:

4.3.1. Direct sugar to hydrocarbon process (DHSC) and alcohol to jet process (A TJ)

The method includes biochemical fermentation or catalytic conversion of sugars from biomass hydrolysis or from direct sugar sources such as sugar cane to hydrocarbon fuels [87]. The process involves hydrolysis of biomass, carbohydrate fermentation, purification and hydropyrolysis [88]. Direct Sugar to Hydrocarbon process does not involve the intermediacy of alcohol. The advantages of the use of this method are plentifully available cost-effective feedstocks that not directly cause food crisis, sustainability and fuel with the reduction in greenhouse gas emission up to 82% [89].

Alcohol formed by the biochemical or thermochemical fermentation of carbohydrates obtained from biomass or thermochemical and thermo biochemical combined conversion of syngas can be subjected to a series of steps to form hydrocarbon fuels [87]. The process mainly includes 4 steps-ethanol dehydration, oligomerization, distillation and hydrogenation [90]. A wide range of the potential feedstock can be used for the process, including starch, cellulose, sugar and waste [23]. The method is very economical since the feedstocks are not much expensive and the process does not need large amounts of energy [20]. Sugar and starch can be converted to alcohol by direct fermentation, but in the case of biomass it must be pretreated to get sugar, which is then directly fermented to alcohol or subjected to gasification followed by gas fermentation [91].

4.3.2. Bio alcohol production

Bio alcohols are produced by thermal and biochemical fermentation of carbohydrates resulted by the hydrolysis of biomass [52]. Biomass sources like corns and cellulose are first hydrolysed to extract sugars and then fermented followed by distillation to get bio alcohol. Direct sugar sources are subjected to fermentation to produce alcohol [92]. Bioalcohol can be produced from a wide
range of biomass feedstock such as wood, agricultural wastes, forest residues and wastes [93]. Methanol, Ethanol and butanol have the potential to use as transportation fuels, but they are not suitable to use as aviation fuel alternatives. The low flash point, low energy density and pure low temperature properties limit its use as aviation biofuel [94].

5. Other alternative fuels production routes

5.1. Liquid hydrogen and liquid methane

Bio hydrogen can be generated from a variety of feedstock like municipal and sewage residues, cellulose forest waste materials and crops [95]. Bio hydrogen can be produced by biomass gasification. At higher temperatures and pressures, biomass is converted to hydrogen with CO and CO₂ as side products. From this hydrogen can be separated by membrane method or chemical methods. Hydrogen can also be produced from pyrolysed oil by catalytic steam reforming [96]. Another method is the biological route using algae and bacteria [97]. Introduction of liquid hydrogen for aviation decreases the greenhouse gas emissions [98]. Biomethane is produced by anaerobic digestion or fermentation of a large number of renewable feedstocks like waste materials, crops and biomass [99]. The major problem with the use of liquid gas fuels is the requirement of modification of aircraft engine which will make fuel system very complex [98].

5.2. Transesterification of oils/fats

Transesterification is the process of the catalytic conversion of fats and oils into fatty acids of alkyl esters which are well known as biodiesel [100]. The method biodiesel production is not much expensive and since it can be produced from non edible oils, it does not create a food-fuel crisis [101]. The biodiesel fuel produced by this method exhibits carbon neutrality, reduced emission of greenhouse gases, non-toxicity and biodegradability [9]. Biodiesel can be used in diesel engines without further engine modification, but it is not a suitable alternative for aviation fuels. Biodiesel possesses low energy density and poor cold flow properties of the fuel causes freezing of fuel in the aircraft engine at higher altitudes [52], Table 1 represents an overview of biojet fuel production routes, renewable sources and various alternative aviation fuels.

6. Industry commitments and collaborations

With the increasing need for alternative aviation fuels, there are many projects and collaborations developing worldwide. There are many public and private programmes including universities, institutes, companies and government organizations [102]. All the projects aim to commercialize renewable aviation fuels through different ways and from different sources. The important intentions behind the development of renewable aviation fuels are (1) decrease the dependence on non-renewable fossil fuel sources (2) reduce environmental impacts (3) use of cheaply available feedstocks (4) reduce the fuel cost. The current commitments and collaborations in this field are discussed here.

Private sector projects on aviation fuel developments are well emerged in United States, concentrating selection of feedstock, conversion routes and scaling up [102]. Commercial Aviation Alternative Fuels Initiative (CAAFI) is a confederation of airlines, airports, manufactures, fuel suppliers and government organizations Federal Aviation Administration (FAA) in the United States [103]. IATA, American Society for Testing and Materials (ASTM), Coordinating Research Council (CRC), Department of Conservation (DOC), Defense Advanced Research Projects Agency (DARPA), Defense Energy Support Center (DESC), International Civil Aviation Organization (ICAO), original equipment manufacturer (OEM) are some of the members in the group. The association stands for development, certification and verification of renewable jet fuel and to support energy safety, environmental security and aviation capitals [104]. Brazilian Alliance is a collaborative group formed by airlines, biomass producers, biofuel researchers and manufacturers. The purposes are (1) support the sustainable aviation fuel development (2) decrease the environmental impacts of aviation
industry and (3) commercialization and scaling up of bio jet fuels [2]. Defence Energy Support Centre and US Military Services work in co-operation for the development, commercialization and certification of alternative jet fuels. They plan to reduce the dependence on petroleum fuels, exploitation of renewable resources and to produce advanced fuel with decreased greenhouse gas emissions.

The US Air Force Research Laboratory is prepared to test the fuels produced by FT process and hydroprocessing of jatropha, camelina, algae oils and animal fats [105]. Biojet Corporation (USA) is a collaborative project including South Pole Carbon Asset Management Ltd. of Zurich, Switzerland, Abundant Biofuels Corporation of Monterey, California, Mitch Hawkins & Co. Inc., of Santa Ynez, California. Biojet Corporation makes an association with algae developers and also uses jatropha and camelina oils as resources [106]. Energy & Environmental Research Center (EERC), USA with DARPA has industrialised a process called catalytic hydrodeoxygenation and isomerization (CHI process). The method makes use of feedstocks such as camelina oil, algal oil, canola oil, corn, tallow and waste grease for the production of bio jet fuels that are highly compatible with conventional fuels [86]. Global Seawater Inc., (GSI) established in UK and USA is a project mainly concerned with the production of alternative aviation fuels from seawater crops like halophytes. The work is primarily based on Salicornia bigelovii, which is a native plant in Europe, United States, South Asia and South Africa [107].

Rentech, Inc. is a USA based company concentrated on the production of hydrocarbon fuels from biomass sources. The project works on Rentech Process the basic principle of which is FT process and it converts biomass, green waste, municipal and solid wastes to synthetic jet fuels. The hydrocarbon fuel produced by the company can be better blended with conventional fuel to use in military and commercial jet fuel [108]. UOP (USA) is a well-known company in the fields of petroleum refining and processing. They have resourcefully synthesized hydroprocessed renewable jet fuels from various natural sources such as camelina oil, algal oil, jatropha oil and tallow by the process of deoxygenation, isomerization and cracking [86]. Universal Oil Products, US mainly focused on hydrodeoxygenation of free fatty acids for fuel production [68]. Amiris, USA with Total Alternative Aviation Fuel aim to produce renewable hydrocarbon fuels by Direct Sugar to Hydrocarbon (DSSH) process with low greenhouse gas emissions and better fuel properties. They also plan to gain acceptance from OEM and to get ASTM and Def Stan authentication [88]. Tecbio, Brazil tries to upraise their crop Babassu palm for biokerosene production with NASA [68]. The Midwest Aviation Sustainable Biofuels Initiative (MASBI) established in 2012 focused to promote midwestern U.S. energy security. The Canadian company Applied Research Associates, Inc (ARA) used hydroprocessed vegetable oil on business jet flight [109].

International Air Transport Association (IATA) is an international trade industry. Their aviation plan is based on four main policies (1) development of fuel technology i.e., finding new energy sources, production of clean bio jet fuels and engine compatibility (2) Aircraft processing with good efficiency (3) Infrastructure (4) favourable aviation economy [110]. Boeing, a multinational American aerospace company that is highly dynamic in the field of development and testing of alternative aviation fuel with Airbus aim to initiate innovative fuel technologies, to improve life cycles, to advance international flight operations and reliable fuel distribution [111]. Aliança Brasileira para Biocombustíveis de Aviação, ABRABA (Brazilian Alliance for Aviation Biofuels), Brazil is collaboration project of institutes, industries and government for the generation of sustainable biojet fuels [112]. Many private companies and organizations are on the road from different countries all over the world mainly U.S, Japan, Qatar, Mexico, Singapore, Brazil, China, Canada and Australia [102]. Airlines have signed agreements with fuel producing companies, Alaska Airlines with Hawai’i Bio Energy, United Airlines with Alt Air and Avianca Brasil with Byogy for the development of bio jet fuels. Alt Air plans for a hydroprocessing plant by 2014 having a capacity of 90 kt/year [109].

Dynamotive Energy Systems Corporation (DESC) in partnership with Tecn SA and IFPen/Axens produces 1 gal of jet fuel at cost between $1.82 and $3.25 from biomass by Dynamotive’s fast pyrolysis and refining processes through two ways [59]. Imperium Renewables, Inc. (IRI) with Pacific Northwest National Laboratory (PNNL) follow Alcohol to Jet process for the jet fuel production using waste materials from forests, municipalities and agriculture [113]. Altair Fuels (US) targets to supply 75 million gal/year of bio jet fuels using potential oil crops like Camelina [114]. Solena (US) follows Fischer tropsch method for the conversion of agricultural and municipal wastes to biojet fuels and it also takes the advantages of a cleaning technology [115]. Virent (US) in partnership with Shell and Cargill uses sugar cane, cone starch and sugar beet as feedstock for the generation of biojet fuels [116]. They also plans to use corn stover, switch grass, wood and bagasse as potential feedstocks [117]. Air Force Certification Office (ACFO) is a fuel certifying agency which has legalized the use of FT fuel blends [118]. SkyNRC, Netherlands planned to start flights with Thomson airlines, Fin Air and Alaska airlines powered by biojet fuel produced from waste cooking oil [34]. Sapphire Energy aim to produce 300–500 b/d algal aviation biofuel within three years [26].

According to Solzyme Inc.,USA, they will produce large amount of oil from microalgae which can be effectively converted to bio jet fuel [2], European Aerospace Defence System in 2010 and US Navy in 2011 tested flight with microalgae bio aviation fuel. European airlines has invested 2.7 billion euro to achieve 4% development by 2020 and IATA plans for 6% development in biofuel production [34]. Alternative Fuels and Biofuels for Aircraft Development (ALFA-BIRD) is an assignment financed by European Union. The objectives of the projects are (1) production of new aviation bio fuels and their analysis, introduction of injection systems and modelling, testing the compatibility of the newly developed fuel [86]. Syntroleum Corporation produces FT fuels using natural gas as the feedstock and USAF (US Air Force) tried flight with 50:50 blend of the produced fuel with JP-8 [119]. Dynamic Fuels, USA is a joint mission of Syntroleum Corporation and Tyson Foods, Inc. aiming the development of advanced feasible routes for the production of high quality aviation fuels and fuel technologies.

Tyson foods supplies animal fats and it is hydroprocessed to clean jet fuels. Their project targets to produce 284 million liters of fuel per year [86]. Avantium Chemicals in Netherlands (Europe) has established the method of catalytic conversion of sugar to 5-hydroxymethylfurfural. It could be used as a component in aviation fuel with good stability and blending properties [120]. Neste Oil Corporation is a worldwide Finland (Europe) based marketing company focused on the production of good value transportation fuels. They use the biomass to fuel process which is well known as NExBTL process. The feedstocks used by them are vegetable oils mainly jatropha and algae as well as animal fats [54,121]. Swedish Biofuels AB (Sweden) company also makes efforts for the development and industrialization of renewable alternative jet fuels. They have secured patents in this field. With LanzaTech they produce jet fuel mainly from wood, forest residues, agricultural wastes and grains. The method of synthesis involves production of sugar from the biomass feedstock followed by fermentation. The resulted alcohols are then chemically converted into hydrocarbon [122].

Airbus is a European aircraft manufacturing company. They focus on the current situation of aviation fuels, development of sustainable biojet fuels, development of technology and certification of Bio SPK. They have also performed test flights with
renewable aviation fuels \[123\], GE Aviation a part of General Electric Company (GE) US uses bio oil hyroprocessing \[68\]. Aviation Initiative for Renewable Energy in Germany (AIREG) work for advanced research and development in aviation biofuels and combining experts in the field to achieve fuels with reduced emissions and sustainability \[124\]. The Sustainable Aviation Fuel Users Group (SAFUG) based in Europe involving Natural Resources Defence Council and the Roundtable for Sustainable Biofuels (RSB) concentrated on production of advanced aviation fuels from renewable sources with minimum impacts on the environment and ecosystems. They also decided to cultivate plants which can financially support undeveloped areas and communities \[125\].

Sustainable Way for Alternative Fuel and Energy in Aviation (SWAFAEA) mainly concerns with lifecycle analysis, compatibility of alternative fuel, environmental influences and fuel economics \[12\]. The Nordic Initiative for Sustainable Aviation, NISA is founded by Nordic stakeholders for the development of a sustainable aviation fuel \[109\]. Lufthansa tested flights with biofuel in 2011 as a part of burnFAIR research project between Hamburg and Frankfurt \[126\]. Initiative Towards sustainable Kerosene for Aviation, ITAKA is a collaborative initiative that targets to connect feedstock cultivators, biofuel producers, distributors and users in developing a large scale camelina bio jet supply chain \[57\]. Air France-KLM has set a schedule for the development of next generation biofuels, new technologies, policies and legislation \[127\].

Sasol (SA) is marketing company which is now functioning in Qatar and establishing a new branch in Nigeria. They adopted the Gas to liquid process (GTL) fuels through Fischer Tropsch synthesis for the synthesis and scaling up of hydrocarbon. They have certified the use of 50:50 blend of FT fuel with JET-A for aviation purpose \[68\]. An Indo-Canadian programme involving Pratt, Universities of Laval, Ryerson, Queens, Whitney, HPCL, Indian Institute of Science Bangalore, IIT, Info Tech, Indian Oil, IIT (K) is signed for renewable fuel production, blending and applications \[128\]. Chinese Academy of Sciences in partnership with Boeing has started Joint Research Laboratory for Sustainable Aviation Biofuels for the production of algal biojet fuels \[112\]. Japan Airlines with Boeing produces biojet fuel from algae, jatropha and camelina oils and uses in aircraft engines with 50:50 blends with Jet-A \[129\].

Virgin Australia, Australia’s second largest airlines company joined with government and other industries work for the development of renewable aviation fuel, fuel technologies and commercialization of alternative aviation fuels for affordable cost \[130\]. Sustainable Aviation Fuel Road Map (SAFRM), an enterprise of the SAFUG was launched targeting local supply chain development of bio jet fuels \[112\]. Queensland Sustainable Aviation Fuel Initiative in Australia focuses on the production and lifecycle assessment of bio jet fuels from oil crops, sucrose and algae. They plan to develop sugar to bio aviation fuel process by yeast fermentation \[131\]. The Global Bioenergy Partnership (GBP), The Roundtable for Sustainable Biofuels (RSB), International Sustainability and Carbon Certification (ISCC), REDcert, The Renewable Transportation Fuel Obligation Sustainable Biofuel Meta Standard (RTFO), Sustainable Biodiesel Alliance are the existing sustainability evaluation programs \[132\].

### 7. Challenges

Even though the need of alternative aviation biofuels are exceeding, there are many challenges to overcome and to achieve the goals. The price gaps between bio and conventional jet fuels, sustainability and financial problems in commercialization are major concerns in the development of alternative jet fuels \[127\]. Economic and environmental issues including land–water usage, greenhouse gas (GHG) and particulate emissions, fuel-food competition are the major obstacles come across. Sustainability is a big obstacle to overcome which depends mainly on the availability of feedstock and the fuel production route that bring out social, economic and environmental impacts \[133\].

#### 7.1. Environmental challenges

One of the major issues that should be faced is the social and environmental impact of fuel production and management. 2.5% of man-made carbon dioxide was from aviation sector in 2005 and it is expected to become 4–4.7% by 2050 \[134\]. The uprising demand for bio jet fuels creates afforestation issues which will affect the fertility of soil and biodiversity and will cause increase in atmospheric CO₂ \[72\]. Use of agricultural land for crop cultivation for biofuel production will cause food scarcity and it will reduce soil quality and water availability in the soil. The use of fertilizers and insecticides will result in soil destruction and water pollution \[135\]. The fuel developed must not arise any human health issues \[136\].

#### 7.2. Production issues

Cost effectiveness of the process and feedstock flexibility are major hurdles related to production process \[137\]. Even though there are projects developing on the basis of algae as feedstock, there are many problems and difficulties related to algae. The selection and production of useful algal species and lipid extraction is a puzzling process \[138\]. The production of biojet fuel from algae needs optimization of the process, production cost, properties and its certification \[139\]. The suitable catalyst selection and right designing of the process are important tasks to be faced by the alternative fuel producers \[140\]. The production process is feedstock dependent and so varying \[141\]. Production process must be consistent, competent and highly efficient.

#### 7.3. Distribution problems

Quality of product and suitable blending for effective functioning are problematic in the supply process \[137\]. The costs of HRJ and BTL fuels are now in a range of $0.80–$2.00/L which is 3 times higher than that for petroleum based jet fuels \[12\]. Fuel infrastructure, fuel marketing, storage of feedstock and fuel, byproducts marketing regulations and certifications are also major tasks to overcome \[44\]. The current production cost of biojet fuels should be reduced; otherwise it will not be feasible and the increasing prize will affect the production investments \[102\]. The coordination of investors and biomass suppliers is also highly essential \[124\].

#### 7.4. Feedstock availability and sustainability

The feedstock which is cost effective that can grow with minimum water supply and fertilizers, with good yield, without affecting the food crops and thereby avoiding food to fuel issues, that possess low greenhouse gas emission and provides economical benefits are largely favoured for the production of aviation biofuels \[20\]. The challenges related to feedstock are availability of feedstock in bulk scale with comparatively low cost and restrictions for large scale applications \[137\]. The major problems associated with algae culture are temperature maintenance and energy requirement \[139\]. Large amount of fuel must be produced to test in aircrafts and need large amount of feedstock \[141\]. While producing alternative aviation fuels, the feedstocks must be selected such as to minimize impact on the land use and water intake \[136\]. Now the availability of biomass feedstock for the
production of bio jet fuel is restricted due to competition with the current fuel requirements [142].

7.5. Compatibility with conventional fuel

Renewable jet fuels must be compatible with the conventional jet fuels. In contrast to conventional jet fuels, bioaviation fuels must not contain sulphur and aromatics, must possess low freezing point and high auto ignition temperature [136]. Separation of bio aviation fuels at large airports will not be easy and some airlines face problems while using the biofuels [143]. In addition there are other problems like introduction of renewable fuel into commercial aviation service, certification, engine and quality testing and application of the fuel in aircrafts [19]. The fuel developed must be resistant to a wide range of operational circumstances, must show good performance and safety guaranteed [21]. Thermal stability and storage stability are two important issues regarding aviation biofuels. Low temperature properties, combustion characteristics and presence of small impurities like metals and micronutrients also do matter [141].

8. Future outlook and recommendations

Defence Logistics Agency Energy (DLA Energy) is now targeted to link market scale production and certification of bio aviation fuels through partnerships with manufactures and government organizations [109]. Production and commercialization of bio jet fuels can influence land, water and food resources, biodiversity and can make economical and social impacts. Shortage of inputs and programmes to scale up sustainable production and distribution of feedstock, lack of cost effective technologies for production of bio jet fuels are the existing complications that slow down the research in this field. The future aviation fuel or the production process (1) must never raise food–fuel competition (2) must not make environmental issues and (3) must be sustainable with tolerable cost.

Considering the feedstock, non-edible oils, biomass and algae can contribute as potential feedstock, while algae can be used as raw material for the production of fuel in the regions such as Australia, Arabia, north-west Africa and deserts in the United States while evaluating their availability [127]. The production process can be improved by adopting new production technologies and by the use of locally available feedstock which will bring out regional development. Involvement of government and other investing organizations and industries, long term policies and other partnerships will provide more job opportunities and will help to maintain the sustainability of the fuel production and distribution.

9. Conclusion

The production of alternative aviation fuels from renewable bioresources is a highly promising technology which is expected to substitute the petroleum based fuels. Among the various processes and alternative fuels, hydroprocessed renewable jet fuel (HRJ) and Fisher Tropsch fuels (FT fuels) have the potential to replace the conventional jet fuels. The main problems with biodiesel and bioalcohols as aviation fuels are their poor fuel properties. The use of liquid hydrogen and liquid methane fuels are favoured, but their high production cost and less suitability to conventional aircraft engines make them less preferred. Many challenges arise including availability of feedstock, compatibility of alternative fuels with conventional fuels, environmental concern and production and distribution issues. The increasing interest of government and international organizations can help the scaling up, commercialisation and supply chain infrastructure to large extent. The use of waste materials from different sources which are largely available as the feedstock can contribute to the issues related to feedstock costs.

References

[1] Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyst KB et al., editors. IPCC Climate change 2007: the physical science basis, Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA; 2007.