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Renewable jet fuel

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Novel strategies for sustainable replacement of finite fossil fuels are intensely pursued in fundamental research, applied science and industry. In the case of jet fuels used in gas-turbine engine aircrafts, the production and use of synthetic bio-derived kerosenes are advancing rapidly. Microbial biotechnology could potentially also be used to complement the renewable production of jet fuel, as demonstrated by the production of bioethanol and biodiesel for piston engine vehicles. Engineered microbial biosynthesis of medium chain length alkanes, which constitute the major fraction of petroleum-based jet fuels, was recently demonstrated. Although efficiencies currently are far from that needed for commercial application, this discovery has spurred research towards future production platforms using both fermentative and direct photobiological routes.

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Introduction

The pursuit for sustainable and renewable fuel production systems is a global challenge of great environmental, social and economic importance. Jet fuels constitute a large sector for the consumption of fossil fuels with a market value of $207 billion in 2012 (accounting for 33% of operating expenses at $110.0/barrel Brent of oil) [1] and steadily rising. Biotechnology could potentially make an important contribution to renewable jet fuel production as already demonstrated in the production of bioethanol and biodiesel for piston engine vehicles. Here we survey the current literature regarding possibilities for renewable production of jet fuels with a particular attention on alkanes — the dominant chemical class found in current jet fuels.

What is jet fuel?

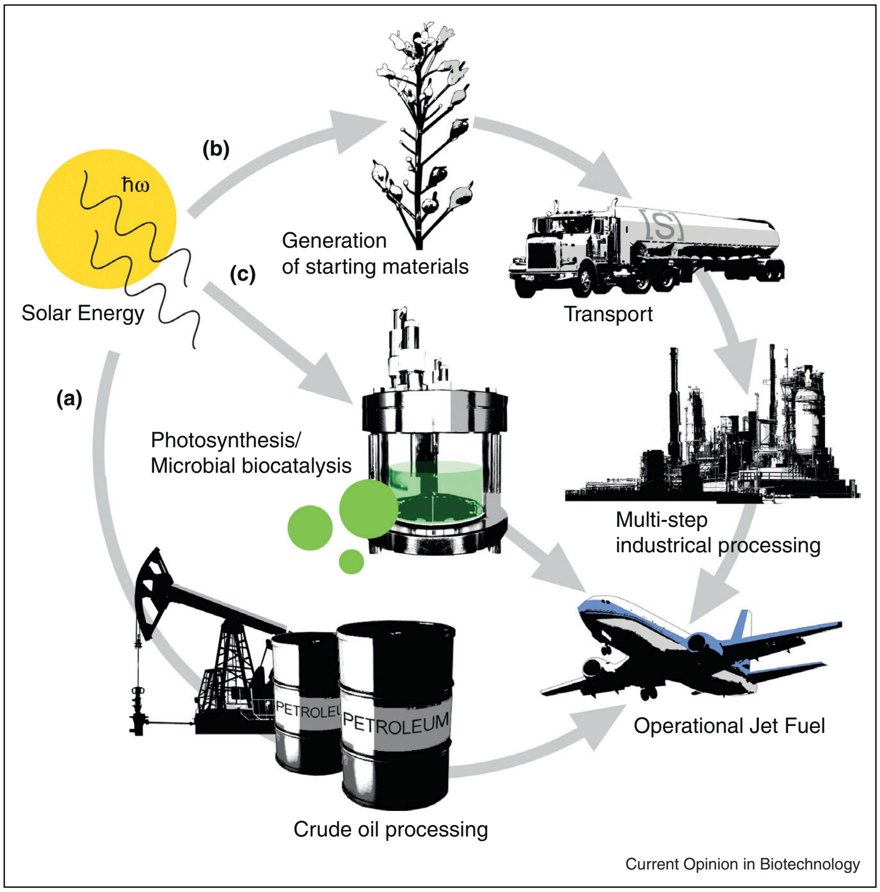
Jet fuel is a generic name for aviation fuels used in gas-turbine engine powered aircrafts. Traditionally jet fuel (or 'kerosene') corresponds to the kerosene distillation fraction of crude oil (~150–275°C) (Figure 1a) which is a complex blend of up to >1000 different chemical compounds. The main components are linear and branched alkanes and cycloalkanes (Table 1) with a typical carbon chain-length distribution of C6–C16 [2,3•]. Since the development of the first jet-powered aircrafts in the late 1930s, the two main operational standards are Jet A used in the US and Jet A-1 used widely elsewhere in the world [2] (Tables 1 and 2). The composition of jet fuels has always been a compromise between the *cost* (availability of suitable raw material and the requirement for processing) and *performance* (propulsion properties, safety, and engine-friendliness) — with very little emphasis on the environmental impact.

Jet fuels differ from traditional combustion engine fuels in their physicochemical properties because of engine-specific technical requirements and operational conditions. The relative proportion of the various hydrocarbon constituents determines the so-called *bulk properties* of the jet fuel (Table 2) including energy content, combustibility, density and fluidity. These attributes can be modified by altering the ratio of hydrocarbons with different molecular weights and geometries. For example, the low-temperature flow properties and volumetric energy content of linear alkanes are poor, but compensated by the branched alkanes and aromatic compounds in the jet fuel mixture, respectively [3•]. Other important factors such as fuel stability, lubricity, corrosivity and cooling characteristics are influenced by *minor components* in the fuel [3•]. These minor components in kerosene-based fuels include sulphur, oxygen and nitrogen hetero-compounds which are minimized to, for example, enhance the combustion properties and reduce the environmental impact. At the same time, specialized chemical additives such as antioxidants, metal deactivators or biocides are supplemented in the parts per million concentration range to improve or preserve important fuel properties such as those listed above [2,3•].

Existing technologies for renewable jet fuel production

Currently there are two promising renewable alternatives that can substitute for petroleum-based jet fuels: Bio Derived Synthetic Paraffinic Kerosene (Bio-SPK) [4] and Fischer–Tropsch Synthetic Paraffinic Kerosene (FT-SPK) [5], produced from renewable oils and biomass, respectively [6•]. Bio-SPK is produced by transesterification of triacylglycerols and fatty acids extracted from plants, algae or recycled sources followed by hydrocracking and hydroprocessing which generates alkanes of desired length, saturation level and branching. FT-SPK

Figure 1



Representation of three alternative routes to produce aviation jet fuel discussed in this study. **(a)** Jet fuel traditionally corresponds to the kerosene distillation fraction of petroleum. **(b)** Synthetic paraffinic kerosenes, Bio-SPK and FT-SPK, produced from biomass or bio-oils of microbial, plant-derived or recycled origin can be used as renewable jet fuel replacements. The process involves the production/collection of the initial substrate material, followed by multi-step industrial processing to generate the final fuel. **(c)** Alkanes, the main components of jet fuels, can also be produced via specific microbial biosynthetic pathways from fatty acid precursors of different lengths. Currently these have only been demonstrated at conceptual level, but could provide a future platform for the direct production of renewable fuels from biomass or directly from sunlight and CO_2.

is obtained through pyrolysis of biomass into synthetic gas (syngas), Fischer–Tropsch synthesis of longer chain alkanes, hydroprocessing and separation. Though the chemical compositions of SPKs and petroleum-based fuels are clearly different (Table 2), they are still very similar in their key technical properties (Table 1) and performance in modern jet aircrafts [4,6$^{\bullet}$,7$^{\bullet}$].

Table 1

Chemical composition of jet fuel

Composition (wt%)	Jet A-1	Bio-SPK	FT-SPK
n-Alkanes	19.6	~10	2.7
Iso-alkanes	29.9	~90	42.8
Monocyclic alkanes	20.3	S.P.	13.8
Polycyclic alkanes	7.3	S.P.	29.1
Alkyl benzenes	14.1	0	11.2
Other hydrocarbons	8.7	0	0.4

Chemical composition of commercial Jet A-1 jet fuel [7], Bio-SPK fuel from jatropha and FT-SPK fuel [7] (wt%); Bio-SPK [4]; S.P. — ‘small percentage’.

The industrial synthesis of SPK has been well established even at large scale, and the products have been successfully evaluated by major commercial airlines in a 1:1 blend with petroleum-derived kerosene [4,6$^{\bullet}$]. Although the development and use of the technology is advancing rapidly in many countries [6$^{\bullet}$], these systems rely on separate infrastructure for the preparation/collection and transport of the starting materials, and the need for multi-step industrial processing to obtain the final fuel (Figure 1b).

Alternative routes towards renewable fuels

Bacteria, yeast and algae already have the capacity to produce a multitude of potential precursors and ready-to-use fuel molecules like ethanol, alkanes and H_2 as part of their native metabolism. The range of product chemistry