



# Catalytic production of aviation jet biofuels from biomass: a review

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## Abstract

The aviation sector is a major emitter of fossil fuel-derived carbon dioxide contributing to global warming. For instance, jet fuel consumed by the aviation industry is 1.5–1.7 billion barrels per year, resulting in 705 million metric tons of carbon dioxide emissions. Aircraft manufacturers have set ambitious goals, aiming for carbon-free growth post-2020 and a 50% reduction in greenhouse gas emissions by 2030. This issue can be solved by replacing fossil fuels with biofuels produced from modern biomass, thus meeting the carbon neutral objective. Here, we review the technologies to convert biomass into jet biofuel with focus on reactants, catalysts, and the chemistry of combustion. Reactants include alcohols, oil, esters, fatty acids, gas and sugars. Catalysts include Fischer–Tropsch catalysts, palladium, platinum, ruthenium, nickel, and molybdenum. The utilization of jet biofuels could potentially reduce greenhouse gas emissions by up to 80%. We also discuss economic implications.

**Keywords** Advanced biofuel pathways · Biomass conversion · Jet biofuel · Catalytic conversion · Combustion chemistry · Sustainable aviation fuel

## Abbreviations

ASTM	American Society for Testing Material	HEFA	Hydroprocessed esters and fatty acids
ATJ-SPK	Alcohol to jet-synthesized paraffinic kerosene	HRJs	Hydroprocessed renewable jet fuel
CHJ-SPK	Catalytic hydrothermolysis jet-synthesized paraffinic kerosene	IATA	International Air Transport Association
FAME	Fatty acid methyl ester	ICAO	International Civil Aviation Organization
FT-BTL	Fischer–Tropsch biomass to liquid	JSPK	Jatropha synthesized paraffinic kerosene
FT-SKA	Fischer–Tropsch-synthesized kerosene with aromatics	LCFSs	Low-carbon fuel standards
FT-SPK	Fischer–Tropsch-synthesized paraffinic kerosene	SAPO	Silicoaluminophosphates oxides
HDCJ	Hydrotreated depolymerized cellulosic jet	SIP-SPK	Synthetic <i>iso</i> -paraffins-synthesized paraffinic kerosene
		STEPS	Stated policies scenario

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## Introduction

Air transportation is a cornerstone in fostering global connectivity, facilitating extensive travel, and bolstering commercial operations. Recent decades have witnessed an unprecedented surge in the aviation industry's expansion, as indicated by data from the International Air Transport Association (IATA) [1, 2]. As of June 2022, global air passenger demand showcased a robust recovery post the coronavirus disease19 pandemic, witnessing a remarkable surge of 76.2% in revenue passenger kilometers on an annual basis [3, 4]. This resurgence, notably in the Asia Pacific markets, forecasts a significant rejuvenation in global passenger travel [5, 6]. Projections foresee a doubling of air travelers in the coming years, consequentially leading to an equivalent rise in aviation fuel consumption. This trajectory sets forth a concerning escalation in emissions of climate-altering gases, heightened reliance on conventional jet fuel derived from petroleum, and an exponential surge in carbon dioxide emissions into the atmosphere [7]. Notably, carbon dioxide emissions in 2021 accounted for over 2% of global emissions, with aircraft emissions reaching approximately 720 million metric tons post the coronavirus disease19 lockdowns [8]. Forecasts indicate a continued rapid rise in these emissions, surpassing 2019 levels. The exponential growth in air travel inevitably raises environmental concerns, chiefly regarding carbon emissions. The aviation industry's surge post-pandemic significantly contributed to global emissions, particularly carbon dioxide, with an anticipated trajectory surpassing pre-pandemic levels.

Aviation fuels are categorized into two primary types: jet fuel and aviation gasoline. Jet fuel, conforming to American society for testing material ASTM D1655 standards, is predominantly utilized by commercial flights powered by turbine engines. Conversely, aviation gasoline, possessing slightly different specifications from jet fuel, is used by light helicopters and small planes flying below 6000 m [9]. Conventional jet fuel production involves distilling crude oil within the temperature range of 205–260 °C. The physicochemical properties of jet fuel are intricately tied to its composition, comprising diverse hydrocarbons such as alkanes, *iso*-alkanes, naphthenic or naphthenic derivatives, and aromatic compounds [10]. Jet fuel serves dual roles beyond merely providing energy for flight, acting as both a hydraulic fluid and a cooling medium for aircraft engines [11].

Fuel costs represent a substantial portion, approximately 24%, of the overall operating expenses within the global aviation sector as of June 2022. The average price per barrel of brent crude oil stands at \$101.2, contributing significantly to these expenses [12, 13]. Projections from

the U.S. energy information administration have consistently forecasted an annual increase in the average jet fuel price by 2.7% until 2050, despite the expected decline in global jet fuel usage. The USA' substantial utilization of aviation fuel plays a role in this pattern [14]. Annually, the aviation industry consumes between 1.5 and 1.7 billion barrels of jet fuel, leading to an estimated emission of 705 million metric tons of carbon dioxide globally [15]. Most aviation emissions, approximately 80%, stem from long-distance flights, contributing to only 12% of the overall transportation emissions [16]. Over the last few decades, the aviation industry's contribution to global warming has steadily increased at an average annual rate of 3.6%, a trend expected to persist with global population growth [17].

Without considerable technological advancements or procedural improvements in engine technologies and flight operations, carbon dioxide emissions from jet fuel are projected to escalate by the year 2050 [18, 19]. Consequently, many aircraft manufacturers have set ambitious targets, aiming for carbon-free expansion since 2020 and targeting a 50% reduction in greenhouse gas emissions by 2030. Enhancing fuel efficiency and adapting aircraft engines can contribute to a yearly 1.5% reduction in greenhouse gas emissions. However, achieving substantial emissions reduction necessitates the widespread adoption of biofuels. Integrating biofuels into jet aircraft could markedly decrease aviation carbon dioxide emissions by 2050.

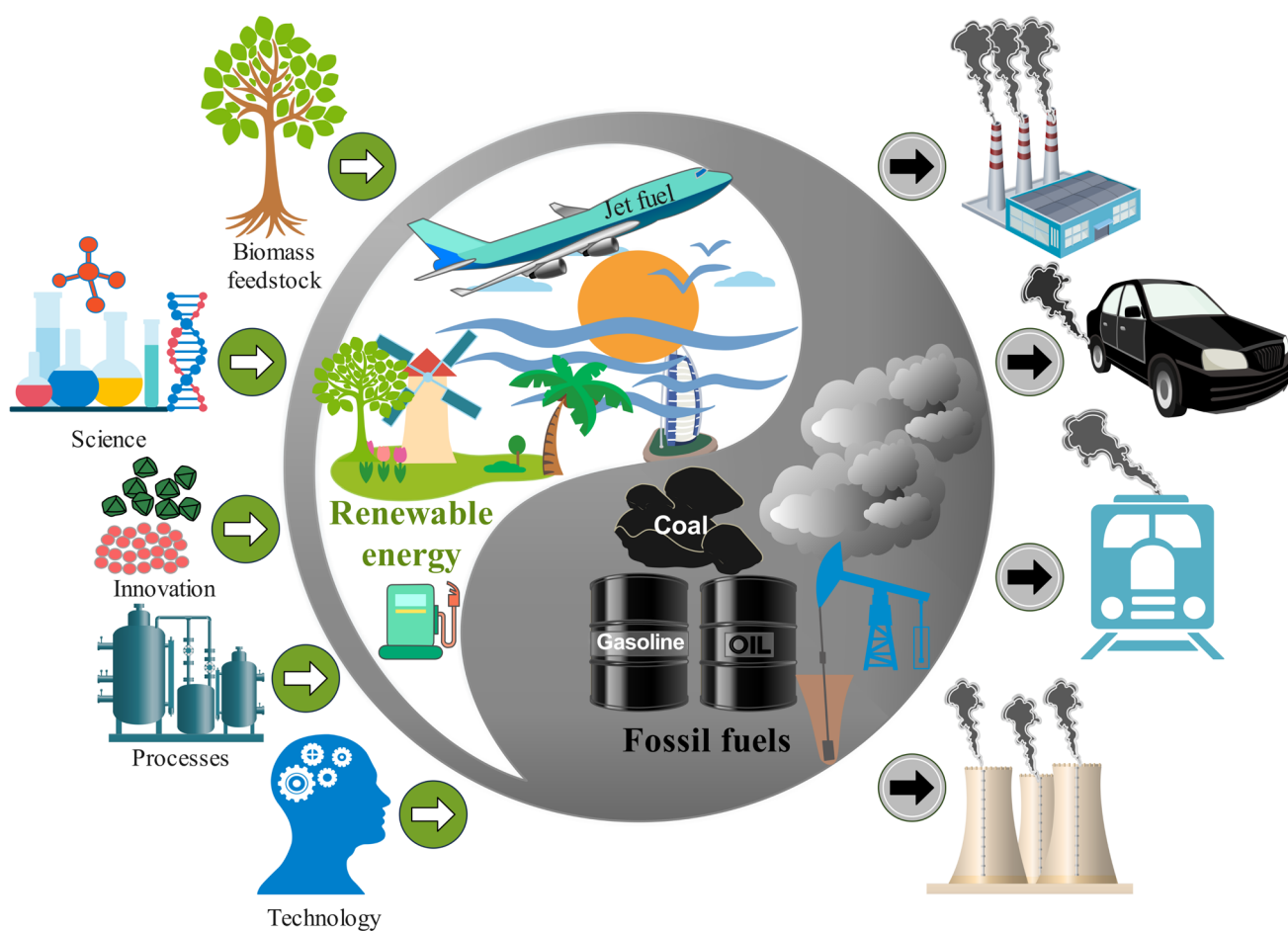
The aviation industry's heavy reliance on fossil fuel-based jet fuel has sparked global concerns regarding its environmental footprint [20, 21]. Biomass-derived resources offer a compelling alternative, potentially reducing carbon dioxide emissions by up to 80% throughout their life cycle. Among these alternatives, jet biofuels, sourced from biomass, stand out as an intriguing solution for aviation fuel needs [22, 23]. Depending on the specific biomass used, jet biofuels exhibit significant potential in curbing carbon dioxide emissions, with some variants emitting up to 85% fewer greenhouse gases per unit of energy than conventional jet fuel [24].

Biomass is a renewable source for generating biofuels, but its sustainability is highly dependent on the type of feedstock used and the production methods [25–27]. Similarly, biofuels derived from biomass hold substantial promise for aviation, a widely utilized mode of travel. Any biomass containing carbohydrates, whether from plants or animals, holds the potential as an energy source [28]. Notably, alternative jet fuels have gained increased attention, evidenced by the growing body of literature featuring keywords like “jet biofuel” or “biofuels aviation” [9, 29, 30]. The global focus on energy security has elevated the role of biomass in the energy matrix, influencing aspects such as politics, economics, technology, food security, and the environment [31, 32]. Among the green technologies, the biomass-to-liquid

pathway is a promising method for producing bio-based chemicals, fuels, and energy, integrating biochemical and thermochemical technologies [33, 34].

This review aims to provide a detailed analysis of the latest breakthroughs in jet biofuel production, explicitly focusing on catalytic conversion and pathway technologies. It offers critical insights into the performance, selectivity, and challenges catalysts face within each category, shedding light on using biomass feedstock as a sustainable and renewable resource for jet biofuel synthesis. Despite extensive research on alternative jet fuel combustion properties, there is a notable scarcity of studies investigating the potential of biomass feedstock as a viable source for jet biofuel production. This review highlights the existing challenges

and limitations associated with various jet biofuel production methods, underscoring the urgent need for innovative approaches and potential enhancements in this burgeoning field. In addition to addressing the advancements in jet biofuel production, this review recognizes the crucial role of these alternative fuels in combating climate change and achieving net-zero emissions. The integration of biomass feedstock as a renewable resource for jet biofuel synthesis offers a sustainable alternative and aligns with the global push for decarbonization and achieving ambitious climate targets. As the world strives to mitigate the impacts of climate change, this review underscores the urgent need for continued research, innovation, and collaboration to unlock the full potential of jet biofuels and pave the way toward a



**Fig. 1** Utilizing biomass feedstock as a sustainable and renewable resource for synthesizing jet biofuel. This diagram illustrates the utilization of technology and novel catalysts in various processes to convert diverse biomass feedstocks into jet biofuel. Advanced technological approaches are being employed to harness the energy potential of biomass sources such as algae, waste oils, lignocellulosic materials, and agricultural residues. These technologies encompass innovative pathways like alcohol-to-jet, gas-to-jet, sugar-to-jet, and oil-to-jet processes, each requiring specific catalysts for efficient conversion. Novel catalysts, including zeolites, metal oxides, and supported metal

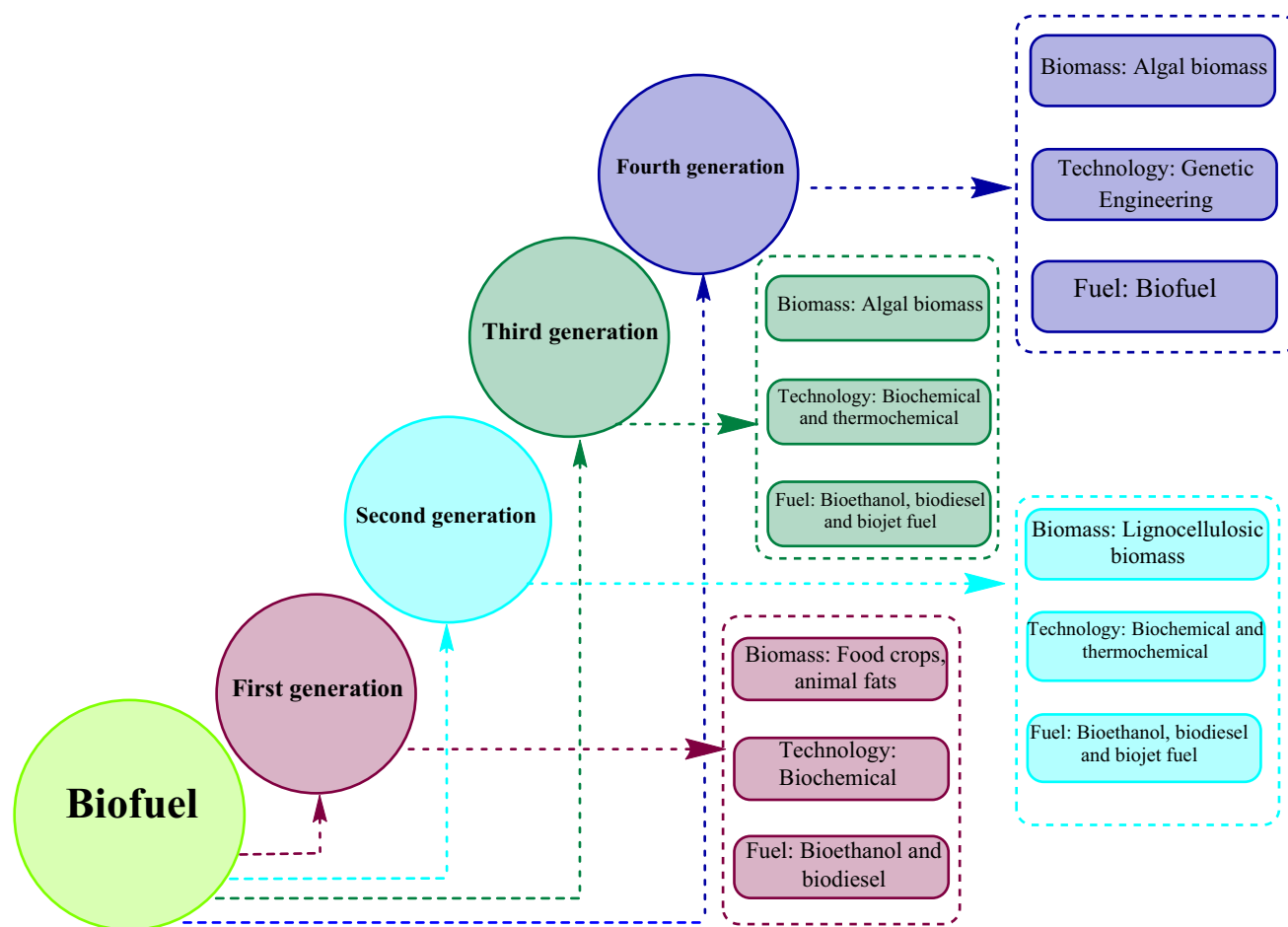
nanoparticles, are instrumental in facilitating the conversion of biomass feedstocks into high-quality jet biofuel with improved yields and reduced energy consumption. This statement acknowledges the vital importance of these alternative fuels in addressing climate change and attaining a state of economic equilibrium with no emissions. Due to the aviation industry's substantial role in greenhouse gas emissions, using jet biofuels produced from sustainable biomass feedstock offers a promising approach to decreasing carbon footprints. It highlights their potential to expedite the shift toward a more environmentally friendly aviation sector

more sustainable and environmentally conscious future, as shown in Fig. 1.

## Biofuel production

Biofuel is a fuel made from biomass, which can exist in solid, liquid, or gaseous forms [35, 36]. The biomass source determines whether it is classified as a primary or secondary biofuel. Primary biofuel materials, like sawdust, pellets, and discarded food, are applied to their original state without undergoing any treatment to produce energy and

heat [37–39]. Secondary biofuels are refined versions of primary biofuels that have undergone treatments and modifications to produce desired outcomes [35, 40, 41]. Secondary biofuels are characterized as first, second, third, or fourth generation based on the type of biomass feedstock and the production process utilized to create them [42–44] as presented in Fig. 2. Bioethanol and biodiesel, considered first-generation biofuels, are produced from agricultural by-products and animal fats [45–48]. The first generation of biofuel can be called conventional biofuel because of the fermentation technology used in its production. Before corn can be considered suitable for ethanol production, it



**Fig. 2** Biofuel generations. Biogenic fuels are classified into several generations based on the type of biomass feedstock, the treatment technology used, and the resulting fuel. The categorization of biofuel generations aids in differentiating various technologies and their sustainability characteristics. First generation is derived from food crops, including corn, sugarcane, and vegetable oils, which generate biofuels such as ethanol and biodiesel. Although these biofuels have played a crucial role in diminishing dependence on fossil fuels, issues related to food security and land-use change have led to a transition toward second-generation biofuels. Second-generation biofuels originate from non-food biomass sources such as agricultural residues, wood, and energy crops. Cutting-edge technologies like biochemical and

thermochemical processes are utilized to transform these feedstocks into biofuels, promoting enhanced sustainability and minimizing competition with food production. Third-generation biofuels emphasize the use of algae as a feedstock, showcasing significant productivity and the potential for carbon capture. These biofuels may address the land-use challenges linked to first and second-generation biofuels. Conversely, fourth-generation biofuels are produced by genetically modifying algae. The progression of biofuel generations indicates a shift toward more sustainable and efficient production techniques, addressing environmental issues and aiming for enhanced energy security moving forward

must undergo several pretreatment procedures [49, 50]. In contrast, using an edible source to produce jet biofuels through the biochemical method is highly unfavorable since it does not contain enough carbon and does not adhere to the required standards.

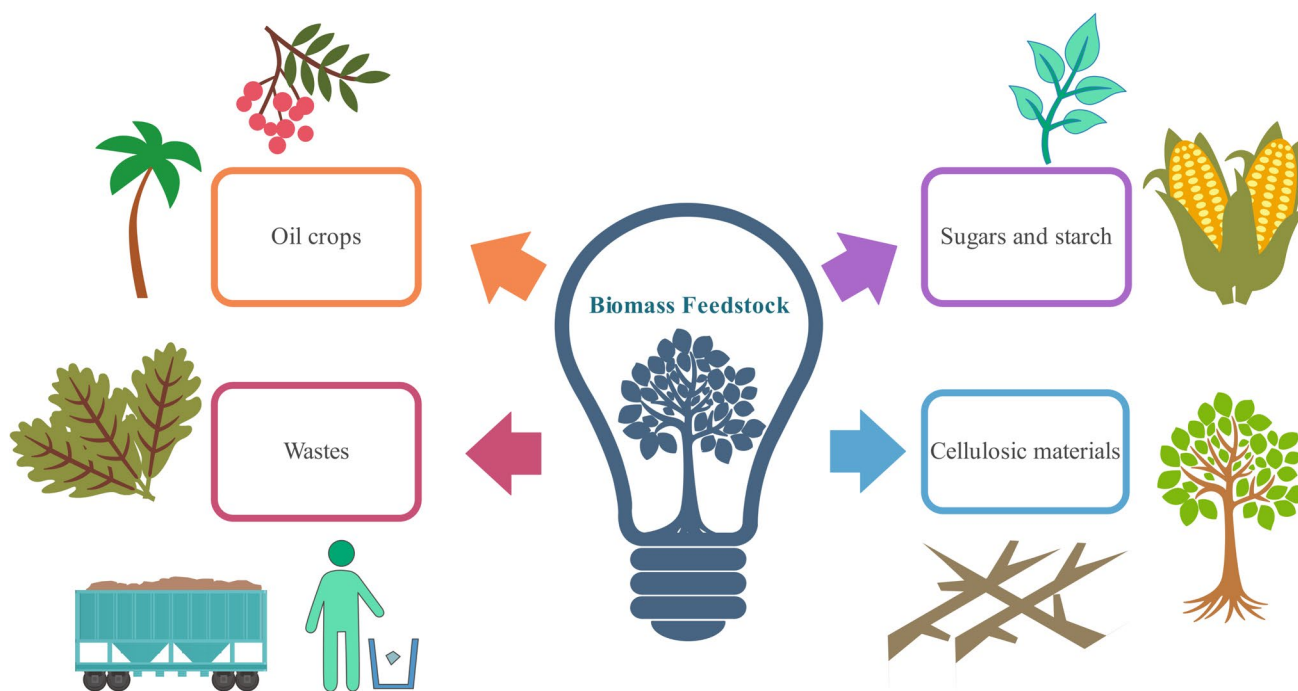
Non-food sources such as waste cellulosic and lignocellulosic biomass, oil crops, and organic waste are used to create second-generation biofuels [51, 52]. These feedstocks significantly improved over their predecessors, which had their own set of problems. They are high in fatty acids and are easily treatable through biochemical or thermochemical methods. Biochemical approaches involve enzymes to break down complex cellulosic materials into simpler monomers, whereas thermochemical methods use heat to transform biomass into compounds rich in hydrocarbons and aromatics [53]. These feedstocks' polysaccharides contain significant sugar, making them ideal for biofuel production. While biofuel demand continues to rise, agricultural by-products can only meet a fraction of that demand at best [54]. Hydrolysis and fermentation are required to convert lignocellulosic material into bioethanol [55]. Both gasification and fermentation, or catalyzed reactions, are utilized as thermochemical processes to create bioethanol [56]. Biodiesel, on the other hand, has gained popularity as a renewable fuel with great potential because of its biodegradability, sustainability, and ability to lessen pollution emissions. Biodiesel offers several advantages over conventional petroleum-based fuels. Most biodiesel is made through transesterification, which may be applied to various feedstocks [57, 58]. Besides biomass, industrial waste streams or by-products, including tall crude, sediments and acid oil, can all serve as hydrogenation feedstock to produce jet fuel. Second-generation biofuels are better suited for long-term use without compromising food security. Using lignocellulosic biomass as a renewable replacement for petroleum is the best choice that meets ASTM requirements.

Third-generation biofuels derived from algae have received much interest because of their scalability, capacity to sequester carbon dioxide, and refining simplicity [44, 59]. Algal biomass cultivation has the advantage of not endangering global food and freshwater resources, whether in open ponds of seawater or on dry land (closed culture systems) [60]. Algal biomass can be converted into biofuel using both biochemical and thermochemical processes. Jet biofuel is typically produced from algae using a thermochemical process, with the co-occurring pyrolysis and deoxygenation processes. However, producing high-quality jet biofuel from algal biomass is possible via a biochemical technique comprising transesterification followed by a hydrogenation process [61, 62]. Biofuel yields can be increased through the use of genetically modified algae in the manufacture of fourth-generation biofuels. Although genetically modified algae biofuels have gained

popularity as an alternative to fossil fuels, concerns about their impact on the environment and human health persist [63]. Fourth-generation biofuels refer to the production of biofuels through genetic engineering of algae. Biomass from microalgae, macroalgae, and cyanobacteria is utilized to produce fourth-generation biofuels [64]. Both enclosed and open systems can be used to cultivate genetically modified microalgae, but each approach presents unique challenges. The enclosed cultivation approach minimizes containment and environmental exposure and provides a more strictly regulated environment. Despite providing superior protection, the confined cultivation system has a significant initial cost. In summary, contemporary biofuel production methods encompass several techniques, including biochemical and thermochemical conversion of biomass feedstocks such as lignocellulosic materials, algae, and waste oils into biofuels. Sophisticated methods consisting of enzymatic hydrolysis, microbial fermentation, catalytic upgrading, and pyrolysis are being employed to enhance the efficiency and production of biofuels.

## Biomass feedstock for jet biofuel

Jet biofuel consists of *n*-paraffins, cyclic alkanes (naphthenes), branching *iso*-alkanes (*iso*-paraffins) and aromatics. However, the fuel's molecular weights and carbon numbers can be considerably impacted by factors such as the refining process and the fuel's unique quality and use. Jet fuel typically has a molecule size distribution between  $C_8$  and  $C_{16}$  [63, 65]. Renewable feedstock biomass, among others, is being studied to replace fossil fuels with biofuels for use in aircraft [66]. As illustrated in Fig. 3, there are typically four types of biomass feedstocks used in manufacturing jet biofuel: sweeteners and lipid sources, oil crops, cellulosic materials, and by-products. When selecting a feedstock, accessibility is a crucial factor, and it is related to the potential output of the cultivated feedstocks. The first-generation group comprises edible food crops, such as wheat, sugarcane, sugar beets, corn, and oil palm [67, 68]. The deoxygenation technique is used to produce biofuel from palm olein, palm-based waste cooking oil, palm kernel oil, and other kinds of palm oil [69]. To assess the efficiency of producing hydrocarbons for jet fuel, they used different catalyst loadings and deoxygenation catalyst types, such as zeolite, calcium oxide CaO, palladium Pd/C, vanadium oxide  $V_2O_5$ , and titanium dioxide  $TiO_2$ , for 2 h at 400 °C. The maximum molar concentration of liquid products, including olefins, *n*-paraffins, *iso*-paraffins, naphthenes, and aromatics, were obtained from the deoxygenation of palm kernel oil using more than 8% weight of palladium Pd/C, with 73% selectivity for jet paraffins  $C_8$ - $C_{16}$  [70].



**Fig. 3** Biomass feedstock for jet biofuel. Multiple biomass feedstocks present significant potential for jet biofuel production, providing various sources for the synthesis process. The feedstocks include a diverse array of materials, such as agricultural residues like corn stover, wheat straw, and sugarcane bagasse; forestry residues including wood chips and sawdust; dedicated energy crops like switchgrass and miscanthus; as well as algae and waste oils and greases from food and industrial processes. Each biomass feedstock has distinct traits and obstacles regarding its availability, processing needs, and sustainability factors. Agricultural residues are plentiful by-products of farming activities and provide a sustainable source for biofuel pro-

duction. Forestry residues represent a notable feedstock source, using wood waste generated from logging and timber activities. Energy crops are cultivated to produce biofuels, showcasing significant biomass yields and promising conversion efficiency. Algae exhibit rapid growth rates and possess a high lipid content, making them a promising feedstock for jet biofuel production. Furthermore, waste oils and greases have the potential to be converted into jet biofuel, aiding in the reduction of waste and enhancing resource efficiency. The use of various biomass feedstocks highlights the flexibility and adaptability of biofuel production methods, enabling a sustainable and varied strategy for jet biofuel synthesis

According to a study by Kumar, Long [71], sugarcane, the most widely grown crop globally, has been changed genetically to increase its lipid content. This modification has made it possible to produce significantly superior yields of commercial vegetable oil per acre than those seen in the past. This article examines the potential for making jet fuel from this innovative, highly productive, and cheap feedstock. Hydrotreated jet fuel from ethanol and lipids are produced in a biorefinery, and the production of both fuels was modeled using a SUPERPRO designer. Approximately 1,600,000 metric tons (MT) of lipid cane can be processed annually. The biochemical conversion of lignocellulosic biomass into jet fuel is a complex, multistep process that encounters numerous obstacles. Lignocellulosic biomass is intrinsically resistant because its lignin component obstructs enzyme access to cellulose and hemicellulose. This requires expensive pretreatment techniques to deconstruct the biomass structure and enhance its suitability for enzymatic hydrolysis. The procedure generally encompasses pretreatment, enzymatic hydrolysis to transform cellulose and hemicellulose into fermentable sugars, fermentation to produce

ethanol, and, ultimately, substantial upgrading processes to convert ethanol into jet fuel. Each stage poses distinct scientific and economic obstacles, such as the requirement for efficient enzymes, ideal fermentation conditions, and effective upgrading technologies. However, to convert lignocellulosic waste feedstock into ethanol, a pretreatment (hydrolysis) is necessary to remove the sugar [72, 73]. Lignocellulose can be turned into ethanol via a biological method, which is then upgraded to jet fuel [74, 75]. Improved upon simulations provided by Petersen and Aneke [76], this study modeled the processes of pretreatment conditioning, hydrolysis and fermentation, steam and power generation and evaporation. Most lignocellulosic biomass is made up of lignin, which has excellent potential as a feedstock in this pathway for manufacturing cyclic alkanes and aromatics using processes like catalytic pyrolysis, hydrogenation, rapid pyrolysis and oxidation [77, 78]. Hydrogenating aromatic  $C_8$ – $C_{15}$  hydrocarbons allowed Bi, Wang [79] to show that the process of turning lignin into hydrocarbons that can be used in jet fuel and diesel fuel includes making  $C_8$ – $C_{15}$  aromatic compounds by breaking down lignin into low-carbon  $C_6$ – $C_8$  aromatic

monomers and then alkylating these aromatics. One more part of the process is hydrogenating aromatics to provide both cycloparaffins and aromatic C<sub>8</sub>–C<sub>15</sub> hydrocarbons.

Zhang, Fan [80] reported that aviation oils have two main hydrocarbon types: alkanes, alkenes, polycyclic and monocyclic aromatic hydrocarbons. Conventional, microwave and solar-aided pyrolysis all provided considerably different yields of aviation oils, ranging from 10.9 to 90.5 wt%, 15.34 to 98.3 wt%, and 6.1 to 87 wt%, respectively. Abu-Saied, Taha [72] utilized green technologies, namely autoclaving, microwaving, and sonication, for the pretreatment of cellulosic fiber waste before enzymatic hydrolysis. The researchers improved the best conditions for aerobic/anaerobic, inoculum size, temperature and pH settings. The best method for improving bioethanol production rates was found to be growing the yeast isolate 10% at 25 °C and pH 5 via anaerobic conditions (33.9%). Han and Sun [81] investigated the conversion of readily available lignocellulose molecules, 5-hydroxymethylfurfural and furfural, to the furanics 2,5-methylfurfural and 2-methylfurfural, respectively. Before hydrodeoxygenation, which reduces the oxygen concentration of fuel fractions, lengthening the carbon chain is the first step. This is because diesel fuel molecules contain more carbons than the molecules of these furans. Waste biomass can be categorized as agriculture and forestry wastes, as well as municipal and food wastes. However, the primary obstacles to using these conversion technologies are their high costs and technical limitations [54, 82]. Despite these challenges, utilizing waste biomass offers significant benefits; circular economies, waste management, and environmental protection are just a few examples [83]. Thermochemical and biochemical techniques can be used to produce biofuels from various wood energy crops and grass [84]. Elephant grass, miscanthus, and switchgrass are promising sources of raw materials for developing both liquid and solid biofuels [85, 86]. Nevertheless, systematic investigations into their conversion to jet biofuel are scarce or non-existent in the literature. Woods have cheaper transportation costs and a higher biomass supply per area than grasslands, making them a preferable option for feedstock [67, 87].

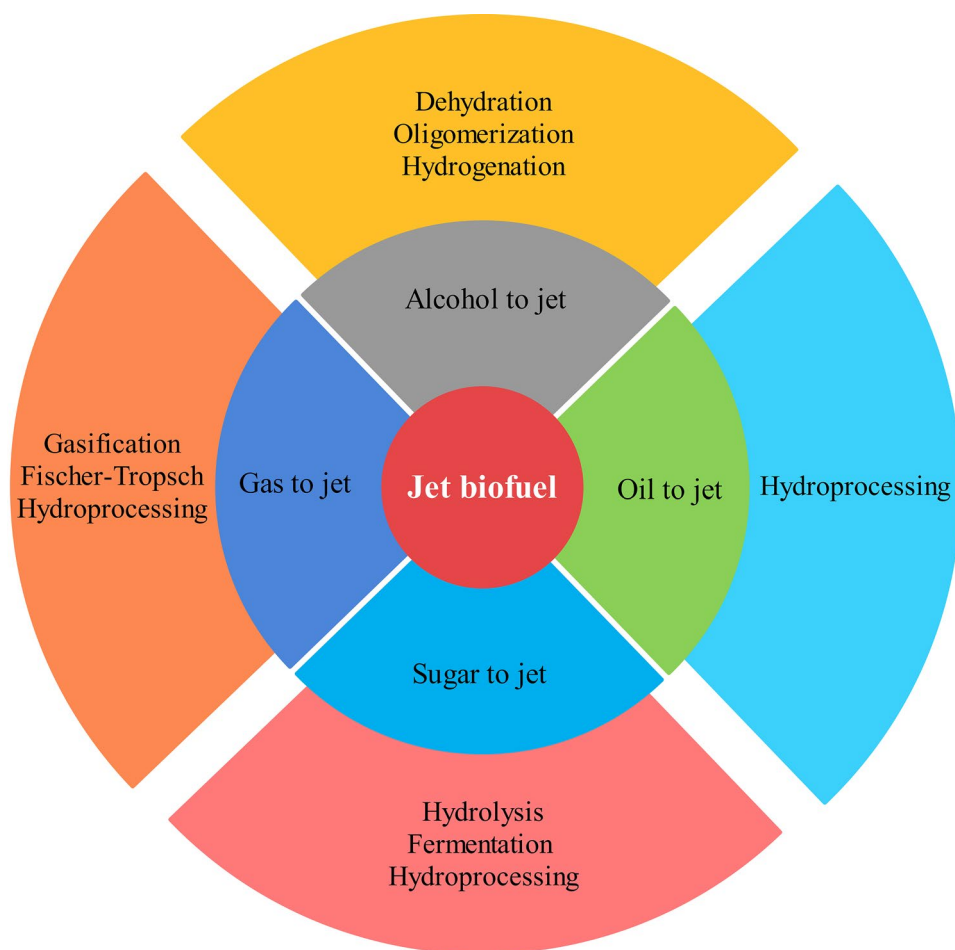
Poplars, a genus of perennial temperate trees, are a promising biofuel feedstock. Recent investigations have demonstrated that hydrogenation can transform hydrocarbons derived from poplar biomass, produced through pyrolysis and fermentation, into jet fuel [88, 89]. Meanwhile, willows, a group of perennial blooming trees, can be found in natural forests, agroforestry systems, and plantations and are a promising source of jet fuel precursors such as alcohols [90], syngas [91], and pyrolysis oil [92]. Several experimental investigations have shown that willow biomass can be efficiently converted into these precursors for jet fuel production. Palm oil, the most inexpensive vegetable oil, is considered an alternative to hydrogen due to its high price

tag in manufacturing hydroprocessed esters and fatty acids (HEFA). This has led to an increase in the popularity of using oil palm as a feedstock to produce bio-aviation fuel [70]. The oil content of castor bean seeds and jatropha, by weight, is roughly 30–40% and 50–60%, respectively [88, 93]. Hydrocracking castor bean and jatropha oils has been proposed by Molefe, Nkazi [94] to boost the generation of bio-aviation fuel. The existing literature suggests that jatropha has been investigated more extensively than castor bean [95, 96]. However, transporting, collecting, and storing significant quantities of biomass wastes, including municipal solid waste and animal manure, pose health and safety risks [97]. Another obstacle to waste biomass's sustainable use is its unpredictable supply [98].

In summary, prospective biomass feedstocks for jet biofuel generation have advantages and disadvantages. Lignocellulosic biomass sources offer a sustainable feedstock alternative that does not compete with food production, hence mitigating concerns regarding food security. Algae biomass is distinguished by its high lipid content and rapid growth rates, offering substantial potential for jet biofuel production. Waste oils and fats are advantageous since they can leverage existing waste streams, aiding in waste reduction and resource efficiency. Nonetheless, barriers such as scalable cultivation and economically viable conversion processes for large-scale, efficient pretreatment and refining technologies, enhancing their viability as sustainable feedstocks for jet biofuel production.

## Conversion technologies for the production of jet biofuel

The commercial advancement of developing biofuel technologies in large-scale production facilities has been impeded by financial, regulatory, scalability, technological inefficiency, and regulatory obstacles [99]. Supply chain challenges for feedstock indicate that obtaining a reliable, large-scale biomass supply is a significant obstacle, primarily due to seasonal fluctuations and competition from other sectors. The infrastructure needs are considerable, encompassing not only the primary conversion facilities but also pretreatment plants and hydrogen generation units. The jet biofuel production route uses conversion technologies to transform biomass feedstocks through various processes. As shown in Fig. 4, the different fuel conversion methods may be broken down into four distinct categories: alcohol to jet, oil to jet, gas to jet and sugar to jet. The processes are further divided into thermochemical and biochemical methods. Biomass feedstocks can be obtained from non-edible oil crops, forest residues, municipal solid waste, agricultural residues, and algae. Using a catalyst, thermo-conversion like pyrolysis, gasification, and liquefaction transforms biomass feedstocks



**Fig. 4** Jet biofuel production technology roadmap encompasses a variety of routes that offer distinct pathways for converting biomass feedstocks into sustainable aviation fuel. Among these routes, the alcohol-to-jet process involves the conversion of alcohols such as ethanol or butanol into hydrocarbons suitable for jet fuel applications. This method leverages advanced catalytic processes to achieve efficient conversion with high yields. The oil-to-jet pathway focuses on converting oils derived from various biomass sources into jet fuel components through processes like hydrotreating and hydrocracking. Sugar-to-jet technology involves the transformation of sugars

obtained from biomass feedstocks into hydrocarbons that meet aviation fuel specifications. This route often involves biochemical conversion methods such as fermentation and catalytic upgrading. Additionally, the gas-to-jet route utilizes syngas derived from the gasification of biomass or waste feedstocks to produce hydrocarbon fuels suitable for aviation use. Each of these production methods presents unique advantages and challenges, contributing to the overall roadmap for developing sustainable jet biofuel technologies. The primary objective is to decrease the carbon emissions resulting from aviation fuels and advocate for sustainable substitutes to traditional jet fuels

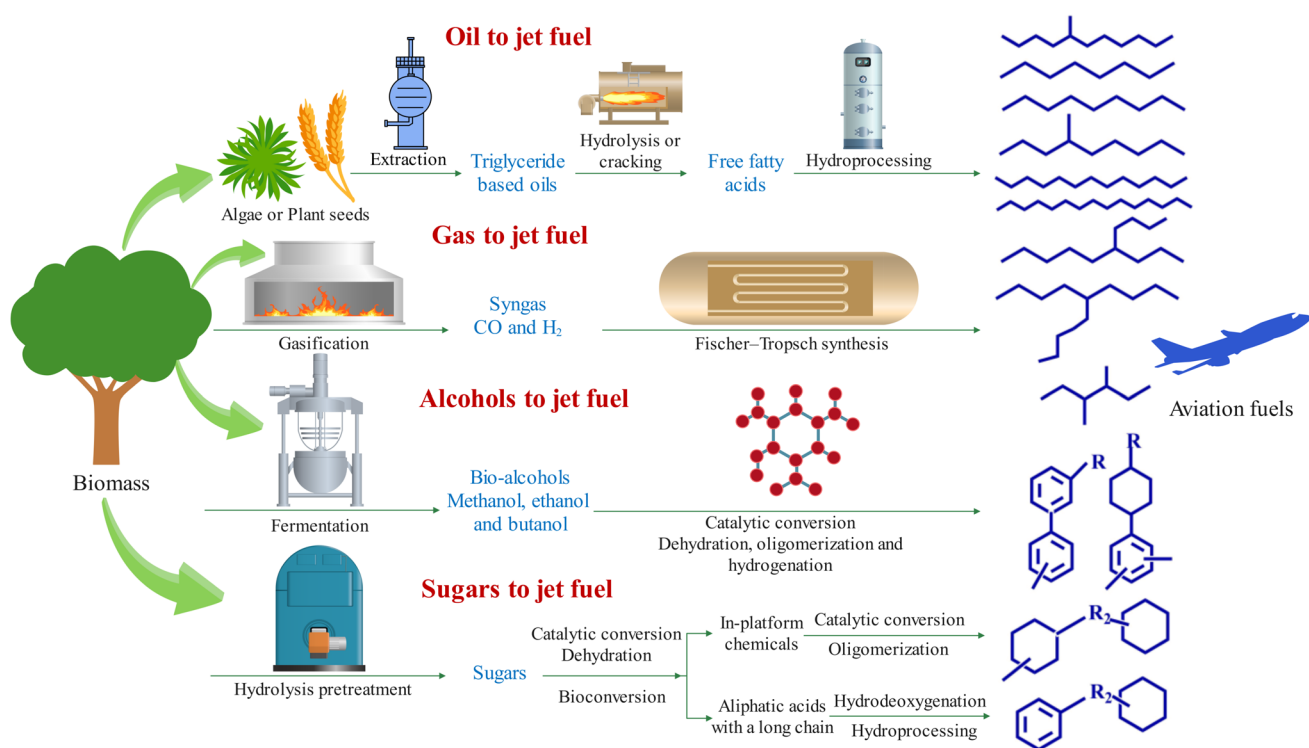
into syngas. Syngas undergoes additional processing via catalytic reactions to create jet biofuel. Figure 5 depicts the bioconversion utilized to manufacture jet biofuel from biomass feedstocks via hydrolysis to yield simple sugars.

### Conversion of alcohol into jet fuel

Alcohol oligomerization, or alcohol to jet fuel, is made by reducing the molecular size of various alcohols such as methanol, ethanol, butanol, and long-chain fatty alcohols [100]. Currently, a blend wall limits ethanol's market share as a gasoline blendstock because most gasoline-powered vehicles can only utilize it up to a maximum of 10–15%. Consequently, a potential route for converting ethanol

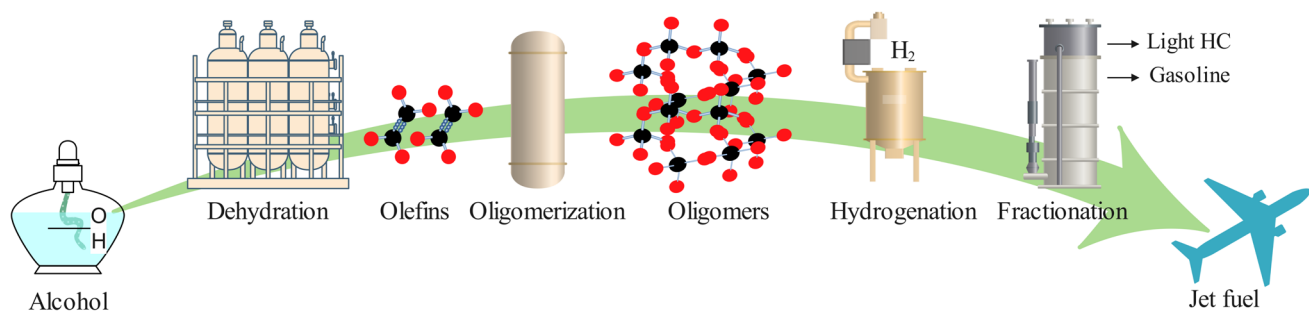
into a jet fuel blendstock is the discovery of drop-in or exchangeable fuels for the jet fuel market. Butanol and ethanol, the two most common alcohols, are the focus of this review because of their widespread use in jet fuel conversion. Alcohols can be used as a drop-in replacement for traditional jet fuel if the differences between their chemical and physical properties are kept to a minimum. The USA mandates a purity range of 99.5–99.9% for anhydrous ethanol added to gasoline to prevent the two from separating [101]. Upgrading ethanol to jet fuel products may require high-purity ethanol; however, this remains debatable. The three-step alcohol-to-jet process, which begins with dehydration and ends with hydrogenation, is used to transform alcohol into jet fuel [102]. The overall process





**Fig. 5** Conversion of biomass into aviation fuels through various pathways involves different processes tailored to each feedstock type. Here is a breakdown of how biomass can be transformed into aviation fuels using different routes. Oil to jet: this pathway involves the conversion of oils and fats, such as vegetable oils or animal fats, into jet fuel through processes like hydrotreating or hydrocracking. These feedstocks can be derived from crops, algae, or waste oils. Gas to jet: this process involves the conversion of syngas (a mixture of carbon monoxide and hydrogen) derived from biomass gasification or other sources into hydrocarbons suitable for jet fuel produc-

tion, typically through Fischer–Tropsch synthesis or other catalytic processes. Alcohol to jet: in this pathway, alcohols such as ethanol or butanol are converted into jet fuel through dehydration and catalytic processes (dehydration, oligomerization, and hydrogenation). These alcohols can be sourced from biomass, waste streams, or renewable sources. Sugar to jet: sugars derived from biomass sources like sugarcane, corn, or lignocellulosic materials can be converted into jet fuel through fermentation, enzymatic hydrolysis, and subsequent conversion processes. CO and H<sub>2</sub> refer to carbon oxide and hydrogen, respectively



**Fig. 6** Alcohol to jet fuel transforms alcohols, such as ethanol or butanol, into jet fuel components. Alcohol undergoes dehydration to eliminate water content, resulting in a more concentrated alcohol solution. Dehydration is a crucial step in converting alcohol into olefins and making it ready for further steps. The dehydrated alcohol is then subjected to catalytic conversion processes to produce oligomers through the oligomerization process. In the hydrogenation process, a hydrogenation catalyst facilitates the conversion of alcohols into

hydrocarbons. Hydrogen gas is introduced into the reaction system as a reactant and acts as a reducing agent. Under suitable reaction conditions (temperature, pressure, and catalyst type), hydrogenation reactions occur, leading to the conversion of alcohols into hydrocarbons. The hydrocarbon mixture obtained from the hydrogenation may undergo further refining processes, such as fractionation, to remove impurities and adjust the fuel properties to meet aviation fuel standards. H<sub>2</sub> and HC refer to hydrogen and hydrocarbon, respectively

for making fuels out of alcohols like ethanol, *n*-butanol and *iso*-butanol is depicted in Fig. 6. Risks involved with scaling up the process have been mitigated thanks to commercial-scale demonstrations of the dehydration, oligomerization, and hydrotreating steps. However, the entire process must be developed and demonstrated using intermediates derived from biomass [103].

Before the introduction of silicoaluminophosphates oxides (SAPO), heteropolyacid catalysts and H-ZSM-5 zeolite research in ethanol dehydration catalysis primarily focused on alumina and transition metal oxides. At 250 °C and 2 h<sup>-1</sup> weight hourly space velocity, 100% of the ethyl alcohol can be hydrolyzed to ethylene with a 99.9% selectivity using a La-2.0% PH-ZSM-5 catalyst [104]. This ethylene production method allows for catalytic oligomerization to linear olefins [105]. Two types of catalysts have been used in commercial oligomerization processes: homogeneous and heterogeneous [106, 107]. In 2002, 680,000 tons of Schulz–Flory-distributed ethylene oligomers were produced by the Chevron Phillips Ziegler one-step technique using the homogeneous Ziegler–Natta catalyst [108]. The optimum conditions for this reaction are 250 bar, 200 °C and 1 × 10<sup>-4</sup> mol of catalyst per mole of ethylene [105]. The main challenge is guaranteeing the scalability of alcohol to jet fuel production to fulfill substantial aviation fuel demands. Technical challenges with attaining requisite fuel quality standards and certification procedures for aviation applications are additional constraints that must be addressed.

### Conversion of oil into jet fuel

The oil-to-jet drop-in alternative jet fuel conversion process is broken down into three sub-pathways in this literature review: pyrolysis, catalytic hydrothermolysis, and hydroprocessed renewable jet, synonymous with hydrotreated esters and fatty acids or HEFA, additionally meaning hydrotreated depolymerized cellulosic jet HDCJ. Only hydroprocessed renewable jet route products have an established ASTM specification and have been approved for blending. Feedstocks for the hydroprocessed renewable jet and catalytic hydrothermolysis processes are triglycerides, although distinct methods are employed to produce free fatty acids. The catalytic hydrothermolysis mechanism uses heat hydrolysis to create free fatty acids, while the hydroprocessed renewable jet process uses propane to cleave glycerides. Pyrolysis of biomass material produces bio-oil. Hydrotreating is similar to catalytic hydrothermolysis, hydroprocessed renewable jet, and pyrolysis. Detailed explanations of each sub-pathway are provided below.

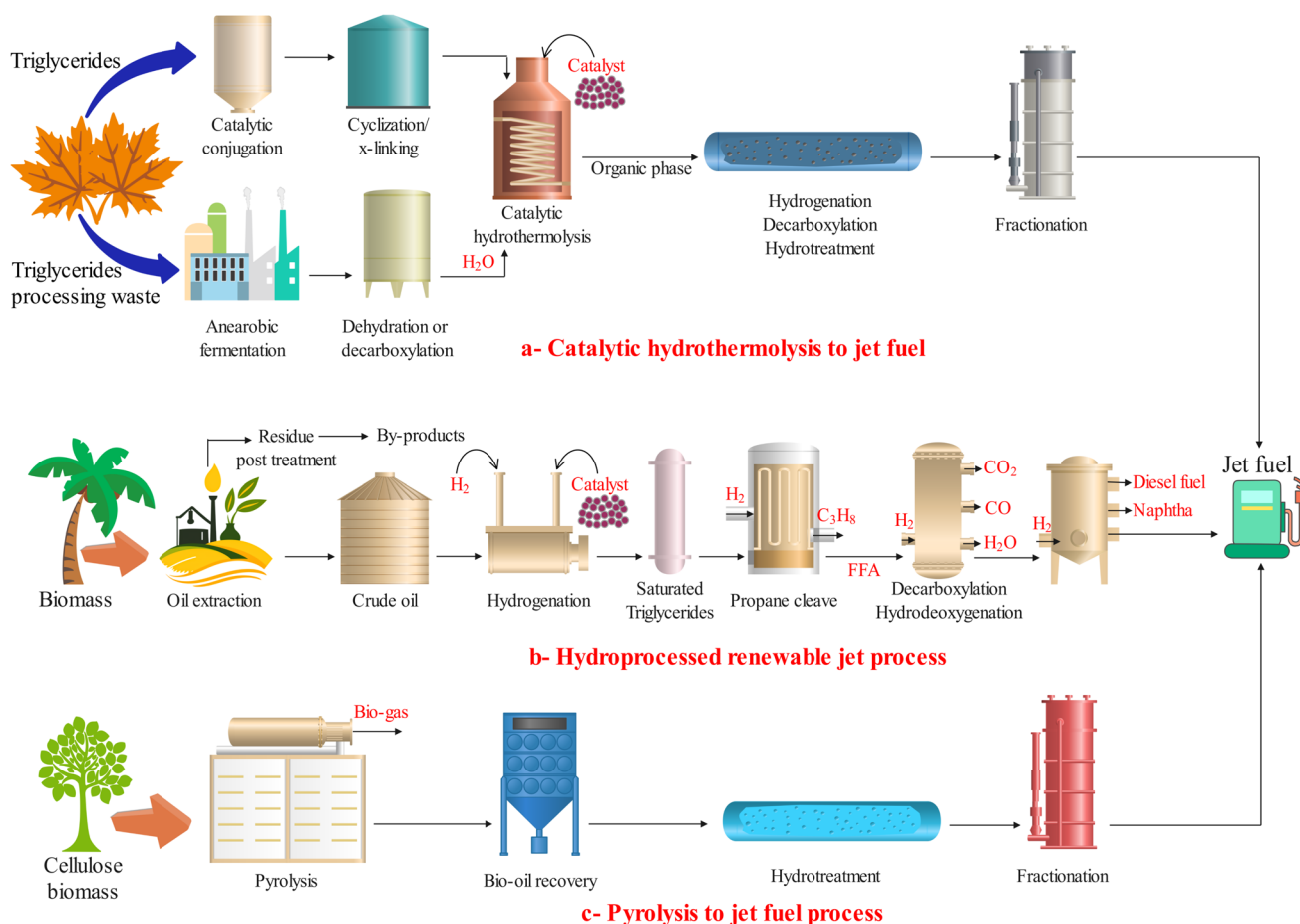
### Catalytic hydrothermolysis

Applied research associates have developed a method to convert algal oils or plants into renewable, fragrant, drop-in fuels; hydrothermal liquefaction, or catalytic hydrothermolysis, was devised and developed. Several processes, including hydrolysis, cracking, decarboxylation, cyclization and isomerization, take place during the hydrothermal method, as shown in Fig. 7, to produce linear, branching, and cyclic hydrocarbons from triglycerides [109]. The catalytic hydrothermolysis reaction is performed with or without a catalyst, with water present at 210 bar and temperatures varying from 450 to 475 °C [109]. Unsaturated molecules, oxygenated species, and carboxylic acids are the final products of decarboxylation and hydrotreatment. Products with carbon atom count between 6 and 28 include aromatics, *n*, *iso*, and cycloalkanes. These products must be decomposed and detached from naphtha, diesel fuel, and jet fuel. To create stable jet fuel that has great cold flow properties and satisfies ASTM and military standards, the catalytic hydrothermolysis process is used. Jatropha, soybean, carinated, camelina and tung oils are only a few of the triglyceride-based feedstocks that can be turned into jet biofuels, according to studies Yakovlieva and Boichenko [110], Eswaran, Subramaniam [111].

### Hydroprocessed renewable jet

The hydroprocessed renewable jet is a commercially viable conversion method with a relatively high maturity level. Recently, it has been used in jet fuel manufacturing for use in military aircraft. Even though hydroprocessed renewable jet gasoline shares many characteristics with conventional petroleum, it also offers the benefits of having a greater "cetane" number, low levels of aromatic compounds, sulfur, and possibly even emissions of greenhouse gases. Figure 7 illustrates a process flow diagram [112]. Catalytic hydrogenation is a method used to convert glycerides or unsaturated fatty acids into saturated forms by adding hydrogen in the liquid state [113].

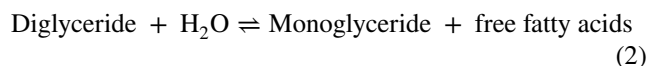
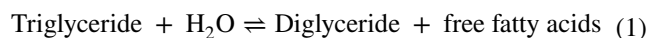
Three moles of free fatty acids are generated during propane cleavage, and the glycerol portion of the triglyceride molecule is converted into propane with the addition of hydrogen H<sub>2</sub> [112]. As can be seen in Eqs. 1–3, thermal hydrolysis is another technique for converting glycerides into free fatty acids [114]. Fatty acids and oils with high triglyceride content can be transformed into one mole of glycerol and three moles of free fatty acids by introducing three moles of water to the fuel sources. When the hydroxyl ion of water combines with the ester group, and the water-derived hydrogen ion is covalently bonded to the glycerol backbone, the reaction produces 3 mol



**Fig. 7** Oil conversion into jet fuel includes a catalytic hydrothermolysis; **a** solvent-based method that involves the conversion of oil triglycerides into jet fuel via a combination of catalyst, heat, and water under high pressure. The combination of elevated temperature and pressures promotes the breakdown of oil molecules into smaller hydrocarbon fragments; subsequently, the catalyst facilitates the rearrangement and conversion of these fragments into hydrocarbons, which are further purified to match the requirements of jet fuel; **b** hydroprocessed renewable jet process in which oil is converted into jet fuel comprises a series of essential stages. Firstly, the feedstock oil is subjected to hydroprocessing, a process in which it is combined with hydrogen and then introduced into a catalyst bed within a hydrotreating reactor operating at elevated temperatures and pressures. Hydrotreating involves removing sulfur, nitrogen, and oxygen molecules from the oil, while unsaturated hydrocarbons are saturated by hydrogenation. Subsequently, the hydrotreated oil is subjected to

hydrocracking with the aid of a catalyst to decompose large hydrocarbon molecules into smaller, more valuable hydrocarbons that are appropriate for jet fuel; **c** pyrolysis to jet fuel strategy for transforming oil into jet fuel contains a sequence of sequential steps. Initially, the oil feedstock undergoes pyrolysis, a thermal degradation process without oxygen, which leads to the fragmentation of bigger hydrocarbon molecules into smaller, more easily vaporized ones. After pyrolysis, the resulting products, which consist of bio-oil, gases, and char, are separated. The bio-oil portion is then subjected to additional upgrading procedures, such as hydrotreating and hydrocracking, to eliminate impurities, enhance stability, and modify the chemical composition to comply with jet fuel requirements. After being improved, the bio-oil is further refined and fractionated to separate the various components of the jet fuel.  $\text{H}_2\text{O}$ ,  $\text{H}_2$ ,  $\text{C}_3\text{H}_8$ , FFA,  $\text{CO}$  and  $\text{CO}_2$  refer to water, hydrogen, propane, free fatty acids, carbon monoxide and carbon dioxide, respectively

of free fatty acids. In order to dissolve water in the oil phase, very high temperatures are required (between 250 and 260 °C). Moreover, high pressure is necessary to keep the reactants in their liquid form. Numerous pharmacological, technical, and personal care products use glycerol as a by-product. The energy-intensive glycerol purification process increases costs but has potential value as a commodity for sale [115].



## Pyrolysis of biomass into jet fuel

Renewable forms of diesel, gasoline and jet fuel can be produced from cellulosic biomass via pyrolysis [116], which is a recent method developed by Wang and Tao [117]. The pyrolysis process produces bio-oil, requiring significant upgrading and refining to comply with jet fuel standards. Technical challenges involve the extraction of oxygenated molecules from bio-oil, which is essential for improving its energy density and stability. The upgrading process requires elevated hydrogen pressures to eliminate contaminants and improve the quality of the bio-oil, assuring compliance with rigorous aviation fuel standards. Therefore, pyrolysis jet fuel is still awaiting ASTM approval. Bio-oils from catalytic pyrolysis are hydro-treated in several steps to create jet fuel range products. Figure 7 depicts the production of jet blend components from oil pyrolysis by hydrotreatment and fractionation without further catalytic improvement. Furthermore, Wei, Liu [10], Elliott, Olarte [118] and others are investigating the transformation of oil pyrolysis into carbon-based fuels, plus jet fuel, by combining pyrolysis and hydrolysis processes. Catalytic hydroconversion is combined with commercial rapid thermal processing engineering for pyrolysis to form the biorefining process integrated system, using feedstocks such as cane bagasse, corn stover, guinea grass, switchgrass, forest residues and algal biomass. Between 42.4% and 44.2% of the jet fuel was recovered using batch vacuum distillation.

In brief, oil pyrolysis to jet fuel is a thermochemical conversion process that utilizes elevated temperatures for decomposing hydrocarbon-rich feedstocks, such as waste oils or plastics, into lighter hydrocarbons appropriate for jet fuel production. This technology offers a viable approach for generating sustainable aviation fuels by utilizing waste materials that would otherwise be disposed of in landfills or burnt. However, challenges, including the necessity for effective catalysts, regulation of reaction conditions, and handling resultant by-products and waste streams, must be tackled to enhance the efficiency and environmental sustainability of oil pyrolysis for jet fuel production. Current research and development focus on improving process efficiency, elevating jet fuel quality, and reducing environmental impacts, underscoring the feasibility of oil pyrolysis as a sustainable method for jet biofuel generation.

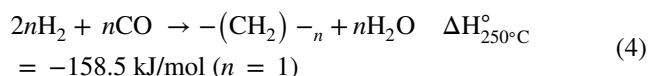
## Conversion of gas into jet fuel

This article details the gas-to-jet pathway, a series of steps for transforming various gases into jet biofuel. Both the Fischer–Tropsch and the gas fermentation pathways are a part of this one, which will be further discussed below.

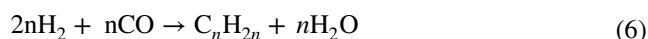
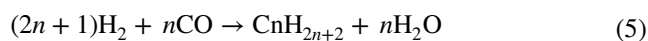
## Fischer–Tropsch biomass-to-liquid process

Using the Fischer–Tropsch method, syngas can be processed into liquid hydrocarbon fuels [119]. Fischer–Tropsch fuels produce fewer emissions when used in jet engines because they typically contain no sulfur and very few aromatics [66]. However, they may continue emitting particles and nitrogen oxides (NO<sub>x</sub>), posing issues based on engine technology and fuel additives. This requires enhancements in engine efficiency and emissions regulation to manage these challenges successfully. According to several recent studies, transforming biomass into synthetic fuels utilizing Fischer–Tropsch technology could give a low-carbon alternative to regular gasoline, kerosene and diesel [120]. This study dissects the Fischer–Tropsch biomass using the liquid FT-BTL method. In the pretreatment phase of the biomass-to-liquid route (see Fig. 8), the moisture content and particle size of biomass feedstocks are improved through drying and grinding [117]. Various gasification methods are available for converting biomass into syngas. High-purity oxygen and steam are used in the gasification process, which heats the biomass to roughly 1300 °C, transforming it into raw syngas. Drying biomass requires a source of heat, and a combustor is employed for this purpose. Water–gas-shift technology is used to fine-tune the hydrogen/carbon monoxide (H<sub>2</sub>:CO) ratio to 2.1:1 after the direct quench syngas cooling system coupled to the gasifier has removed ash and tars.

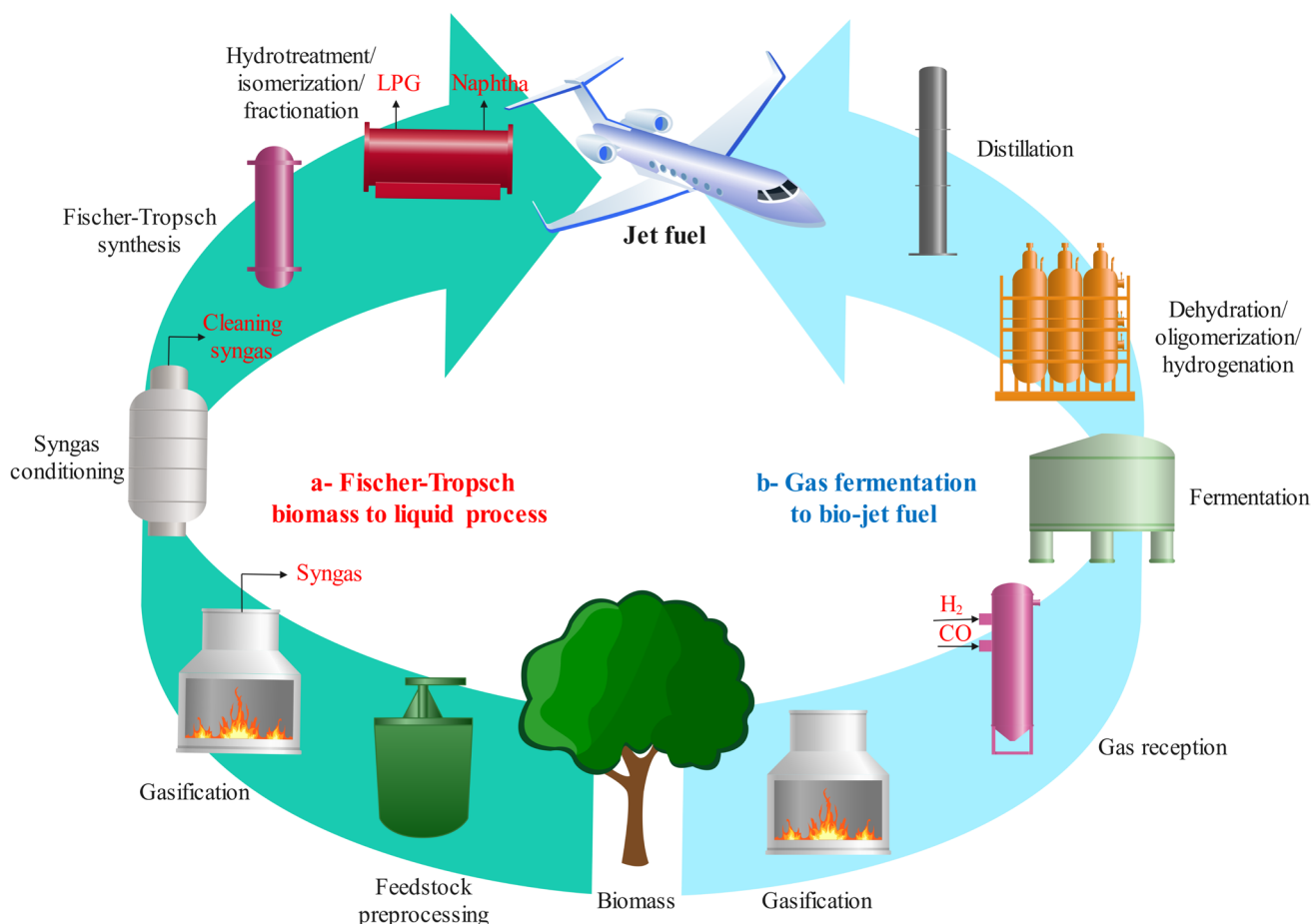
An effective Fischer–Tropsch catalyst should have high hydrogenation activity to facilitate the conversion of CO into higher hydrocarbons. The Fischer–Tropsch reaction can be catalyzed by either iron or cobalt and typically occurs at pressure between 10 and 60 bar and temperature varying from 200 °C to 400 °C [121]. This reaction is characterized as a surface polymerization process. In this process, the reactants CO and H<sub>2</sub> adsorb and dissociate on the catalyst's surface, leading to the formation of a chain initiator [122]. The reaction continues through chain transmission, chain removal, and product desorption. This type of product distribution can be described by the gradual addition of CH<sub>2</sub> monomers to the expanding chain, as illustrated in the following equation Eq. (4)



Fischer–Tropsch reaction is represented in Eq. (5), which leads to the creation of alkanes, and Eq. (6), resulting in the production of alkenes, with water being the predominant oxygenated product. [123]



The water–gas-shift (WGS) reaction, illustrated in Eq. (7), is a reversible process concerning CO and is



**Fig. 8** Gas to jet fuel can be accomplished via two methods: **a** Fischer–Tropsch biomass-to-liquid route comprises a series of crucial steps. Biomass feedstock is subjected to gasification to generate syngas, consisting of carbon monoxide and hydrogen. The syngas is further purified to eliminate contaminants before its introduction into the Fischer–Tropsch reactor, where a catalyst facilitates the transformation of syngas into long-chain hydrocarbons. After the synthesis, the final products are subjected to hydroprocessing in order to eliminate impurities and modify the molecular structure. The obtained hydrocarbons undergo refinement to separate the constituents of jet fuel, which are then combined with regular jet fuel; **b** jet biofuel produc-

tion by gas fermentation is the conversion of gases, such as carbon monoxide or hydrogen, into bio-based jet fuel through fermentation. This pathway often consists of the following steps: Initially, the gas feedstock is employed by specifically designed organisms in a fermentation process to generate bio-based intermediates such as alcohols or organic acids. Subsequently, these intermediates undergo additional processing to produce hydrocarbons through dehydration, oligomerization, and hydrogenation. The hydrocarbons obtained are refined and purified to comply with aviation fuel requirements.  $H_2$  and CO refer to hydrogen and carbon monoxide, respectively, while LPG refers to liquefied petroleum gas

generally considered to produce  $CO_2$  as a primary product [124]. Iron-based catalysts are effective in facilitating the WGS reaction, making them significant contributors to Fischer–Tropsch chemistry when used as catalysts.



A group of catalytic procedures known as Fischer–Tropsch synthesis is employed to transform syngas into liquid hydrocarbons. Two prominent Fischer–Tropsch operating modes are low and high temperature. Iron-based catalysts can produce olefins and gasoline at  $340\text{ }^\circ\text{C}$ , whereas diesel and linear wax are products of the low-temperature process, which runs at  $230\text{ }^\circ\text{C}$  through cobalt or

iron catalysts [125, 126]. Methane and long-chain hydrocarbons are among the products of the Fischer–Tropsch process, and they also generate oxygenated compounds, such as aldehydes, alcohols, and carboxylic acids. Catalyst deactivation and undesired methane formation can be avoided by promptly dissipating the heat created during the Fischer–Tropsch process [127–129].

### Gas fermentation

Liquid biofuels can be cultured from syngas instead of upgrading it via catalysis from Fischer–Tropsch syngas to jet biofuel (see Fig. 8). Gasification is the initial step in the conversion of lignocellulosic biomass to syngas. Alcohols

like ethanol and butanol can be produced by acetogenic bacteria using cooled syngas [130]. Acetate, butyrate, ethanol, butanol and 2,3-butanediol are all by-products of carbon monoxide and hydrogen consumption by *Clostridium acetogenic* bacteria. In addition, diverse microbial strains can produce other products through various biochemical routes, such as acetate, acetone, and isopropanol [130, 131]. Mixed alcohols, 2,3-butanediol or ethanol, can be upgraded into jet fuel using the alcohol-to-jet method. This involves dehydration, oligomerization, hydrogenation, and distillation. Gas fermentation is a more flexible process than the Fischer–Tropsch route when it comes to feedstocks, and it can tolerate contaminants better [132]. It uses 57% less energy overall than the Fischer–Tropsch route, which uses 45% less energy than gas fermentation. Increased yields of primary products can be achieved through gas fermentation of any organic material, including lignin. The procedure requires less expensive enzymes and operates at lower temperatures, resulting in lower operational costs [117, 130]. Using biological systems as catalysts decreases the chance of catalyst poisoning by permitting a wider range of hydrogen/carbon monoxide (H<sub>2</sub>:CO) ratios and increasing tolerance to pollutants. Fuel crops, farm by-products, and municipal and industrial organic waste can all be converted to gas through gas fermentation [131]. In conclusion, gas fermentation has multiple potential benefits, such as higher yields and lower operational costs than conventional biochemical or thermochemical methods.

### Conversion of sugar into jet fuel

Jet fuel can be made from sugar intermediates by one of two different processes. Sugars and sugar intermediates are catalytically converted to hydrocarbons in the first step [133]. The biological conversion of intermediates made of carbs and sugars into hydrocarbons is the second step [133]. There are many different aspects to studying the fermentation of hydrocarbon fuels and fuel intermediates. Several companies, including LS9, are attempting to commercialize jet fuel derived from biomass fermentation [117].

### Catalytic conversion of sugars to hydrocarbons

The catalytically converting plant sugars to high-energy hydrocarbon molecules is depicted in Fig. 9 and is implemented using virent's bio-forming platform. In the first stage, soluble sugars are produced from the biomass feedstock. To accomplish this, lignocellulosic feedstocks are typically pretreated and then enzymatically hydrolyzed to create C<sub>5</sub> and C<sub>6</sub> sugars [133, 134]. The Viridia process is another option for transforming biomass into sugars [135]. The soluble sugars are then purified and concentrated to remove any remaining particulates or contaminants to improve the sugar-to-jet

step [136]. The economics of a process are greatly enhanced by closed-loop techniques that recycle unreacted species, yet isolating the product composites may be technically challenging [137].

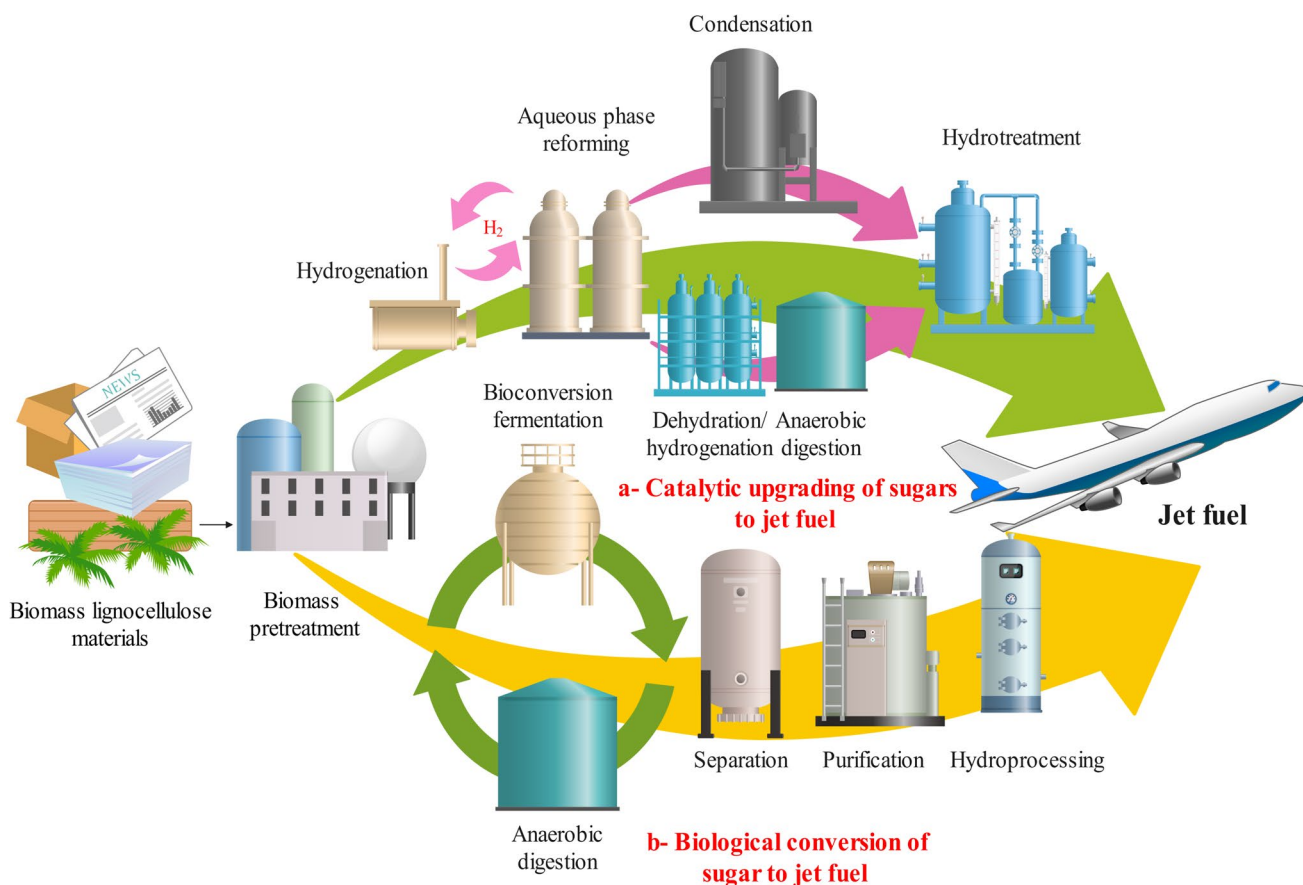
### Bioprocessing of sugars to hydrocarbon

Explaining every possible scenario for various biological processes that can produce jet fuels and hydrocarbon intermediates is challenging. Some examples of products from biological conversion include pentadecane, isoprene, fatty alcohols, 2,3-butanediol, fatty acids, fatty esters and farnesene [138, 139]. Moreover, similar to farnesene, various biological processes may replicate the same chemical structure. For instance, farnesene can be generated anaerobically, one via 1-deoxy-d-xylulose-5-phosphates DXP pathway and another via the mevalonic acid route [140]. The general mechanism for converting biomass into jet fuel biologically is represented in Fig. 9. After pretreatment, enzymatic hydrolysis is used to break down biomass into its constituent sugars, C<sub>5</sub> and C<sub>6</sub>, which are then extracted and concentrated [141]. Change of life form after the hydrolysate is concentrated; either anaerobic or aerobic processes create the intermediate hydrocarbon product [142, 143]. Jet fuel is made by a series of finishing operations, including separation, oligomerization, and hydrotreating [89].

In summary, the transformation of sugar into aviation fuel has numerous obstacles that must be addressed for commercial feasibility. A notable difficulty is the cost-effectiveness of sugar-based feedstocks, as their availability and pricing fluctuate based on agricultural practices, market demand, and rivalry with food production. Process efficiency and yield optimization are essential in converting sugars to jet fuel, necessitating sophisticated technology and catalysts to improve conversion rates and product quality. A significant problem is the scalability of the sugar-to-jet fuel industry in satisfying the extensive demands of the aviation industry. Moreover, guaranteeing the sustainability of feedstock procurement, reducing environmental repercussions, and adhering to aviation fuel regulations are essential obstacles that must be addressed for sugar-derived jet fuels to emerge as a viable and sustainable option in the aviation industry.

### Catalysts utilized for jet biofuel conversion processes

Catalysts play a crucial role in jet biofuel conversion technologies by facilitating selective reactions, improving efficiency, and ensuring economic feasibility. Longer approval, certification, and testing processes hinder the adoption of alternative jet fuels in aviation industries.



**Fig. 9** Catalytic upgrading of sugars to jet fuel. **a** Sequential process that transforms sugars obtained from biomass into hydrocarbons that are appropriate for utilization as jet fuel. Initially, sugars are obtained from biomass feedstock, such as cellulose or starch, via pretreatment processes such as hydrolysis. Next, these sugars undergo catalytic conversion with specialized catalysts at specified temperature and pressure conditions. The process of catalytic upgrading involves the dehydration, isomerization, and hydrogenation processes of sugars that convert them into hydrocarbon molecules that closely resemble

the components found in traditional jet fuel. The hydrocarbons obtained are then subjected to additional purification. **b** Sugars are obtained from biomass feedstock and then transferred to specialized microorganisms or genetically modified microbes that have the ability to ferment these sugars. During fermentation, microorganisms metabolize carbohydrates to generate bio-based intermediates such as fatty acids or alcohols. These intermediates undergo additional decarboxylation, hydrogenation, and dehydration processing to produce hydrocarbons similar to jet fuel components.  $H_2$  refers to hydrogen

Therefore, it is crucial to enhance the certification procedure and maximize the current technology routes to lower aviation carbon emissions [144, 145]. Therefore, manufacturing substitute jet fuels often uses heterogeneous catalysts instead of homogeneous catalysts. The bulk surface of the supported metal or impregnated heterogeneous catalysts is inherently important as an active catalytic phase. Assisted catalysts are the most effective catalysts for producing jet fuel [146], as shown in Table 1. Effective catalyst selection depends on the characteristics of the feedstock, the desired product distribution, and the process conditions. Continuous advancements in catalyst design, including bimetallic systems and hierarchical supports, are essential for improving the efficiency and sustainability of jet biofuel production.

### Fischer–Tropsch catalysts

Catalyst selection and operational conditions are critical to achieving optimal performance in terms of activity, selectivity, and stability. Catalysts commonly utilized in the Fischer–Tropsch reaction are iron (Fe) or cobalt (Co)-based metal complexes, which facilitate the breakdown of carbon monoxide into hydrocarbon chains, including ethylene monomers, under operating conditions of 10–40 bar pressure and temperatures ranging from 200 to 300 °C. Recent studies on bifunctional catalysts have explored enhancements in activity and selectivity, optimizing their performance for higher efficiency in hydrocarbon production. For instance, reports indicate that ruthenium enhances  $C_{5+}$  and carbon oxides conversion fraction when deposited over cobalt/aluminum oxide ( $Co/Al_2O_3$ ), compared to monometallic  $Co/Al_2O_3$

**Table 1** Catalysts play crucial roles in the conversion pathways of jet fuel

Categories	Conversion steps	Feedstock	Catalysts	Characteristics
Fischer–Tropsch	Fischer–Tropsch process	Biomass-derived syngas	Iron, cobalt, ruthenium, nickel	Ruthenium: reactive, high cost, low availability Nickel: lower cost, methanation catalyst Cobalt: low temperature, high selectivity for long-chain paraffins, good hydrogenation catalyst Iron: high temperature, effective for CO-rich syngas and facilitates the water–gas-shift (WGS) reaction, hydrogenation of carbon dioxide
Hydroprocessed esters and fatty acids	Hydrogenation/cracking/isomerization	Oils and fats	Palladium, platinum, ruthenium, nickel	Palladium: most active, favoring decarboxylation (DCOx) and decarbonylation (DCO) Platinum: high conversion rate and hydrodeoxygenation selectivity, high levels of catalytic activity and selectivity for isomerizing alkanes Ruthenium: the ability to withstand deactivation by water, high cost, poor reusability Nickel: low cost, hydroprocessing of oils and methyl esters of fatty acids, hydrodeoxygenation efficiency improvement
Alcohol to jet	Alcohol dehydration/oligomerization	Ethanol, butanol	Aluminum oxide Al <sub>2</sub> O <sub>3</sub> , beta zeolite, and Si–Al phosphate (SAPO) zeolite, nickel	Conversion of ethanol and selectivity of ethylene (HZSM-5 > NiAPSO-34 > SAPO-34 > $\gamma$ -Al <sub>2</sub> O <sub>3</sub> ),

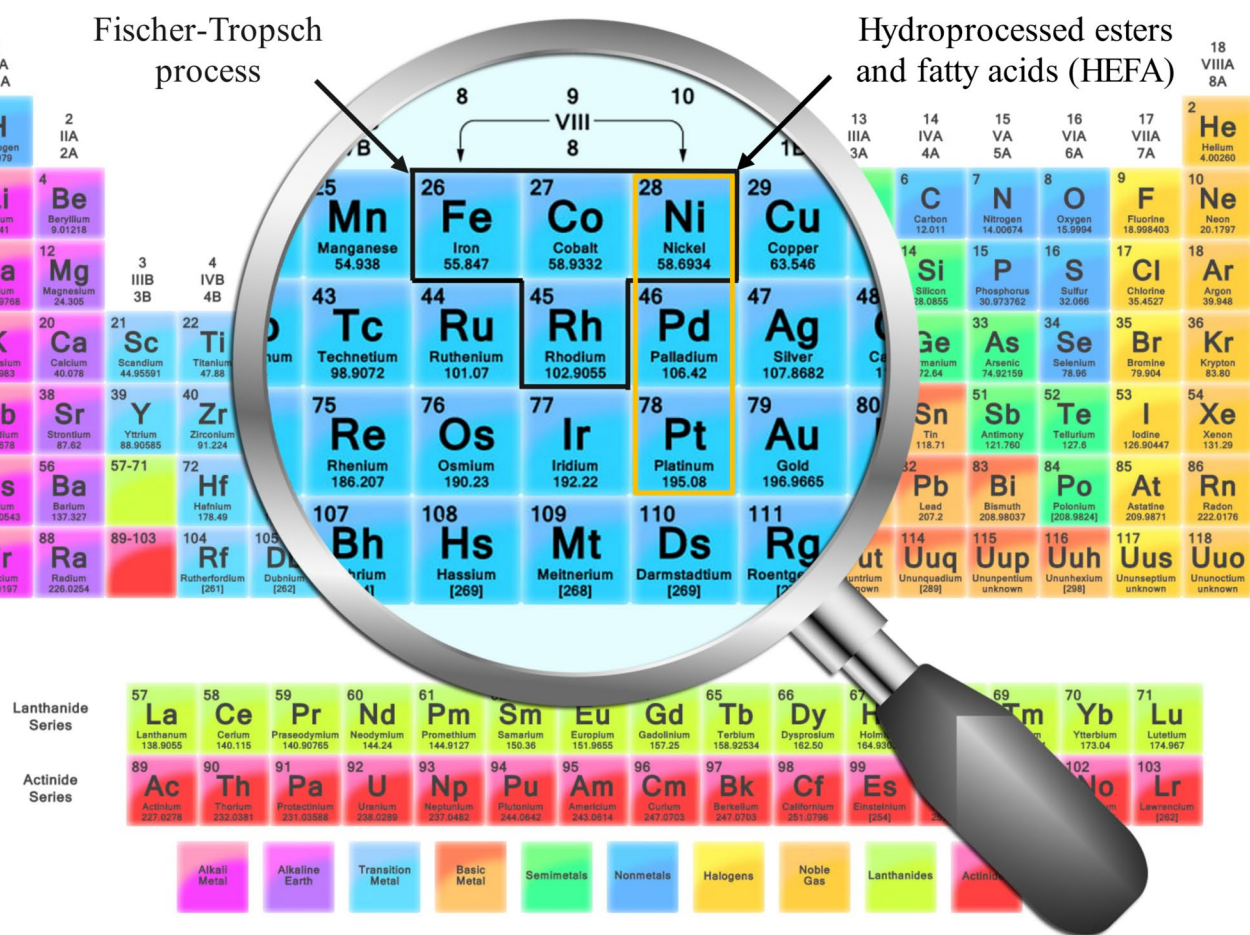
The table illustrates the effective catalysts, the different pathway conversion techniques, and their respective properties. Ruthenium, nickel, cobalt, and iron are renowned catalysts in the Fischer–Tropsch process. Moreover, palladium, platinum, ruthenium, and nickel are essential elements for the hydroprocessed esters and fatty acids process. Conversely, the conversion process from alcohol to jet fuel necessitates specific catalysts like aluminum oxide, nickel, and various zeolite variants. DCOx and DCO denote decarboxylation and decarbonylation, respectively. The abbreviations SAPO, HZSM-5, NiAPSO-34, SAPO-34, and  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> correspond to silicoaluminophosphates oxides, high-silica zeolite socony mobil-5, nickel aluminophosphates silica oxide-34, silicoaluminophosphates oxides-34, and  $\gamma$ -aluminum oxide

[147]. It was also discovered that the ruthenium dispersal on iron and cobalt catalysts had a greater value and noticeably better activity than on a monometallic ruthenium/aluminum oxide (Ru/Al<sub>2</sub>O<sub>3</sub>), despite having lower ruthenium loading. Both bimetallic catalysts exhibited higher carbon oxide conversion than Ru/Al<sub>2</sub>O<sub>3</sub>, indicating that increasing the surface concentration of ruthenium through reduction-deposition with iron or cobalt can enhance the performance of Ru-M/Al<sub>2</sub>O<sub>3</sub> catalysts [148].

Regarding relating performance to temperature, low-temperature Fischer–Tropsch synthesis produces hydrocarbons with molecular weights > C<sub>20</sub>, resulting in waxy and thermally inefficient products. In contrast, high-temperature (300–350 °C) Fischer–Tropsch generates olefins ranging from C<sub>3</sub> to C<sub>11</sub>, which can be converted into gasoline [149]. Successful Fischer–Tropsch synthesis requires certain catalytic properties, including high-temperature resistance, good selectivity for the desired product and

excellent water resistance due to several secondary Fischer–Tropsch reactions that produce water [119, 150]. The primary metal catalysts most commonly employed in Fischer–Tropsch synthesis include iron (Fe), cobalt (Co), nickel (Ni) and ruthenium (Ru) [151]. In terms of catalyst efficiency when supported on alumina, the preferred order is ruthenium Ru > iron Fe > nickel Ni > cobalt Co, whereas the latest ranking for unsupported catalytic activity is iron Fe > cobalt Co > nickel Ni > ruthenium Ru [150]. Despite its high reactivity, ruthenium's cost and limited availability render it for widespread implementation. Conversely, nickel, although less expensive and frequently used as a methanation catalyst, faces challenges related to coking. Therefore, industrial Fischer–Tropsch processes often utilize iron and cobalt catalysts [126]. Cobalt catalysts are usually utilized in Fischer–Tropsch reactions at low temperatures, while iron catalysts are more frequently applied at high temperatures. Co serves as an effective hydrogenation catalyst that initiates





**Fig. 10** Fischer–Tropsch and hydroprocessed esters and fatty acids (HEFA) approaches used in jet fuel production. These processes heavily rely on specific metal catalysts, which are closely associated with elements found in the periodic table. Syngas conversion into hydrocarbons is facilitated by commonly employed catalysts in the Fischer–Tropsch process, including iron, cobalt, nickel and ruthenium, which are members of the transition metal group. Transition metals are characterized by their wide range of oxidation states and potent catalytic activity. In contrast, the HEFA process employs cat-

alysts such as molybdenum, nickel, palladium, and platinum, which are also transition metals, to perform the hydrotreating and hydrocracking events during which esters and fatty acids are converted into components of jet fuel. Highlighting these elements in the periodic table emphasizes their catalytic characteristics, which are essential for facilitating the conversion processes in generating sustainable aviation fuel. HEFA refers to the approach of hydroprocessed esters and fatty acids

the creation of hydrocarbon chains from olefins, producing valuable isomerized hydrocarbons [152]. On the other hand, iron-based catalysts are particularly effective at transforming carbon dioxide into high molecular weight hydrocarbons [151] as they can naturally generate hydrogen from carbon dioxide. For high-temperature Fischer–Tropsch synthesis, iron catalysts have been utilized in both supported and bulk forms, including precipitated or fused catalysts combined with manganese, copper, silica, or potassium [153].

### Hydrotreated esters and fatty acids catalysts

An excellent catalyst for hydrotreated esters and fatty acids (HEFA) process has high selectivity toward deoxygenation, hydroisomerization, and cracking. Additionally, for HEFA

jet biofuel production, it is beneficial to generate hydrocarbons that are suitable for jet fuel, which includes isomerization and cracking abilities. Catalysts with low acidity tend to exhibit poor catalytic efficiency, promote hydrocracking, yield lighter products, and are more prone to carbonization [154]. However, the criteria for an effective HEFA catalyst are influenced by the catalyst preparation methods [146]. There is increasing interest in various catalysts with acid-active sites [155], such as monometallic catalysts.

### Monometallic catalysts

The hydrodeoxygenation reaction can be catalyzed by noble metals from Group VIII, including nickel, ruthenium, palladium and platinum [156]. These metals are effective in

hydrogenation, isomerization and cracking reactions in numerous jet biofuel research studies, as portrayed in Fig. 10. The following section describes the use of monometallic catalysts for the deoxygenation of fatty oils and acids.

**Palladium** Deoxygenation catalysts were tested in a recent study, specifically nickel/ $\gamma$ -aluminum oxide, palladium/ $\gamma$ -aluminum oxide and platinum/ $\gamma$ -aluminum oxide (Ni/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, Pd/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and Pt/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>). These catalysts were evaluated using a hypothetical diet consisting of tripalmitin and oleic acid in a 3:1 molar ratio. The results showed that palladium/ $\gamma$ -aluminum oxide (Pd/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>) was the most effective deoxygenation catalyst, demonstrating a preference for decarboxylation over hydrogenation. The ester and carboxylic acid functions undergo decarbonylation instead of hydrogenation, leading to the formation of carbon chains of varying lengths [157]. However, the limited stability, surface area, and sensitivity of aluminum oxide Al<sub>2</sub>O<sub>3</sub> support to water poisoning and crystallite rupture may contribute to poor hydrogenation performance [158]. Additionally, hydrodeoxygenation of crude hydrolyzed almond oils and macauba pulp was investigated using a palladium/carbon (Pd/C) catalyst, as reported by Silva, Fortes [159]. Almond fatty acids were found to have the highest deoxygenation rates due to their lower unsaturated component content, which tends to limit the catalyst's activity. Although the product had a high hydrocarbon content, according to cold performance testing, 5% and 1% v/v blends with commercial jet fuel did not start hardening until 47 and 60 °C, respectively.

**Platinum** Hydrodeoxygenation is a process where platinum exhibits high selectivity and conversion due to its high dispersion, electron density, and low acidity [160]. It also demonstrates strong activity and selectivity as a catalyst for *n*-alkane isomerization. Dissociating hydrogen molecules produces hydride ions, and hydrogen spillover can enhance the acidity of the catalyst [161, 162]. Platinum is widely supported by various acidic oxides to improve its dispersion in hydrodeoxygenation reactions. For example, jet biofuel with a yield of 42–48 wt% and an aromatic content exceeding 12% was produced by hydrotreating soybean oil using a catalyst composed of 1% platinum on aluminum oxide and silicoaluminophosphates oxides (1% Pt/Al<sub>2</sub>O<sub>3</sub>/SAPO-11) in a trickle-bed reactor. Following this, a dinickel phosphide-supported zeolite (Ni<sub>2</sub>P/HY) catalyst was utilized for mild hydrocracking, and a Pt/Al<sub>2</sub>O<sub>3</sub>/SAPO-11 catalyst was employed for further isomerization at a rate of 0.5% [163]. The process was conducted for over 1000 h at temperatures between 375 and 380 °C, with a liquid hourly space velocity (LHSV) of 1 h, and a pressure of 30 atm. However, the high cost of platinum catalysts limits their industrial adoption. Another significant drawback is their susceptibility to

carbon monoxide poisoning. Despite the need for additional isomerization and cracking, platinum demonstrates outstanding hydrodeoxygenation capabilities when processing biomass into jet biofuel.

**Ruthenium** Hydrodeoxygenation reactions have garnered interest due to ruthenium's resistance to inactivation by water. However, its high cost and poor reusability limit its widespread application. The ruthenium (Ru/C) catalyst has demonstrated superior performance in oil production (60 wt%) and deoxygenation levels (90 wt%) for fast pyrolysis oil compared to typical hydrotreatment catalysts, such as sulfided cobalt molybdenum/aluminum oxide (sulfide CoMo/Al<sub>2</sub>O<sub>3</sub>) and nickel molybdenum/aluminum oxide (NiMo/Al<sub>2</sub>O<sub>3</sub>) [164]. In studies involving a ruthenium catalyst enhanced with USY zeolites, hexadecane hydrocracking was conducted at 250 °C and under a hydrogen pressure of 45 bars. For example, in a fixed bed reactor, the Ru-USY-15-P catalyst, with a 5 wt% loading, outperformed platinum catalysts by achieving a 24% aviation fuel fraction at a conversion rate of 71% [165]. Additionally, proton and metal-modified beta zeolites, specifically Ru-H-Beta-300 (with 2.5 wt% Ru), were effectively utilized in the hydrocracking of hexadecane at 240 °C and 45 bar, producing 24% jet biofuel within four hours [166]. Although proton platinum-modified beta zeolites (Pt-H-Beta-25) yielded the highest jet biofuel output (29% in 4 h), this method also generated significant amounts of gaseous products and organic coke, resulting in a low yield of liquid phase products [167].

**Nickel** Nickel is becoming increasingly popular in deoxygenation catalysts, as it is approximately 1000–2500 times less expensive than palladium and platinum, respectively [168, 169]. Research has focused on using nickel-based catalysts to hydrotreat fatty acid methyl esters and oils to generate jet biofuel-grade hydrocarbons. Typically, a nickel catalyst is incorporated into a bimetallic system to enhance the efficiency of hydrodeoxygenation [170]. The conversion of alkanes and selectivity can be adjusted by varying the molar ratio of nickel to other metals, as well as the reducibility and acidity of the support [171]. Nickel-molybdenum disulfide/aluminum oxide (Ni-MoS<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>) catalysts have been studied for their potential to hydrodeoxygenate palm kernel oil. Significant hydrodeoxygenation activity was observed at 300 °C, especially with prolonged contact time and both fast and low liquid hourly space velocities (LHSV), while the production of decarboxylation/decarbonylation increased rapidly with rising reaction temperatures.

**Molybdenum** Research on molybdenum's potential as a catalyst for HEFA reactions is limited. However, molybdenum is frequently taken as a supplement in trimetallic or bimetallic catalyst systems to improve catalytic per-

formance [172, 173]. A recent ground breaking study by Zhang, Shi [174] investigated the role of a monometallic molybdenum-supported zeolite catalyst, Mo/HZSM-22, in converting palmitic acid into hydrocarbons for jet fuel production. Their findings revealed that increasing the reduction of  $\text{Mo}^{6+}$  to  $\text{Mo}^{4+}$  and  $\text{Mo}^{4+}$  to  $\text{Mo}^0$  at annealing and reduction temperatures of 550 and 600 °C, respectively, led to higher carbon retention. Notably, 61.7% of the reserved carbon was *iso*- $\text{C}_{16}$  alkanes, with a selectivity of 89.3% for  $\text{C}_{16}$  alkanes. These results suggest a heightened potential for producing *iso*-alkanes.

### Catalysts for conversion of alcohol into jet fuel

The effective conversion of biofuels from alcohol to jet fuel typically involves two key phases: dehydration of alcohol and oligomerization, both of which necessitate the use of a catalyst. Research into alcohol dehydration has progressed significantly, primarily due to the importance of ethylene in producing various chemicals and synthetic polymers such as ethylbenzene, polyethylene, ethylene oxide, polystyrene, ethylene dichloride, and polyvinyl chloride [175, 176]. There has been considerable interest in developing catalysts for these reactions, mainly because the oligomerization phase is often viewed as a critical processing challenge. Initially, alcohol-to-jet studies employed inexpensive oligomerization catalysts based on polyphosphoric acid. However, the overall efficiency was limited by issues such as poor selectivity and productivity, inadequate thermal stability, and corrosion concerns [102].

#### Alcohol dehydration catalysts

Dehydration of ethanol can occur via two possible chemical routes: (i) an intramolecular process that enhances ethylene production and (ii) an intermolecular bimolecular reaction that generates diethyl ether [177]. Diethyl ether is favored at lower temperatures around 300 °C, while ethylene is formed at higher temperatures exceeding 300 °C [178]. Various catalysts have been explored for ethanol dehydration, including aluminum oxide  $\text{Al}_2\text{O}_3$ , heteropolyacid catalysts and other materials studied as potential ethanol dehydration catalysts, zeolites, and transition metal oxides. Conversely, mildly acidic materials, such as inorganic acids, zeolites, metal oxides, and aluminum oxide catalysts, have been studied for isobutanol dehydration [10]. Currently, SAPO zeolite and zeolites such as beta and HZSM-5 are considered the most effective catalysts for ethanol dehydration [179, 180].

Catalyst activity can be improved, and catalyst deactivation can be minimized by supporting the catalysts on mesoporous silica materials such as SBA-15. Proof of concept studies have revealed that supported catalysts can maintain 85% conversion for 30 h while regenerating through air

movement [181]. Recent studies have demonstrated that pure high-silica RHO zeolite exhibits higher catalytic selectivity and activity compared to ZSM-5 [182] and aluminum oxide at temperatures between 250 and 400 °C as a result of its high porosity and enormous specific surface area [183]. The alcohol-to-jet procedure's high selectivity for ethylene can also be improved by metal ion doping of ZSM-5 zeolites. For example, molybdenum Mo/HZSM-55 wt% catalyst produced 67% ethylene selectivity as opposed to 53% for HZSM-5 alone after 10 h at 230 °C [184]. This improvement is attributed to the molybdenum species on the outer surface of HZSM-5, which are more readily reduced during the ethanol dehydration reaction, leading to increased medium and weak acidity as well as enhanced catalytic performance and stability. Lanthanum-modified phosphorous (HZSM-5 0.5% La-2% PHZSM-5) is a catalyst with remarkable improved anti-coking capability and catalytic performance, with a selectivity of 99.9% for ethylene and a selectivity of 96.6% for ethanol, resulting in a 100% conversion rate even after 72 h at 259.85 °C and 97.4% conversion [104].

The reactivity of alcohols is influenced by factors such as the length of the chain, number of branches, rate of dehydration, and optimum catalyst [185]. Although not extensively studied, it is impossible to make alcohol into jet biofuel without first dehydrating isobutanol and *n*-butanol. In contrast to the dehydration of *n*-butanol, which yields just linear butenes, producing linear butenes by the skeletal isomerization of these alcohols requires a more acidic catalyst and a higher temperature [186]. Alcohols are more effectively dehydrated at Bronsted acid sites than Lewis acid sites [187], and catalysts with more Bronsted acid sites promote faster dehydration of butanols [188]. The rate of alcohol dehydration processes can be accelerated by incorporating Bronsted acid functions with compound ingredients like tungsten oxide ( $\text{WO}_3$ ) and sulfate ( $\text{SO}_4^{2-}$ ).

#### Catalysts for oligomerization

Following alcohol dehydration, oligomerization and hydrogenation are crucial to synthesizing jet biofuel. However, these reactions are often complex and require three distinct catalysts. Researchers have sought to create a single catalyst capable of facilitating both oligomerization and dehydration, but none have succeeded [189]. Isobutyl alcohol can be dehydrated, and the resulting isobutylene can undergo oligomerization more efficiently with a catalyst such as a strong acidic zeolite. However, the fuel produced with this catalyst is generally of lower quality compared to fuels produced through separately catalyzed reactions [67]. Zeolites are considered the best acid catalysts, and ethylene oligomerization is typically carried out at higher temperatures [190]. It has been suggested that an oligomerization catalyst be encapsulated within a composite framework, similar to

HEFA catalysts to increase catalytic activity and promote the formation of aromatic-based hydrocarbons. One successful implementation of this approach involved using the 3D mesoporous silica NiAlKIT-6 material, which achieved an ethylene conversion rate of 95.97% under specific conditions. This catalyst maintained consistent  $C_{8+}$  selectivity and demonstrated over 80% catalytic stability throughout 30 h of operation, effectively eliminating coke production via regeneration [191]. By adjusting nickel cation concentration at the acid site and the acidity, researchers were able to modify the distribution of the oligomerized compounds [192].

A study by Guo, Guo [189] investigated the catalytic oligomerization of isobutyl alcohol into jet fuels utilizing dealuminated zeolite beta. Their analysis revealed that isobutyl alcohol could be effectively oligomerized on this catalyst, resulting in a selectivity of over 50% for  $C_{8-16}$  compounds with a conversion rate of 98%. Luo, He [193] introduced a novel synthetic approach that combines two processes: dehydrating alcohols into light olefins via the SAPO-34 catalyst and polymerizing olefins into jet fuels utilizing the nickel@iron@H $\beta$  (2%Ni@5%Fe@H $\beta$ ) catalyst. Implementing a dual-bed reaction system significantly improved the selectivity of jet fuel generation during the catalytic conversion of acetone, butanol and ethanol (ABE) as well as low-carbon alcohols. This comprehensive strategy yielded a remarkable fuel selectivity of 80.1% for jet-range applications and a substantial conversion rate of 94.8% for acetone, butanol and ethanol. Liao, Liu [194] successfully developed carbon-encapsulated nickel molybdenum (NiMo) catalysts aimed at directly enhancing the conversion of aqueous bio-ethanol. The nickel molybdenum nanocomposite, with a NiMo@C ratio of 6/1, exhibited remarkable performance, achieving an 89.4% conversion rate of bio-ethanol and a yield of higher alcohols at 42.1 C-mol%. Significantly, the selectivity for  $C_{8-16}$  compounds reached 44.7%, allowing their further hydrodeoxygenation to produce jet biofuels.

The tin-nickel/chitosan (Sn-Ni/CS) catalysts were developed by Chen, Zheng [195] by modulating the electron density surrounding the nickel active site via tin doping, leading to an augmented electron density around the nickel species. Employing tin doping, the Sn-Ni/CS-500-1/1 catalyst demonstrated a selectivity above 85% for higher alcohols while simultaneously attaining a 60% ethanol conversion at an operating temperature of 230 °C.

### Conversion prerequisites for jet biofuel processes

Fischer–Tropsch synthesis efficiency is influenced by several reaction conditions, including carbon monoxide conversion, reaction temperature and the hydrogen/carbon monoxide ( $H_2/CO$ ) ratio. The research highlighted that regardless of the ( $H_2/CO$ ) ratio, adding water to syngas enhances catalytic activity and boosts  $C_{5+}$  selectivity [196]. As the reaction

temperature rises, both the ratio of olefins to paraffins and  $C_{5+}$  selectivity decrease, while carbon monoxide conversion occurs alongside selective methane ( $CH_4$ ) production. Conversely, higher  $H_2/CO$  ratios result in increased methane selectivity, improved carbon monoxide conversion and decreased  $C_{5+}$  selectivity. This can lead to higher olefins/paraffins ratio [197]. In the HEFA process, pressure and reaction temperature dictate selectivity for gasoline, diesel, and jet alkanes [198]. Under reaction temperatures of 300 °C decarboxylation and decarbonylation reactions predominate, whereas the hydrodeoxygenation reaction is most common around 270 to 300 °C [199]. Green diesel production benefits from temperatures between 300 and 350 °C, as minimal hydrocarbon cracking occurs at these levels [200]. However, higher temperatures lead to improved jet biofuel selectivity due to more efficient molecular breaking. For example, at temperatures between 350 °C and 390 °C, hydrocracking for both used and fresh cooking oils increases the jet biofuel selectivity from 6.21 to 20.04% and from 5.57 to 22.24%, respectively [201]. Temperatures above 330 °C also result in a broader spectrum of hydrocarbons in the jet biofuel spectrum, including more aromatics and isomers [16].

Atmospheric pressure conditions are theoretically conducive to deoxygenation reactions. Nonetheless, the primary components of the diesel fraction produced under these conditions are *n*-alkanes in the  $C_{15-19}$  range [202]. Utilizing high-pressure hydrogen can improve catalyst stability and reduce the formation of unsaturated hydrocarbons [203]. Furthermore, increased pressure conditions favor hydrodeoxygenation over alternative reactions [204]. At high pressure, isomerization and cracking are promoted, leading to the generation of unwanted lighter hydrocarbon fractions. This has most likely occurred because of the interaction of hydrogen and free radicals with hydrocarbons. As reaction pressure increases, the probability of collisions between dissociated hydrogen and alkyl carbonium ions, rises, thereby enhancing catalytic efficiency, accelerating the reaction rate, and producing medium-chain hydrocarbons [205]. The ability of the alcohol-to-jet selectively produce specific products is influenced by reaction conditions, similar to the HEFA method. For instance, at 300 °C, the selectivity of ZSM-5 zeolites for ethylene dropped from 89 to below 60% [183]. Table 2 displays recent studies that have effectively satisfied the criteria for catalytic conversion in the production of jet biofuel.

### Catalytic performance

Homogeneous catalysts are known for their high efficiency and cost-effectiveness, but they often pose environmental challenges due to the volume of waste generated and the difficulty in separating them from the reaction mixtures [223]. Researchers have investigated heterogeneous

**Table 2** Jet biofuel production involves the crucial role of catalysts in different pathways, such as alcohol-to-jet and oil-to-jet, which significantly impacts both efficiency and sustainability

Pathway	Conversion method	Catalyst	Set up	Reaction conditions	Yield and selectivity %	References
Alcohol to jet	Direct upgrading of ethanol to jet fuel	NiMo@C	Stainless steel autoclave	240 °C H <sub>2</sub> at ambient pressure 12 h	42.1 C-mol% 44.7% C <sub>8</sub> -C <sub>16</sub>	Liao et al. [194]
	Upgrading of aqueous ethanol	Sn-Ni/CS	Autoclave reactor	230 °C H <sub>2</sub> at ambient pressure 12 h	37.3 C-mol% 85% for higher alcohols	Chen et al. [195]
	Direct upgrading of aqueous ethanol	Na-doped porous Ni@C nanocomposite	Stainless steel autoclave	250 °C H <sub>2</sub> at ambient pressure 24 h	35 C-mol% 51.9% C <sub>4</sub> -C <sub>7</sub> 33.8% C <sub>8</sub> -C <sub>16</sub>	Zhong et al. [206]
	Catalytic oligomerization of isobutyl alcohol to jet fuels	Zeolite beta catalyst	Steel batch reactor	240 °C 1.0 MPa N <sub>2</sub> 4 h	Not available 59% C <sub>8</sub> -C <sub>16</sub>	Guo et al. [189]
	Alcohol dehydration to light olefins	SAPO-34 Ni@Fe@Hβ	Double bed reaction mode	200 °C 4.0 MPa Ar 3 h	75.9 C-mol% 80.1% jet range fuels	Luo et al. [193]
	Olefin polymerization to jet fuels through an integrated process					
	Hydrogenation ethanol conversion products	Pt/C	Batch autoclave reactor	250–300 °C 8.0–10 MPa H <sub>2</sub> 1.5 h	15–20 C-mol% Aromatic hydrocarbons	Chaipornchalerm et al. [179], Tret'yakov et al. [207]
	Ethylene oligomerization	Hierarchical ZSM-5 zeolite	Throughput four-channel flowrence reactor	300 °C 3.5 MPa 10 h	Not available 15–20% C <sub>9+</sub> aliphatics	Mohamed et al. [208]
	Catalytic transfer hydrogenation, aldol condensation, dehydrogenative coupling, and ketonization reactions	Zr-based multifunctional catalysts	Gas phase continuous-flow reaction	300–350 °C H <sub>2</sub> at atmospheric pressure 6 h	Not available 40% jet fuel range fraction	Gagliardi et al. [209]
	Direct dehydration-oligomerization of higher alcohols	Phosphotungstic acid (HPW) loaded on beta-zeolite (Hβ)	Batch reactor	200–260 °C 1.0 MPa N <sub>2</sub> 12 h	Not available 59.5% C <sub>8</sub> -C <sub>16</sub> jet fuel precursors	Liu et al. [210]
	Integrating biomass fermentation and catalytic synthesis	Bi-functional catalyst (HSAPO-34/NiHβ)	Double bed reactor	200 °C 5.0 MPa N <sub>2</sub> 5 h	70.9 C-mol %	Zhang et al. [211]

Table 2 (continued)

Pathway	Conversion method	Catalyst	Set up	Reaction conditions	Yield and selectivity %	References
Oil to jet	Ketonization and hydrogenation, aldol condensation, C-C coupling	Ni/ZSM-5 Cu/ZrO <sub>2</sub>		350 °C 6.0 MPa 3 h	Not available 77.1% C <sub>7</sub> -C <sub>18</sub> jet-fuel precursors	Luo et al. [212], Sun et al. [213]
	Hydrocracking of used cooking oil	NiMo/SiO <sub>2</sub>	Multilevel hydrocracking reactor	425 °C H <sub>2</sub> gas with a flow rate 20 mL/minute 2 h	42.80 C-mol % 39.48% of jet fuel fraction C <sub>9</sub> -C <sub>15</sub>	Agharadatu et al. [214]
	Deoxygenation by hydro-treating	Pt/mesopor. $\gamma$ -Al <sub>2</sub> O <sub>3</sub>	Fixed bed reactor	380 °C 4.0 MPa H <sub>2</sub>	73.3–78.6 C-mol %	Baik, Lee [215], Jeong, Bathula [216]
	Low-temperature pyrolysis of waste cooking oil (WCO)	CaCO <sub>3</sub> /MgCO <sub>3</sub> /SiO <sub>2</sub>	Three-necked round-bottom flask	380 °C N <sub>2</sub>	56.46 C-mol % 43.55% linear hydrocarbon, 11.1% cyclic hydrocarbon, and 1.02% aromatic	Tamim et al. [69]
	Deoxygenation of palm oil	Pd/Al <sub>2</sub> O <sub>3</sub>	Flow reactor	330 °C 5.0 MPa H <sub>2</sub> 1 h	79.5 C-mol %	Rahmawati et al. [217], Srifa et al. [218]
	Thermal hydroconversion of used palm cooking oil	Phosphoric acid-modified nano-zirconia PO <sub>4</sub> -ZrO <sub>2</sub>	Double furnace semi-batch reactor	550 °C H <sub>2</sub> at atmospheric pressure 2 h	39.44 C-mol % 33.92% jet fuel fraction	Saviola et al. [219]
	Pyrolysis fuel oil (PFO)	NiMoAl catalyst	Fixed bed reactor	360 °C 4.0–5.0 MPa H <sub>2</sub> 1 h	Bicyclic naphthenes	Samoilov et al. [220]
	One-step liquefaction, cracking and hydrogenation of <i>Chlorella sorokiniana</i> microalgae	NiMo/ $\gamma$ -Al <sub>2</sub> O <sub>3</sub>	Three-phase slurry reactor	350 °C 5.0 MPa H <sub>2</sub> 4 h	10.7–26.1 C-mol % C <sub>16</sub> -C <sub>18</sub>	Marangon et al. [221], Marinič et al. [222]

Catalysts in the alcohol-to-jet pathway play a crucial role in transforming alcohols such as ethanol into jet fuel components under different conditions. This process presents a promising avenue due to the adaptability of alcohol feedstocks and progress in catalytic techniques, as shown in the table. On the other hand, catalysts involved in the oil-to-jet pathway are essential for transforming oils derived from biomass into high-quality jet fuels, highlighting the potential of various feedstock options. Both pathways show potential for sustainable jet biofuel production, but the alcohol-to-jet pathway stands out as particularly promising because of its flexibility in using various alcohols and the advancements in catalytic technologies designed for this conversion process. HSAPO-34 refers to silica-alumina phosphate zeolite catalyst

catalysts to address these issues and enable catalyst recycling, which has led to more effective and environmentally friendly processes. The generation of high-quality jet biofuel depends significantly on reaction conditions and catalyst supports, with the former playing a more critical role [205]. During the reaction, reactant intermediate products build up on and within the porous framework of the catalyst, resulting in many catalysts losing their catalytic activity [224], as demonstrated in Table 3.

## Combustion chemistry, properties, and environmental impact of jet biofuels

As concerns about global warming and manmade carbon emissions grow, it is critical to comprehend the combustion characteristics of jet biofuels; considerable research has been done on the combustion qualities of alternative jet fuels, including the thermal stability of jet biofuels [229, 230]. In an aircraft turbine engine, evaporation of jet biofuel and ignition by high-velocity, hot air co-occur [95]. Incomplete

**Table 3** Characteristics of catalyst performance: The Fischer–Tropsch method transforms synthesis gas, a combination of hydrogen and carbon monoxide, into liquid hydrocarbons

Catalysts	Problems	Solutions
Fischer–Tropsch	High molecular mass hydrocarbons (waxes): lower diffusion rates and reactivity levels Conditions with water vapor: enhance the sintering action Sulfur compounds (block the active sites)	Using supports such as aluminum oxide could help reduce the sintering effect Tsakoumis, Rønning [225] With its strong hydrogenation ability, ruthenium could help prevent carbon buildup on catalyst surfaces Parnian, Khodadadi [197] Because of electronic interactions, applying catalytic structural promoters may increase the dispersion of the active phase and the catalytic stability Peron, Barrios [153] Using mesoporous catalysts could stop blocking support's micropores, and adding small amounts of hydrogen will prevent the unsaturated hydrocarbons' formation Choi, Lee [224]
Hydroprocessed esters and fatty acids	Leaching problem faced by commercial hydrotreatment plants is induced by water molecules formed through hydrodeoxygenation more than decarboxylation and decarbonylation Less acidity	The enlargement of the pore size catalyst to improve hydroprocessed esters and fatty acids process efficiency The hydrocracking and isomerization conversion of hydroprocessed esters and fatty acids catalysts could be improved using heteropolyacids, such as phosphotungstic acid. Improvements in jet biofuel production from methyl palmitate using phosphotungstic acid HPW loaded on nickel/mesoporous material Ni/ MCM catalyst Zhang, Cheng [155] Higher selectivity for longer-chain hydrocarbons has been seen when promoter copper Cu has been added to nickel, making it appropriate for use in diesel engines Wu, Yao [226], Loe, Santillan-Jimenez [227]
Alcohol to jet	Poor surface acidity Pore structure	The distribution of metal ions on the zeolite surface, their coordination state and interaction processes may lead to changes in the surface acidity and pore structure, resulting in enhanced catalytic activity Zhan, Hu [104] High temperatures (623–773 K), where the direct ethylene pathway is predominant, and increasing conversion rates are possible if the catalyst's Lewis acid sites prevail Banzarakt-saeva, Ovchinnikova [228]

An obstacle in Fischer–Tropsch operations involves refining catalysts to boost efficiency and selectivity toward desired hydrocarbon outputs. Resolutions encompass exploring innovative catalyst components and design to amplify product yields while curbing undesired by-products. Additionally, fine-tuning process parameters is vital to heighten the overall effectiveness and economic feasibility of Fischer–Tropsch synthesis. Hydroprocessed esters and fatty acids technology concentrate on converting sustainable raw materials, like vegetable oils or animal fats into aviation fuels. A critical aspect of these procedures revolves around achieving elevated conversion rates and upholding fuel quality standards, necessitating the development of effective catalysts and procedural conditions to enhance conversion efficiency. Alcohol-to-jet procedures pertain to the conversion of alcohols such as ethanol or butanol into jet fuel. Challenges in this domain involve formulating catalysts that exhibit high selectivity and stability throughout prolonged reaction durations, optimizing process conditions for cost-efficient production, and guaranteeing the compatibility of resultant fuels with existing aviation infrastructure. Solutions entail progress in catalyst design to enhance alcohol conversion rates, product selectivity, and process refinement for augmented efficiency. HPW and Ni/ MCM refer to heteropolyacids phosphotungstic acid and nickel/mesoporous catalysts

fuel combustion can release pollutants and unburned hydrocarbons, producing smoke or soot at sufficiently high concentrations [231, 232]. The smoke point, particulate matter, carbon dioxide, carbon monoxide emissions and derived cetane number (DCN), which characterizes the fuel's ignition properties, are all useful metrics for assessing the combustion characteristics of jet biofuel [233, 234].

Successful test flights have demonstrated the feasibility of using aviation biofuels. However, "biofuel" encompasses a broad range of chemical properties. Conventional biofuels, such as alcohols, ethers, esters, and other nitrogenated compounds, differ significantly from bio-aviation fuel, which contains no oxygen [235]. According to reports, most biofuels, including bio-aviation and conventional hydrocarbon fuels, also produce pollutants like soot and polycyclic aromatic hydrocarbons PAHs [236]. However, synthesizing carbonyl molecules like acetaldehyde, formaldehyde, higher aldehydes, acetone, and ketones can reduce emissions compared to pure hydrocarbon molecules of the same molecular size. The production of hazardous combustion pollutants from conventional biofuels is primarily avoided by deoxygenating the fuel source during the production of bio-aviation fuel. Recent research suggests that the molecular origin of soot may be linked to ring configurations like cyclopentadiene, which have a weak C–H bond. Breaking these bonds produces radicals with extended pi-electron conjugation times [237].

Growing stabilized radicals undergo recurrent coupling reactions that prolong conjugation and result in cluster formation. Hence, careful consideration must be given to the modulation of the aromatic percentage when creating jet biofuel [238]. Although the molecular classes differ, jet biofuel can still benefit from what we know about jet fuel made from petroleum. Studies on alternative bio-aviation fuels have focused on how the chemical structure affects auto-ignition, specifically examining the effects of cycloparaffinic, *iso*-paraffinic, and aromatic structures. Moreover, oxidative steam reforming contrasts with the fuel reformation of aviation jet fuel derived from petroleum jet propellant-8 (JP-8) and hydroprocessed renewable jet fuel HRJs [239].

To meet the various aviation fuel requirements, the chemical groups should be balanced appropriately, as concluded in Walluk, Bradley [240] study. In a survey by Fortin and Laesecke [241], nine samples of aircraft turbine fuel, including synthetic Fischer–Tropsch, petroleum, and renewable fuels derived from biomass feedstock, were tested for kinematic viscosity. The measured viscosities were found to differ significantly. Although jet biofuel has a comparable hydrocarbon makeup, it offers two key advantages: it uses a feedstock of renewable carbon and is sulfate-free, both of which have considerable environmental benefits. Current environmental studies focus primarily on assessing the effects of combining bio-aviation

fuels with conventional aviation fuels. In a flame tube facility, Hicks, Tedder [242] tested jet propellant-8 (JP-8) and bioderived aviation fuel for emissions and combustion performance. The combustion efficiency and emissions were found to be comparable for both jet propellant-8 and aviation fuel generated from plants, and both exhibit a similar hydroxyl OH picture structure at the dome outlet. Table 4 provides a summary comparison of different fuels and their properties, including smoke point, flash point, freezing point, viscosity and density.

As mentioned earlier, an alternative fuel for airplane blending components must undergo an approval process that can take 5–10 years. Compared to other transportation fuels, jet fuel must adhere to tighter and more stringent requirements [243]. Turbine engine performance is susceptible to the chemical composition of jet biofuels. Unlike traditional jet fuels, which can include hundreds of distinct hydrocarbons, synthesized hydrocarbons often have simpler chemical compositions. Alcohol to jet-synthesized paraffinic kerosene ATJ-SPK, Fischer–Tropsch hydroprocessed synthesized paraffinic kerosene FT-SPK, and hydroprocessed esters and fatty acids HEFA are composed of *n*-, *iso*-, and cycloparaffins. At the same time, at least 97% of farnesane is *iso*-paraffin in synthetic *iso*-paraffins, HEFA, FT-SPK, and ATJ-SPK have little aromatic content, while up to 20% weight of alkylated aromatics are present in FT-SPK/A [95]. Evaluating the performance aspects of jet biofuels and comparing them with specified requirements is crucial for ensuring fuel safety, reliability, and compatibility with current aircraft components and aero engines ASTM D7566-18. Jet biofuel's performance characteristics are critical for gauging the potential of "drop-in" alternative jet fuels. The performance features of jet biofuels are divided into thermal oxidation stability, low-temperature fluidity, fuel compatibility, fuel volatility, aircraft system and combustion property, and fuel metering to conduct a thorough assessment of jet biofuels' operational qualities and figure out how the chemical composition of jet biofuels relates to their physical properties.

Jet fuel's ability to evaporate and burn in the presence of quickly moving hot air in a turbine engine is crucial. Unburned hydrocarbons and particulate matter are emitted primarily due to incomplete combustion, which harms the environment. Smoke or soot describes these highly concentrated visible particulates [70]. Fuels with high smoke points have a low likelihood of smoke production. Although ASTM D7566 does not contain a smoke point limit for synthetic hydrocarbons, numerous studies have been conducted on jet biofuels' smoke point [244]. Inhaling particulate matter emissions can be hazardous as they can lead to the creation of haze and smog. The main contributing factor to their particulate matter emissions is the percentage of aromatics in alternative jet fuel [159, 245].



**Table 4** Comparison of different fuels and their properties, encompassing smoke point, freezing point, flash point, density, and viscosity, is critical in fuel selection

Fuel	Smoke point (mm)	Freezing point (°C)	Flash point (°C)	Density at 15 °C (kg/m <sup>3</sup> )	Viscosity at – 20 °C (mm <sup>2</sup> /s)	References
Jet A1	25	– 54.5	48	816	4.08	Goh et al. [172], Duong et al. [252]
Shell FT-SPK	40	– 55	44	737	2.6	Yang et al. [95], Corporan et al. [253]
Sasol FT-SPK	> 40	< – 77	44	762	3.8	Yang et al. [95], Corporan et al. [253]
Branched cyclohexane fuel	–	– 80	–	804	34.4	Han et al. [254]
Geranyl acetone-derived fuel	–	– 72	51	–	–	Ju et al. [255]
Used cooking oil HEFA	> 50	– 54.3	42	760	3.8	Buffi et al. [256]
Palm kernel oil	41.3~45.3	–	52~60.5	790~870	1.88~9.63	Why, Ong [70]
Soybean oil	–	< – 47	> 38	> 775	–	Lim et al. [257]
Waste cooking oil	> 50	– 54.3	42	759.9	3.8	Goh et al. [258]
Hydrogenated orange oil and D-limonene	18	– 47	38	775~840	3.09	Donoso et al. [251]

In the realm of commercial aviation, Jet A-1 serves as a primary fuel choice, characterized by a carbon number distribution ranging from 8 to 16. The carbon number range of jet fuel undergoes stringent control within fuel refining processes to achieve optimal fuel attributes. Among alternative jet fuels, Shell FT-SPK fuel, distinguished by a relatively narrow carbon range predominantly composed of C<sub>9</sub> and C<sub>10</sub> linear *n*-paraffins, exhibited the highest volume swell percentage at 9.6%. Fuels with elevated smoke points tend to burn more cleanly, making them preferable for culinary purposes to mitigate the emission of harmful substances. Fuels with lower freezing points offer advantages in colder climates by maintaining liquid form at lower temperatures, ensuring improved flow and usability. Moreover, fuels with higher flash points facilitate safer handling and storage practices. Enhanced fuel densities generally correlate with increased energy content per unit volume, translating to heightened fuel efficiency. Fuels featuring lower viscosity levels promote smoother flow, enhancing combustion efficiency and ease of handling. These properties are pivotal in determining fuel performance, safety, and overall efficiency. Jet A1 denotes traditional kerosene, while Shell FT-SPK and Sasol FT-SPK signify companies that assessed Fischer–Tropsch -synthesized paraffinic kerosene fuels; HEFA pertains to hydroprocessed esters and fatty acids

Jet biofuel generated from bio-based by-products is a potential replacement for traditional jet fuel with regards to lowering the environmental impact of aviation. Life-cycle assessment is commonly used to examine the environmental consequences of jet biofuels [127, 246]. Moretti, Vera [247] presented both consequential life-cycle assessment and attributional models (attributable cause) to evaluate a novel jet biofuel made from potato waste in the Netherlands. Both models produced conflicting results regarding this jet biofuel's overall environmental performance. According to the attributional life-cycle assessment, this jet biofuel can decrease greenhouse gas emissions by almost 60% compared to traditional jet fuel. Jet biofuels demonstrate life-cycle greenhouse gas emissions that are 89–91% lower than those of fossil jet fuels. This significant decrease is especially pertinent for production chains using wood-based feedstocks via sophisticated methods like rapid pyrolysis and hydrothermal liquefaction [248]. The European Union's Renewable Energy Directive has a goal for biofuels to achieve a minimum of 65% lower emissions than fossil fuels, with several jet biofuels anticipated to surpass this, with reductions of around 90% by 2025. In Sweden, the regulatory framework requires that jet biofuels must maintain a carbon footprint

not exceeding 16 g CO<sub>2</sub>eq/MJ by 2021, reducing to a range of 8–10 g CO<sub>2</sub>eq/MJ by 2025. This aligns with the broader EU goal of reducing emissions from aviation fuels. The aviation sector is projected to require over 100 billion liters per year of jet biofuel by 2050 to meet its emission reduction targets, which translates into a substantial decrease in overall aviation-related greenhouse gas emissions. Current consumption data indicate a gradual increase in sustainable aviation fuel SAF usage, with approximately 24.5 million gallons consumed in 2023, reflecting growing interest and investment in jet biofuel technologies.

In contrast, using imported soybean meals as feed was predicted by life-cycle assessment to raise greenhouse gas emissions by 70%, or if switching to European animal feed would result in a significantly reduced benefit (5–40%) for reducing climate change. Sundararaj, Kumar [249] investigated how different biofuel blends affect gas turbine performance and emissions. The blends were mixed with traditional kerosene-type Jet A1 in variable proportions and evaluated in a combustion chamber resembling a can with two separate operating conditions. By measuring the rise in temperature, emission indices, and combustion efficiency, the performance of the combustor for different mixes was

assessed. The general pattern shown was a noticeable reduction in unburnt hydrocarbons, carbon monoxide, and soot with increasing stages in the blends of camelina. However, because camelina-based blends burn at higher temperatures, the nitrogen oxide (NO<sub>x</sub>) emissions somewhat increase.

In their study, [250] investigated the effects of adding ceria nanoparticles CeO<sub>2</sub> (NPs) and jatropha synthesized paraffinic kerosene JSPK to jet-A aviation fuel on emissions. The engine's can-combustor was operated under realistic flying conditions. Aviation turbine fuel Jet-A (ATF), JSPK (20%) blended with 80% Jet-A (A80J20), and JSPK (70% blended with 30% Jet-A (A30J70) were the three basic fuel combinations employed in the study. Adding nanoparticles to the base fuel blends at weights of 0.5 and 1 percent resulted in nine different fuel types. Based on the findings, it was determined that a higher concentration of ceria nanoparticles led to a reduction in nitrogen oxide NO<sub>x</sub>. Moreover, the combination of jatropha and ceria CeO<sub>2</sub> resulted in reduced carbon monoxide, unburnt hydrocarbons, and soot emissions. Therefore, ceria nanoparticles CeO<sub>2</sub> NPs can be a significant addition to aviation fuel as they help eliminate harmful emissions. Orange peels leftover from orange juice production were used to make orange oil through steam distillation. To enhance the quality of the orange oil and reduce its sooting tendency, distilled D-limonene and orange oil were subjected to hydrogenation reactions at pressures ranging from 3 to 18 bar, which are scientifically practicable. Hydrogenated orange oil and D-limonene were examined in terms of their characteristics at varying conversion rates. The temperature at which crystallization begins, as well as other vital parameters such as viscosity, density, flash point, smoke point, lubricity, and heating value, were determined. According to Donoso, Bolonio [251], to assess the viability of these hydro-biofuels as bio-based aircraft blending components, they were mixed with Jet A1. The results showed that up to 15% of partly hydrogenated Jet A1 could be combined with orange oil without significantly affecting the aircraft's performance. However, flammability mitigation measures would be required for Jet A1 to use more drop-in biofuel.

## Strategies and economic implications

The role of renewable energy sources in the current energy system is growing. Wind, solar, hydro, and geothermal power are all examples of renewable energy that can be used as a green replacement for more conventional fuels [259, 260]. There are many reasons for expanding renewable energy sources, including increasing concern about climate change, declining costs of renewable technologies, and government policies promoting renewable energy [261]. Renewable energy sources, including jet biofuel production,

have become increasingly important in supplying enough energy without increasing pollution levels around the globe and have several advantages over traditional energy sources, including reduced dependence on foreign oil, lower greenhouse gas emissions and improved energy security [262, 263]. In addition, renewable energy technologies are becoming more efficient and cost-competitive, making them an attractive option for both large-scale and small-scale energy users. However, challenges remain, including the intermittency of some renewable energy sources and the need for additional infrastructure and storage to fully realize their potential [264]. Table 5 presents a comparative analysis of the characteristics of each pathway, including energy efficiency, greenhouse gas emissions, and minimum selling price. Nonetheless, renewable energy supply is critical to our efforts to transition to a more sustainable energy future. Figure 11 depicts a projection of the global renewable energy supply up to the year 2050. This illustration provides insights into the potential growth and development of sustainable energy sources from various countries. In addition, Fig. 12 demonstrates a projection of the global energy supply up to the year 2050 IEA [265]. The figure presents estimated trends in global energy production, considering factors such as population growth, economic development, technological advancements, and energy policies [266]. According to the forecast, renewable energy sources like wind, solar, hydropower, and cutting-edge bioenergy will increase their part of the global energy mix, while the share of fossil fuels like coal, oil, and gas will decline. Concerns about climate change and the necessity of reducing emissions of greenhouse gases are motivating this transition to renewable energy sources [267]. However, achieving a sustainable energy future will require significant investments in renewable energy infrastructure and innovative policies to support their deployment.

Several countries have set goals to enhance their use of jet biofuel in the aviation sector to mitigate the adverse effects of aviation on the environment. Jet biofuel manufacturing and distribution still face issues concerning its economic sustainability. It is predicted that global aviation will see a 5% annual increase by 2050 [8, 268]. ASTM D 1655 is a standard developed by the ASTM subcommittee on aviation fuels. Hydrocarbon distillate products now available on the market meet these criteria, and they are sourced from fossil fuels such as natural gas liquid condensates, crude oil, shale oil, heavy oil, and oil sands. Fischer–Tropsch-synthetic paraffinic kerosene (FT-SPK), and hydroprocessed esters and fatty acids (HEFA) are two examples of alternative jet fuels that have recently been authorized by ASTM and published in the ASTM D7566 Standard. Specifications for aviation turbine fuel with synthesized hydrocarbons are defined as alternate fuels that can be blended with semi-synthetic jet fuel and yet meet the standards set out in ASTM D1655

**Table 5** Comparative analysis of different pathways for jet biofuel production, such as hydroprocessed esters and fatty acids (HEFA), catalytic hydrothermolysis (CH), Fischer–Tropsch (FT), and alcohol to Jet (ATJ), involves evaluating various characteristics including energy efficiency (MJ), greenhouse gas emissions (g CO<sub>2-eq</sub>/MJ), and minimum selling price (USD•gallon<sup>-1</sup>)

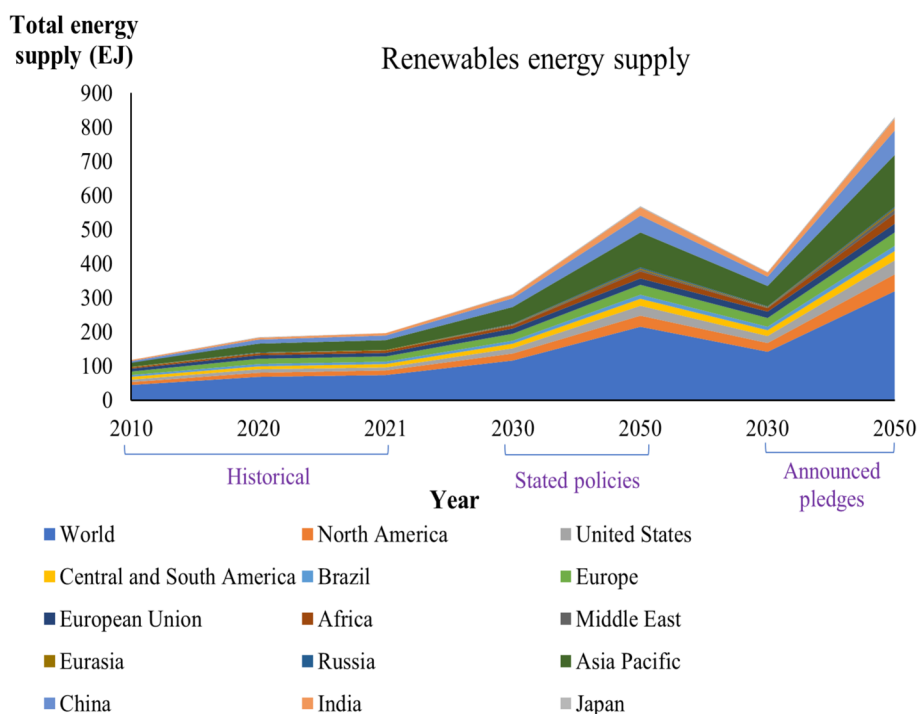
Pathway	Feedstock	Energy efficiency (MJ)	GHG emission (g CO <sub>2-eq</sub> /MJ)	MJSP (USD•gallon <sup>-1</sup> )	References
Hydroprocessed esters and fatty acids (HEFA)	Camelina oil	3.5–4.5	3.06–53.10	1.63–4.62	Wei et al. [10], Shila and Johnson [286]
	Soybean oil	3.5–4.5	31.0–57.0	3.82–4.39	D’Ascenzo et al. [287], Song et al. [288], Rosales et al. [289]
	Jatropha	3.5–5.0	33.0–40.0	5.42–5.74	Sharma et al. [277], Zemanek et al. [290], Abdudeen et al. [291]
	Waste oils and animal fat	4.0–5.0	13.30–21.40	2.36–4.73	Osman et al. [57], Monteiro et al. [292], Liu and Yang [293]
	Microalgae	4.0–6.0	27.0–38.0	31.98	Martinez-Villarreal et al. [294], Atnoorkar et al. [295], Prussi et al. [296]
Catalytic hydrothermolysis	Camelina oils	0.58–0.89	21.20–39.30	2.48–3.23	Wei et al. [10], Natelson et al. [297], Tzanetis et al. [298]
	Lignocellulose	Not available	Not available	3.66–5.06	De Jong, Hoefnagels et al. [299], Wang et al. [300]
Fischer–Tropsch	Woody biomass	0.40–0.53	–1.60–18.20	6.23–7.57	Wei et al. [10], De Jong, Hoefnagels et al. [299], Bhatt et al. [301]
Alcohol to jet	Sugar cane	3.0–6.0	–27.0–19.7	3.65–8.08	Voß et al. [302], Costa Silva et al. [303]
	Corn grain	Not available	47.5–117.5	3.84–6.63	Wang et al. [304]
	Lignocellulose	Not available	32.0–73.0	7.30–7.82	Björnsson and Ericsson [248], Emmanouilidou et al. [305], Hong et al. [306]

HEFA processes, which involve the hydroprocessing of oils and fats, are known for their relatively high energy efficiency and low greenhouse gas emissions compared to conventional fossil fuels. However, the minimum selling price of HEFA jet biofuel can be influenced by the cost and availability of feedstock oils. Fischer–Tropsch technology, which converts syngas into liquid hydrocarbons, can achieve moderate to high energy efficiencies but may have higher greenhouse gas emissions compared to some other pathways. Alcohol-to-jet processes can vary in energy efficiency depending on the specific alcohols and conversion methods used. Greenhouse gas emissions from alcohol to jet pathways are generally lower compared to conventional jet fuels. The minimum selling price of alcohol to jet biofuel is influenced by the cost of alcohol feedstocks and the efficiency of the conversion process. The greenhouse gas emission of conventional jet fuel is 90 g CO<sub>2-eq</sub>/MJ. MJ refers to megajoules

[269]. All jet fuels must comply with strict specifications defined by the original equipment manufacturer’s documentation for engines and airframes and approved by regulatory authorities [270]. These requirements are met by fuel specifications such as Def Stan 91–091 in Europe, EI/JIG AFQRJOS in the USA, GOST 10227 in Russia, GB 6537 in China, and ASTM 1655 in the USA. There has been some debate over whether or not jet fuel can legally contain trace amounts of fatty acid methyl ester (FAME). On May 2, 2015, the European Joint Inspection Group recognized FAME as an identified incidental material in jet fuel at concentrations of up to 50 parts per million [271]. Properties and requirements for aviation biofuels are codified in ASTM standards. These standards are used to test all aviation biofuel

candidates [272]. The reliability of research activities can be determined by the results of ASTM tests, which serve as dependable indicators. Figure 13 illustrates that developing various ASTM activities directly results from research in this field.

The high price of jet biofuel is a significant obstacle to its use in the economy. Depending on the feedstock, the production costs of jet biofuel can be higher than those of conventional jet fuel [261]. According to research commissioned by the European Commission, manufacturing jet biofuel costs roughly two to four times that of conventional jet fuel. In addition, the distribution infrastructure for jet biofuel is inadequate, driving up its cost. Despite these challenges, there are several opportunities for adopting jet biofuel in



**Fig. 11** Renewable energy supply in exajoules (EJ) from 2010 to 2021 (Historical), projected scenarios from 2030 to 2050 based on stated STEPS policies and announced pledges scenario APS. Based on data from 2010 to 2021, the worldwide renewable energy supply has substantially increased. This growth is particularly evident in integrating renewable sources like solar, wind, hydropower, and bio-fuels. This expansion indicates a transition toward cleaner and more sustainable energy sources as a reaction to environmental issues and the need for security in energy supply. When considering the projected scenarios from 2030 to 2050, which are based on the STEPS and APS, it is expected that the availability of renewable energy will

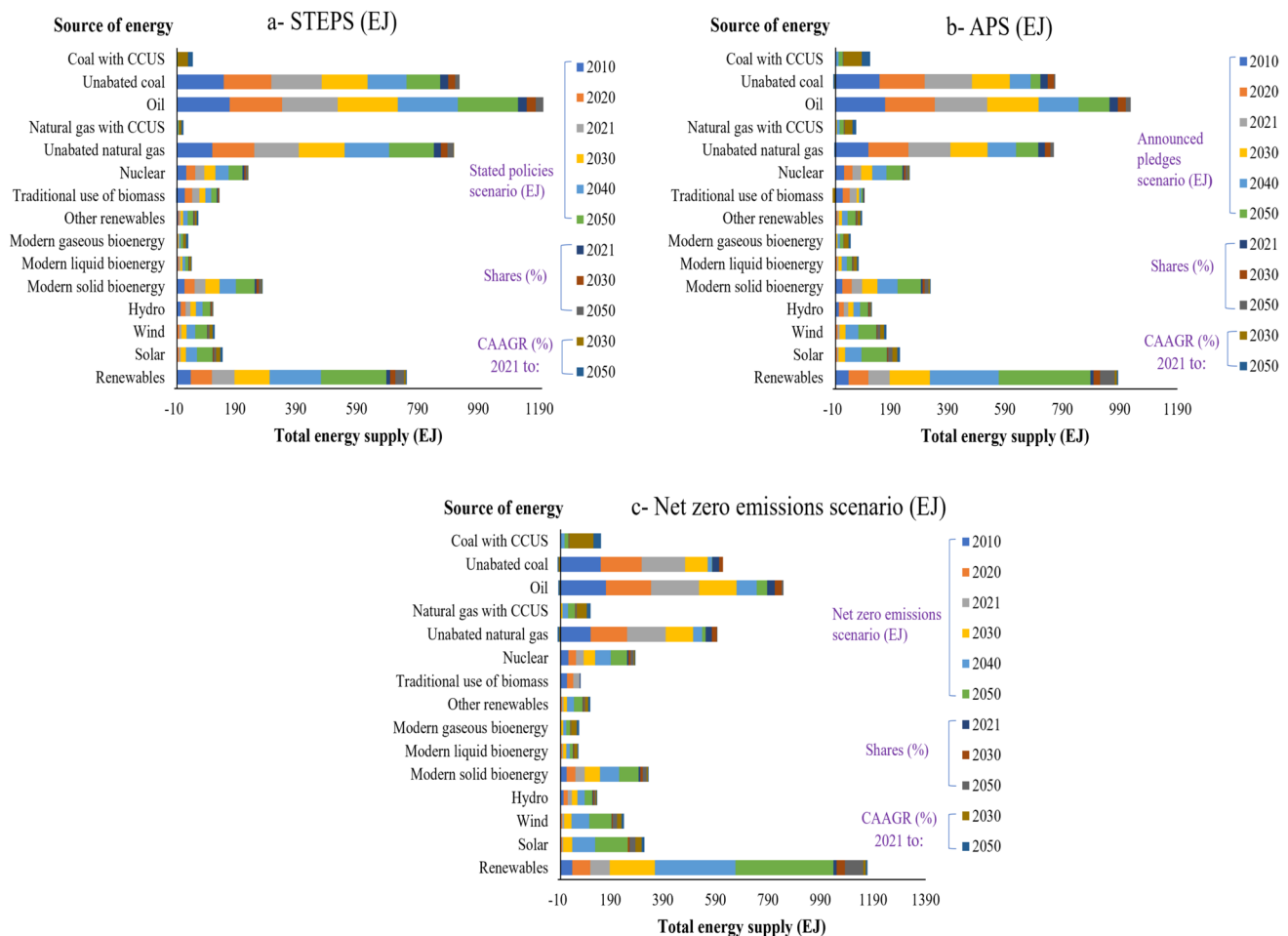
consistently increase. According to the STEPS scenario, which considers existing laws and pledges, renewable energy is projected to influence worldwide energy composition substantially. Conversely, the APS scenario, which mirrors more ambitious objectives and commitments made by governments and organizations, forecasts a faster pace of expansion for renewable energy. This suggests that the proportion of renewables in the total energy supply will increase by 2050. These scenarios highlight the continuous shift toward a more environmentally friendly and low-emission energy future propelled by the growing use of renewable energy technology. EJ refers to exajoules

the aviation industry. For instance, jet biofuel production can create new employment opportunities in the agriculture and energy sectors and provide a new source of revenue for farmers. Additionally, since aviation is a major source of greenhouse gas emissions, jet biofuel can help reduce this factor. Greenhouse gas emissions can be reduced by up to 80% when using jet biofuel, according to the International Air Transport Association (IATA) [3, 273].

Two broad categories of policies regarding biofuels are typically easy to spot: “technology push” and “market pull”. These policies complement each other and promote biofuel production and market development differently. Combining the two policy forms is required to increase jet biofuel production and use significantly. Since commercial volumes of jet biofuels are currently low, the application of mandates for jet biofuels may be premature despite the importance of market-pull policies in biofuel expansion. Further research and development will be necessary to expand the market for jet biofuels, and market-pull policies can help create demand for jet biofuels as they become more widely

available IRENA [274]. Effective price-based market-pull policies will play a considerably more critical role in promoting jet biofuel than they did in developing conventional biofuels like bioethanol/biodiesel due to the significant price differential between the two. Investment in existing and planned jet biofuel production facilities will benefit from these policies, complementing “technology push” measures [275]. Grants or loan guarantees for jet biofuel-specific facilities will need to account for the more significant capital expenditure (CAPEX) required to create them due to the complexity and increased investment needed in producing jet biofuel compared to conventional biofuels. Jet biofuel costs will be lowered for consumers, and more investors will be attracted to the market if regulations like these are implemented [276].

Jet biofuels’ development and production expenses vary markedly according to the technology utilized. Fuels generated by the hydroprocessed esters and fatty acids (HEFA) route are now anticipated to be three to six times more expensive than traditional jet fuel, with a cost of roughly

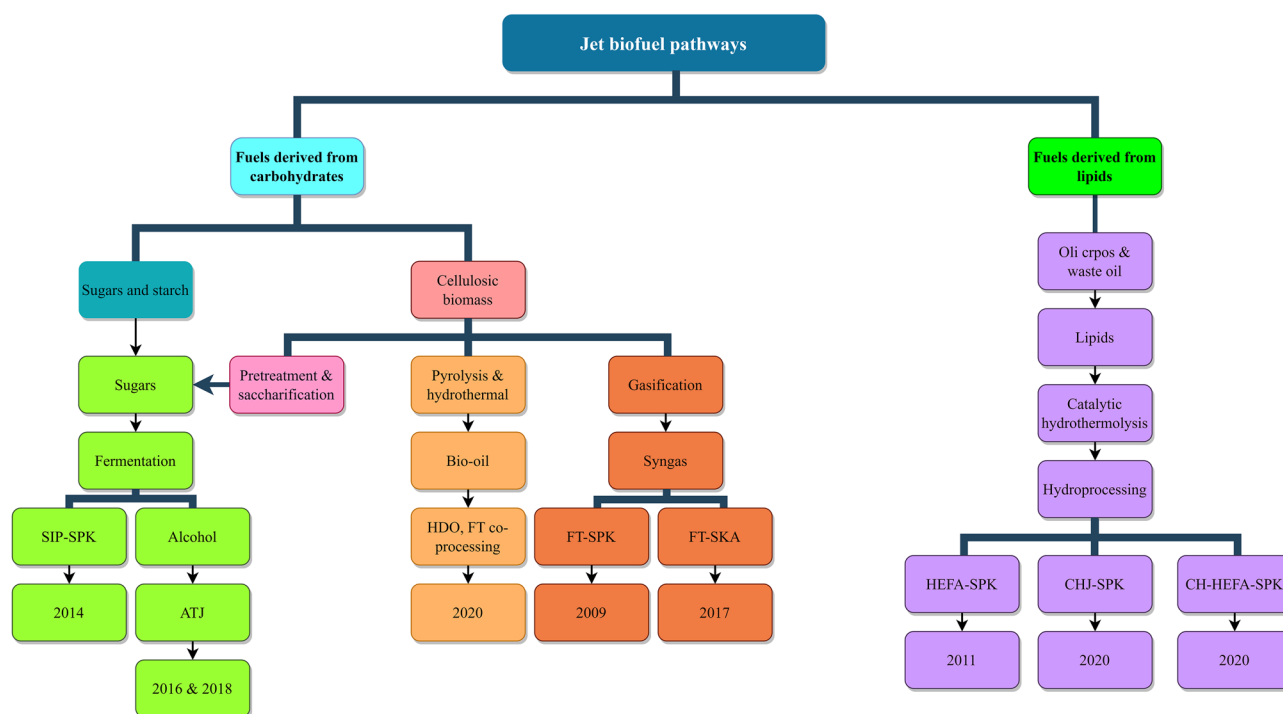


**Fig. 12** World energy supply in exajoules (EJ) under three projected scenarios; **a** stated policies scenario STEPS; **b** announced pledges scenario APS and **c** net-zero emissions by 2050. The STEPS considers existing policies and commitments within the anticipated global energy supply framework across three different scenarios. It suggests a steady rise in the use of renewable energy while maintaining dependence on fossil fuels, resulting in a moderate expansion in the total energy supply. APS has more ambitious objectives and commitments, aiming for a more rapid shift toward renewable energy sources while significantly reducing the combustion of fossil fuels. In con-

trast, the scenario of net-zero emissions by 2050 establishes a more assertive path by prioritizing a swift transition to renewable energy sources and the widespread implementation of carbon capture technologies. This approach aims to substantially decrease emissions and a near-total elimination of fossil fuels by 2050. These scenarios illustrate different approaches to achieving a sustainable energy future, underscoring the significance of policy choices and pledges in influencing the worldwide energy infrastructure. EJ refers to exajoules, STEPS, and APS refer to stated policies and announced pledges

\$2,124 per tonne as of September 2020, equating to about \$1.70 per liter [274]. The elevated cost is a major barrier to broad adoption in the aviation industry. Comprehensive techno-economic research revealed that the minimum selling price (MSP) for lignin-based jet fuel varies between \$6.35 and \$1.76 per gallon, depending upon conversion rates and manufacturing capacity. For alternative methods such as alcohol-to-jet (ATJ), minimum selling price estimates fluctuate between \$3.65 and \$5.21 per gallon [277]. These numbers underscore the variety in economic feasibility across various biofuel production techniques. Capital expenditures for bio-refineries generating jet biofuels may be considerable. A lignocellulosic ethanol biorefinery, which

also produces lignin jet fuel, with capital expenditures projected between \$38 million and \$39 million for a production capacity ranging from 1.5 to 16.6 million gallons annually [278]. These investments are essential for increasing output and realizing economies of scale. Although current jet biofuel prices are significantly higher than conventional jet fuel, projections indicate that as more facilities come online, prices could decrease. The International Civil Aviation Organization (ICAO) suggests that achieving the necessary scale may require building approximately 170 new large bio-refineries annually from 2020 to 2050, necessitating an investment of \$15 billion to \$60 billion annually. The choice of feedstock greatly influences both the cost and greenhouse



**Fig. 13** ASTM-approved periodic jet biofuel pathways. ASTM has recognized several jet biofuel routes generated from carbohydrates and lipids, therefore assuring their adherence to aviation fuel standards. Carbohydrate-based approaches generally entail the transformation of sugars obtained from biomass sources by methods such as fermentation and catalytic upgrading to generate bio-based jet fuels. In contrast, lipid-based routes transform oils and fats derived from sources such as algae, waste oils, or oilseed crops into environmentally friendly jet fuels by methods such as hydroprocessing. The ASTM-approved routes guarantee that jet biofuels produced from carbohydrates and lipids satisfy rigorous criteria for characteristics such as energy content, freezing point, and stability. This allows them to

be implemented as direct substitutes for traditional jet fuels and contribute to the global effort to decrease greenhouse gas emissions in the aviation industry. SIP-SPK, ATJ, HDO, FT, FT-SPK, FT-SKA, HEFA-SPK, CHJ-SPK and CH-HEFA-SPK refer to synthetic *iso*-paraffins- synthesized paraffinic kerosene, alcohol to jet, hydrodeoxygenation, Fischer–Tropsch, Fischer–Tropsch-synthesized paraffinic kerosene, Fischer–Tropsch—synthesized kerosene with aromatics, hydroprocessed esters and fatty acids-synthesized paraffinic kerosene, catalytic hydrothermolysis jet-synthesized paraffinic kerosene and catalytic hydrothermolysis-hydroprocessed esters and fatty acids-synthesized paraffinic kerosene, respectively

gas emissions profiles of jet biofuels. For instance, using cellulosic feedstocks like corn stover can yield a minimum fuel selling price between \$1.01 and \$1.32 per liter, depending on process efficiencies achieved through metabolic engineering [259]. Furthermore, integrating sustainable land-use practices can enhance both economic viability and environmental sustainability.

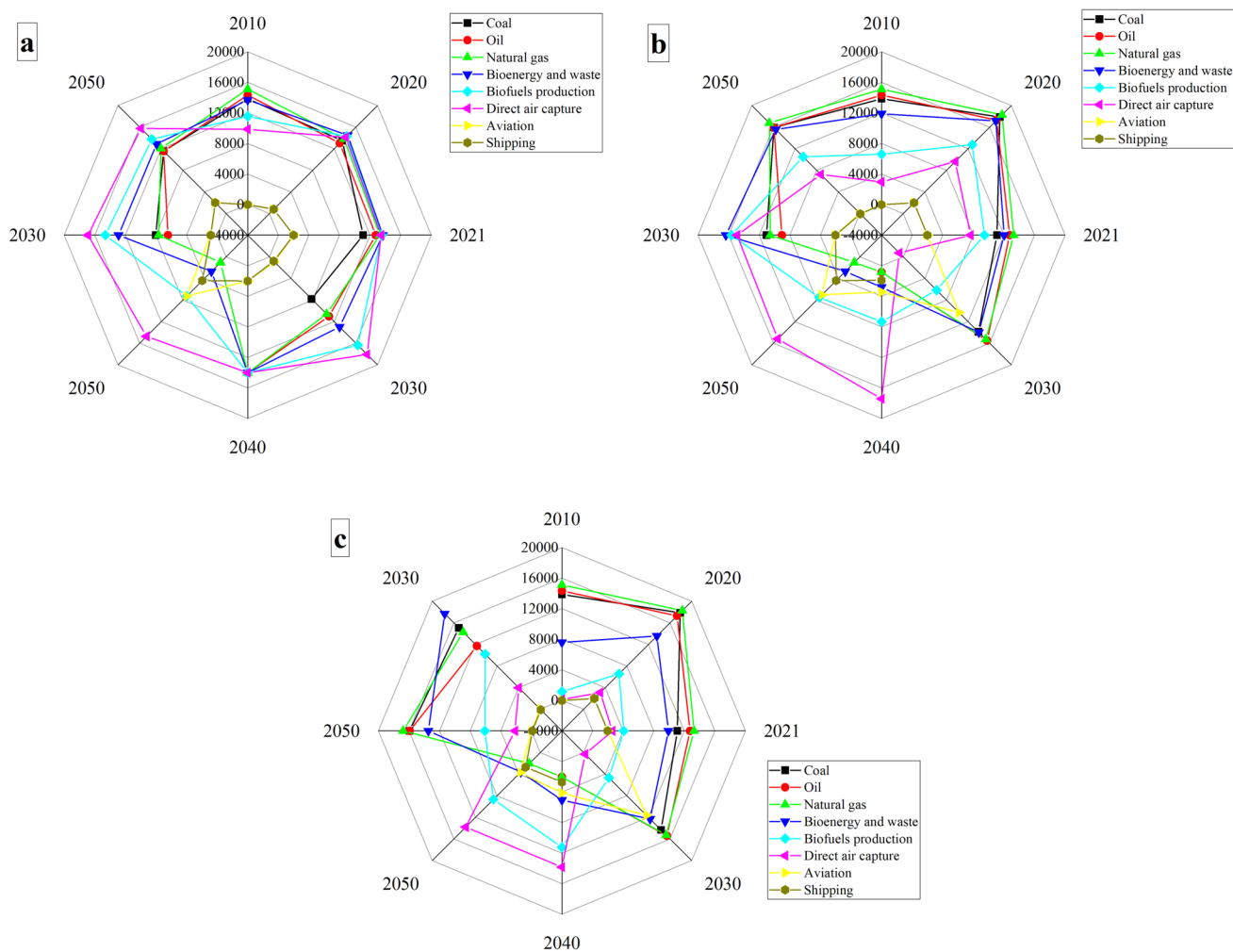
As demonstrated in Sweden and Norway, market-pull policies like mandates should be linked to emission reduction targets, such as those used in low-carbon fuel standards LCFSSs, rather than just defining volumetric fuel targets where the actual carbon intensity of the jet biofuel is less essential [279, 280]. This method will be more successful in lowering carbon emissions and encouraging the creation and usage of more environmentally friendly jet biofuels [281, 282]. The focus on carbon intensity reflects that reducing carbon emissions is critical in mitigating climate change, and policies prioritizing this goal will be more effective in promoting the adoption of jet biofuels with a lower carbon

intensity. By implementing market-pull policies linked to emission reduction targets, supporting a low-carbon economy and encouraging the development of more sustainable jet biofuels is a win–win for policymakers [283]. Although over 60 nations have implemented biofuel blending mandates and other obligation policies to increase the use of bioethanol and biodiesel, so-called drop-in biofuels continue to face significant challenges [284]. Generally, limited blends of lower-carbon fuels have been utilized under these mandates and policies, except in Brazil, where flex-fuel vehicles account for the vast majority of sales. However, a significant obstacle known as the blend wall has hindered the use of these fuels and poses a major impediment to achieving substantial reductions in carbon emissions within the transportation sector. The blend wall refers to the technical limitation of ethanol blended with gasoline, typically no more than 10% by volume, without modifying the existing fuel infrastructure or engines. Developing new technologies and infrastructure to get around this restriction is critical

for increasing reliance on biofuels and achieving carbon emission reduction targets [285]. The graph represented in Fig. 14 depicts the global carbon dioxide emissions for the period between 2010 and 2050, incorporating three distinct projected scenarios: (I) stated policies scenario (STEPS), (II) announced pledges scenario (APS) and (III) net-zero emissions by 2050 Scenario.

## Perspective

The aviation industry has experienced significant growth due to the increasing demand for long-distance travel. However, greenhouse gas emissions have risen as fossil jet fuel has become more widely used. Sustainable aviation fuel (SAF) has emerged as a critical technique to minimize carbon emissions from the aviation sector, which has environmental repercussions [262]. Recent investigations have highlighted challenges and limitations associated with producing jet bio-fuel using various technologies, which must be addressed to improve future sustainability.



**Fig. 14** World carbon dioxide emissions in millions of tonnes (Mt CO<sub>2</sub>) based on three projected scenarios adopted from the International Energy Agency IEA report [265]; **a** stated policies scenario STEPS; **b** announced pledges scenario APS and; **c** net-zero emissions by 2050. Within three specified scenarios, STEPS predicts a steady escalation in emissions due to existing policies and obligations, leading to a mild elevation in global carbon dioxide levels. APS considers increasingly ambitious goals and commitments, resulting

in a decelerated increase in carbon dioxide emissions as nations and organizations become more determined to decrease their carbon dioxide footprint. Conversely, the net-zero emissions by 2050 scenario aim to substantially reduce carbon dioxide emissions worldwide by 2050, requiring swift and comprehensive decarbonization strategies in many industries. These scenarios highlight the need for proactive actions and ambitious goals to reduce climate change and shift toward a more sustainable, low-carbon future

- Due to numerous issues with the production process and the fuel's viability from an economic standpoint, commercial utilization is comparatively restricted [172].
- Depending on the feedstock and processing method, paraffinic and naphthenic chemicals are the main constituents for jet biofuel. Some likewise contain aromatic compounds. The conventional HEFA and Fischer–Tropsch procedures produce no aromatics or cycloalkanes, which may result in specific performance problems [307].
- Investigating new alternatives for non-edible feedstocks through supply assurance over the extended term makes it possible to change the options for feedstock jet biofuel generation usage.
- Isomerization, cyclization, and aromatization convert fuel precursors into cycloalkanes, *iso*-paraffins and aromatics. It is challenging to create cycloalkanes, *iso*-paraffins and aromatics from hemicellulose and cellulose despite these hydrocarbons being essential for aviation fuels. To ensure that the lignocellulosic aviation fuel produced from the transformation process meets quality criteria, isomerization, cyclization, and aromatization must occur.
- The complex fatty acid and impurity makeup of raw biomass feedstock will reduce the conversion process's activity and selectivity of catalysts [308, 309].
- Hydrogen is added after functional groups that contain oxygen are removed. One of the distinguishing characteristics of biomass that sets it apart from fossil fuels is its high oxygen concentration. Deoxygenation or hydrodeoxygenation is often essential to convert biomass or its derivatives into valuable liquid fuels.
- Catalysts that can selectively break C–O–C bonds, form C–C bonds, or have tunable catalytic activity are urgently needed to speed up hydrogenolysis and hydrogenation reactions.
- The selectivity of jet biofuel can be enhanced by creating a more efficient catalyst for its processing. Enhancing the catalyst's strong hydrodeoxygenation activity or activating more of its metal sites would be an example of this [310].
- Economically viable and environmentally responsible techniques should be employed in the catalytic transformation of biomass into jet fuel. Highly integrated systems must be created to accomplish these objectives.
- *Feedstock availability*: the availability of sustainable and renewable feedstock is essential in the process of creating jet biofuel. Unfortunately, there is a scarcity of feedstock at the moment, and there is a need to develop new and innovative approaches for sourcing and producing feedstock.
- *Catalyst development*: catalysts that efficiently and selectively transform feedstock into jet biofuel are urgently needed. Catalysts must be able to operate under mild conditions and selectively convert the feedstock into the desired product.
- *Process optimization*: high yields and selectivity can only be achieved by carefully tuning the catalytic conversion process. The process must be optimized to minimize energy consumption and waste generation.
- *Techno-economic analyses of emerging pathways*: perform thorough techno-economic evaluations of novel jet biofuel generation techniques, including Fischer–Tropsch synthesis and alcohol-to-jet (ATJ) processes. Comprehending the economic ramifications of these technologies will facilitate the identification of feasible avenues for commercial expansion. Recent evaluations indicate that while HEFA is economically feasible, other paths require more research to achieve cost competitiveness.
- *Integration with renewable energy sources*: explore the integration of jet biofuel production processes with renewable energy systems to enhance sustainability. Utilizing renewable energy for biofuel production can significantly lower greenhouse gas emissions and operational costs. This aligns with trends toward decarbonizing the aviation sector through sustainable practices.
- *Life-cycle assessment (LCA) Updates*: consistently upgrade life-cycle evaluations of jet biofuels to include updated information on emissions reductions and environmental effects. Ongoing improvements to life-cycle assessment are essential for maintaining adherence to regulatory frameworks such as the EU's renewable energy directive, which requires substantial reductions in greenhouse gas emissions from aviation fuels.
- *Pilot projects for commercialization*: launch pilot initiatives that illustrate the scalability of jet biofuel generation systems in practical environments. Pilot programs may provide essential data on operational difficulties and economic feasibility, facilitating wider implementation in the aviation sector. Cooperation among academic institutions, businesses, and governmental bodies may further these efforts.

Jet biofuel production through catalytic conversion is a promising approach for decreasing greenhouse gas output and bolstering aviation's long-term viability. However, several challenges exist in this process, including various obstacles. These challenges need to be addressed to optimize the jet biofuel production process through catalytic conversion.

Despite these challenges, there are several promising perspectives for jet biofuel production through catalytic conversion, including:



- *Integration with existing refineries*: refineries can be retrofitted to produce jet biofuel, which can provide the necessary infrastructure as well as materials for producing jet biofuel.
- *Co-feeding with fossil fuels*: co-feeding bio-feedstock with fossil fuels can help to increase the usage of renewable energy sources while decreasing the carbon intensity of fossil fuels.
- *Use of waste biomass*: jet biofuel can be developed from waste biomass, aiding in waste reduction and contributing to environmental sustainability.

Overall, jet biofuel production through catalytic conversion has the potential to help the aviation sector minimize greenhouse gas emissions and advance sustainability. However, more study and development are needed to address the current barriers and realize the full potential of this strategy.

## Conclusion

The complete replacement of petroleum-derived fuels in aviation can be accomplished by using a catalyst to convert biomass feedstock into jet biofuel. This jet biofuel can be produced from various biomass sources, including sugarcane, cellulosic materials, soybean oils, palm oil, and municipal solid wastes. Previous research has reviewed the conditions and outcomes of catalytic conversion for producing jet biofuel, focusing on selecting suitable feedstock, developing catalysts, and ensuring responsive circumstances. This review highlighted recent breakthroughs that underscore the impact of optimizing catalytic processes to increase fuel yield and minimize production expenses. Various challenges faced were also discussed, including feedstock variability and the necessity for strong catalysts capable of functioning under the severe conditions characteristic of biomass conversion. To convert biomass feedstocks into jet biofuel, scientists are constantly working to improve the efficiency of the existing catalysts. Non-food biomass feedstocks such as algae, switchgrass, and used cooking oil can produce jet biofuel with minimal environmental impact. In an effort to reduce aviation's contribution to global warming, bio-based fuels derived from by-products may eventually replace conventional jet fuels. Researchers are seeking more effective and affordable methods for producing this fuel to ensure the long-term success of catalytic conversion in jet biofuel generation. However, the economic viability of jet biofuel production remains a challenge, and the development of infrastructure and policy frameworks is necessary to support its adoption. Although the price of producing jet biofuel is now higher than that of conventional jet fuel, the economic

opportunities and environmental benefits justify further investment in its production and distribution. In conclusion, jet biofuel, produced from biomass feedstock using catalytic conversion, is a promising alternative to fossil fuels in aviation, capable of lowering carbon emissions and fostering long-term growth.

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**Author contributions** Ahmed E. Mansy was involved in the investigation, methodology, writing—original draft, visualization, data curation, and writing—review and editing. Samuel Daniel contributed to the investigation, visualization, and writing—review and editing. Cedric Karel Fonzeu Monguen assisted in the validation and writing—review and editing. Hao Wang contributed to the validation and writing—review and editing. Ahmed I. Osman assisted in the investigation, conceptualization, visualization, and writing—review and editing. Zhen-Yu Tian was involved in the conceptualization, supervision, visualization, and writing—review and editing.

**Data availability** No data were used for the research described in the article.

## Declarations

AIO declares that he is the Editor of Environmental Chemistry Letters.

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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