Editorial Corner

Sustainable Aviation Fuel: A Greener Future for Aviation Industry

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The aviation industry has been experiencing exponential growth due to rising economic progress and global connectivity. This sector is instrumental in the national and international economy and plays a vital role in modern society [1]. In 2018, the aviation industry transported around 64 million tons of freight and 4.3 billion travelers. This activity generated USD 6.7 trillion worth and 65 million employments [1], [2]. However, aviation fuels (C_9-C_{16}: n-/iso/cyclo-paraffin, aromatics, and naphthalene) are primarily obtained from non-renewable fossil-based resources. In 2005, the commercial airlines consumed 260 million cum of aviation fuels, and it was increased to 330 million cum in 2018. The growing air transportation poses severe environmental threats. The aviation sector emitted more than a gigaton of carbon worldwide in 2019. As the demand for aviation fuels is anticipated to increase 2-3 times by 2050 compared to 2019, it is essential to diminish the environmental impacts of this sector [3]. Sustainable aviation fuel (SAF) derived from renewable biomass is the only eco-friendly alternative to circumvent the dearth of fossil resources and climate change. Therefore, the net-zero emission policy has been adopted by many countries, and many more are expected to participate in this noble initiative. The SAF is projected to be the primary contributor to achieving this mission, offsetting carbon capture, infrastructure and operational improvement, and development of new aircraft technologies, which are 85% more proficient compared to the 1960s (Figure 1) [4]. In 2020, 0.1 billion liters of SAF were consumed in airlines, contributing less than 0.05% of aviation fuels [5]. However, the contribution of SAF to net-zero emissions is projected to be 65% by 2050 (Figure 1) [6]. Therefore, transitioning from conventional aviation fuels to SAF is essential for achieving carbon neutrality [7].

Current SAF manufacturing technologies: SAF are "drop-in" fuels that can be used directly in aviation engines. Current SAF manufacturing encompasses Fischer-Tropsch (FT) synthesis, hydro-processed esters and fatty acids (HEFA), power-to-jet (PtJ), alcohol-to-jet (AtJ), and hydro-processing of fermented sugar (HFS) technologies that use diverse biomass feedstock. These SAFs qualify for blending with aviation fuels under the American Society for Testing and Materials (ASTM) D7566. The FT synthetic paraffinic kerosene (FT-SPK) was approved in 2009 and involves the gasification of lignocellulosic biomass to syngas (CO and H_2), which is then converted to long-chain alkanes by the FT reaction [8]. The long-chain alkanes are subsequently converted to SAF-range hydrocarbons by a combination of hydrotreatment and catalytic cracking (Figure 2). It is one of the earliest approved processes under ASTM D7566 Annex A1 with a maximum blending limit of 50% [9]. This process produces sulfur-free SAF with low aromatic content. However, syngas purification is crucial to remove the tar, solid particles, and sulfur compounds to avoid fouling of the reactor. The catalyst, pressure, and temperature govern the chain length of the hydrocarbons [10]. This technology can also be adapted for diverse feedstocks to produce SAF with similar fuel properties. However, the disparity in the fuel properties for different biomass arises due to operating conditions [10], [11]. The FT-SPK process is later extended to introduce aromatics up to 20%, known as FT-SPK with aromatics (FT-SPK/A) [12], [13]. The aromatics are introduced by adding alkylated aromatics. This process is classified under ASTM D7566 Annex A4, and the maximum allowable blending is limited to 50% [13]–[15]. Natural gas, coal, and biomass are the possible feedstocks for FT-SPK/A [14]. To qualify for ASTM D7566, the coal tar was used as a feedstock in FT-SPK/A. However, the integrated process involving aromatization, oligomerization, and alkene-aromatic alkylation displays the potential of FT-SPK/A to produce SAF with fuel properties similar to synthetic Jet A1 [13], [15].

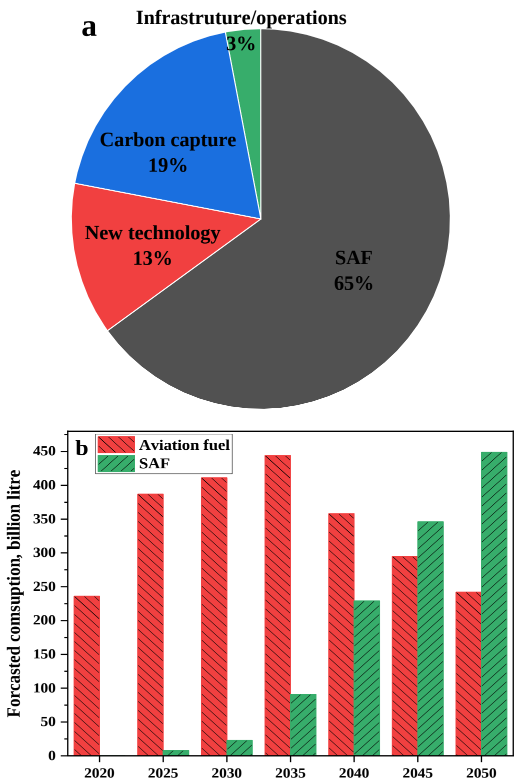

Figure 1: (a) Contribution of different strategies to achieve net-zero emissions in 2050. (b) Projected SAF and aviation fuel consumption by the International Air Transport Association.

The HEFA was certified in 2011 under ASTM D7566 Annex 2 with a maximum permissible blending limit of 50% [14]. Neat HEFA can be used as aviation fuel with further technological advancements. The HEFA is produced from waste cooking oil, animal fats, vegetable oil, algal oil, and pyrolysis oil. The process involves hydrocracking and isomerization of free fatty acids. The oil is first hydrogenated at 393–493 K and 10–50 bar hydrogen over nickel catalysts to saturate triglycerides [16]–[18]. The saturated triglycerides are then converted to free fatty acids via hydrolysis, which, upon hydrodeoxygenation (HDO) and decarboxylation, produces C_{16}–C_{18} hydrocarbons [19], [20]. These straight-chain paraffins are further subjected to hydro-isomerization and cracking to obtain C_9–C_{16} SAF [13], [16]. Recently, hydrocarbon hydro-processed esters and fatty acids (HC-HEFA) from algae (Botryococcus braunii) was certified under ASTM D7566 Annex A7 with the maximum blending limit of 10%, which does not conflict with food security [21]. On the other hand, the AtJ process involves: 1) dehydration of small-chain alcohols (C_1–C_4) to olefins, 2) oligomerization of olefins, and 3) hydrogenation of oligomerized olefins into SAF. AtJ was certified in 2015 under ASTM D7566 Annex A5 with a blending limit of 50% [12], [13]. AtJ is currently limited to ethanol and can be extended up to C_5 alcohols with technological advancements [22]. In particular, isobutanol is known to produce aromatic components, which are useful for enhancing the valve sealing within the engine [13]. However, AtJ-derived SAF possesses low energy density, which makes it suitable only for short-haul flights.

The HFS produces iso-paraffin-rich SAF by hydroprocessing of biomass-derived farnesene ($C_{15}H_{24}$) [16]. The process involves sugar fermentation using genetically engineered yeasts, followed by its hydrogenation to farnesane ($C_{15}H_{32}$). In 2014, the HFS was certified under ASTM D7566 Annex A3 with 10% blending limit [12], [13]. The farnesane has high energy density with combustion characteristics comparable to Jet A [13], [23]. However, the blending is limited due to its long carbon chain and high viscosity [12]. The projected cost of HFS is €4000 per ton, which is the highest among the SAF production routes [24]. Conversely, the PtJ combines carbon capture, electrolysis, and FT reaction [12]. The captured CO_2 and electrolysis-derived hydrogen are subjected to the reverse water gas shift reaction to produce syngas. The syngas can also be produced from CO_2 and H_2O using a renewable energy-powered solid oxide electrolysis cell [25]. The FT reaction then converts syngas into hydrocarbons, which, upon downstream processing, produce SAF. However, high electricity demand is a major bottleneck in PtJ.

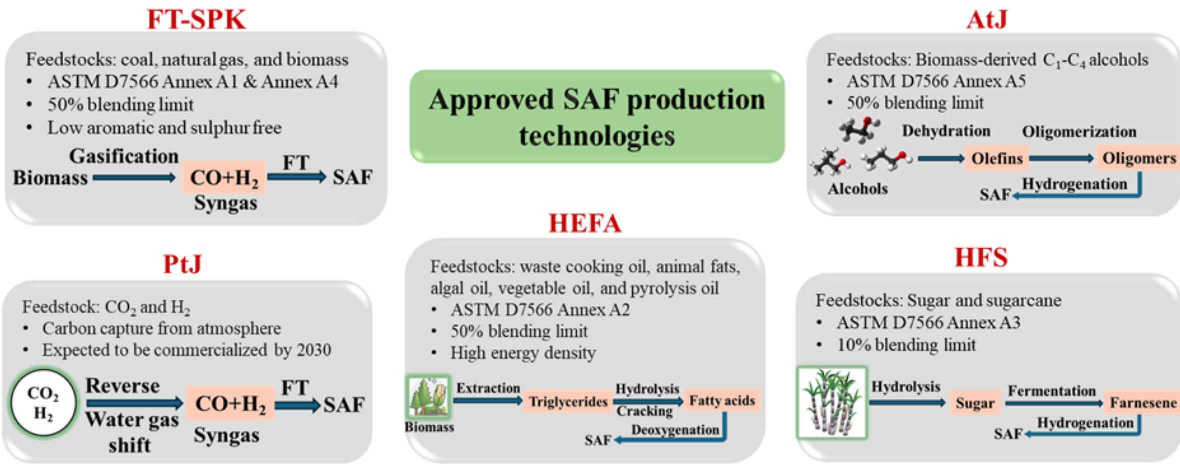

Figure 2: ASTM-approved SAF production pathways.

Upcoming pathways. In recent years, numerous researchers have proposed several new SAF production routes using biomass-derived platform chemicals [26]. For instance, furfural and 5-hydroxymethyl furfural are the prominent platform chemicals formed by cyclo-dehydration of xylose and hexose, respectively. However, these platform chemicals have only 5–6 carbon atoms in their structure, well below the number required for SAF. These new approaches thus involve C-C coupling reactions for enhancing carbon chain lengths by alkylation, hydroxyalkylation-alkylation, aldol condensation, and ketonization [1], [27], [28]. While hydroxyalkylation-alkylation reaction occurs at a moderate reaction temperature in the presence of acid catalysts, the ketonization involves condensing two carboxylic acids with the release of CO_2 and H_2O [29]. The C-C coupled product is then deoxygenated to the SAF-range alkanes over metal-supported catalysts [27], [28]. These routes can also produce branched and cyclo-paraffin-rich SAF with better fuel properties than linear paraffin and aromatics.

Challenges and future directions of SAF. While SAF has tremendous potential, significant research efforts are needed to address technical, social, and economic challenges, and this effort should not compromise soil fertility, food security, deforestation, and biodiversity [30]. The uninterrupted supply of biomass is the major barrier. The production cost of SAF is €0.88–1.09 per litre via HEFA and €1.43–1.87 per litre via FT-SPK, depending on the feedstock, which is only 2–8% higher than aviation fuels [16], [31]. The HEFA represents the leading and commercially developed SAF, while FT-SPK is rapidly gaining ground. The costs can be reduced further through process optimization and technological improvements. However, the cost of the feedstock, biomass supply chain, and policy support from governments and international organizations are also extremely important for the growth of the nascent SAF industry [32]. The scaling up of the SAF processes hinges on the effective alliance among biomass suppliers, transporters, SAF manufacturers, policymakers, and airlines. The collaboration overcomes the challenges associated with the manufacturing technology, logistics, and economic barriers for large-scale SAF production, which will lead to achieve circular economy [33].

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