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Review

Sustainable Aviation Fuels: Addressing Barriers to Global Adoption

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Abstract

The aviation industry is responsible for approximately 2–3% of worldwide CO_2 emissions and is increasingly subjected to demands for the attainment of net-zero emissions targets by the year 2050. Traditional fossil jet fuels, which exhibit lifecycle emissions of approximately 89 kg CO_2-eq/GJ, play a substantial role in exacerbating climate change, contributing to local air pollution, and fostering energy insecurity. In contrast, Sustainable Aviation Fuels (SAFs) derived from renewable feedstocks, including biomass, municipal solid waste, algae, or through CO_2- and H_2-based power-to-liquid (PtL) represent a pivotal solution for the immediate future. SAFs generally accomplish lifecycle greenhouse gas (GHG) reductions of 50–80% (≈20–30 kg CO_2-eq/GJ), possess reduced sulfur and aromatic content, and markedly diminish particulate emissions, thus alleviating both climatic and health-related repercussions. In addition to their environmental advantages, SAFs promote energy diversification, lessen reliance on unstable fossil fuel markets, and invigorate regional economies, with projections indicating the creation of up to one million green jobs by 2030. This comprehensive review synthesizes current knowledge on SAF sustainability advantages compared to conventional aviation fuels, identifying critical barriers to large-scale deployment and proposing integrated solutions that combine technological innovation, supportive policy frameworks, and international collaboration to accelerate the aviation industry's sustainable transformation.

Keywords: sustainable aviation fuels (SAF); lifecycle greenhouse gas emissions; renewable feedstocks; renewable energy; technical challenges; energy diversification; net-zero aviation

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1. Introduction

The aviation industry, while indispensable to global transportation and commerce, casts a significant environmental shadow through its carbon emissions [1]. There is an urgent demand for solutions that balance both the operational needs of the industry and the planet's ecological health [2,3]. Foremost among these solutions is the emergence and rising prominence of Sustainable Aviation Fuels (SAFs) [4]. SAFs are advanced biofuels, synthetic concoctions, and other eco-friendly alternatives engineered to diminish aviation's carbon footprint [5]. Their production arises from an increasingly palpable need to address the adverse effects of traditional jet fuels [6]. A distinguishing feature of SAFs is their versatility of origin, as they can be produced from a wide range of feedstocks, including organic biomass, waste products, and other renewable resources [7]. However, their large-scale adoption is constrained by scalability, cost, and the need to meet American Society

for Testing and Materials (ASTM) certification requirements. Advanced technological pathways such as Fischer–Tropsch (FT) synthesis, hydroprocessing, and bioconversion enable the production of several SAF categories [8]. Including hydroprocessed esters and fatty acids (HEFA), Fischer–Tropsch (FT) liquids, and alcohol-to-jet (ATJ) fuels [9]. This broad feedstock base and diverse technological options position SAFs as a dynamic and promising solution to aviation's environmental challenges [10]. Figure 1 provides an illustration of lifecycle of SAF.

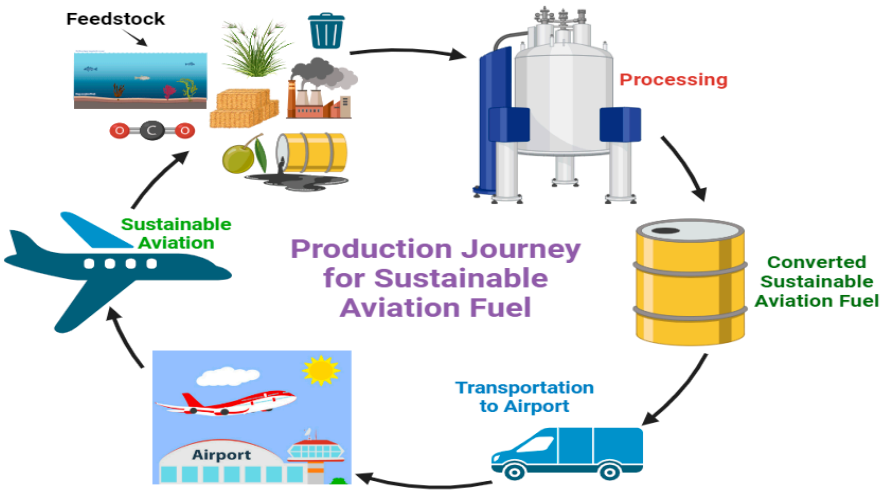

Figure 1. The lifecycle for sustainable aviation fuel (SAF).

The escalating significance of Sustainable Aviation Fuels (SAFs) has incited extensive scholarly investigations, culminating in a plethora of thorough reviews that have methodically scrutinized diverse facets of the development of sustainable aviation fuel. Recent extensive reviews have concentrated on various dimensions of SAF inquiry, encompassing production methodologies, the sustainability of feedstocks, and techno-economic evaluations. Cabrera and Melo de Sousa offered a comprehensive synthesis of the utilization of sustainable fuels within the aviation sector, elucidating production techniques for both biofuels and synthetic fuels while pinpointing feedstock sustainability and scale-up costs as pivotal shortcomings [4]. Detsios et al. executed a critical analysis of alternative aviation fuel pathways, juxtaposing HEFA, FT, ATJ, and electro-fuels, whilst accentuating the absence of coordinated scale-up frameworks and heterogeneous life cycle assessment (LCA) methodologies [11]. Specialized reviews have also surfaced, such as the systematic analysis conducted by Emmanouilidou et al. on solid waste biomass as a feedstock for SAF, which identified feedstock variability and contaminant management as significant challenges [12]. More recently, Wandelt et al. undertook a meta-review synthesizing over sixty surveys and overview papers, uncovering fragmentation within the survey literature and advocating for integrated research agendas [13]. Nevertheless, these antecedent reviews have primarily concentrated on isolated technical components or specific feedstock categories, with a dearth of integrated evaluations that concurrently address the intricate interplay between technological progression, economic feasibility, environmental sustainability, and regional policy disparities. Moreover, the majority of existing reviews have insufficiently tackled the burgeoning relevance of carbon capture and power-to-liquid technologies within the scope of comprehensive strategies for the deployment of SAF.

Unlike alternative solutions such as hydrogen- or electric-powered aircraft, SAF is a true drop-in option. It is fully compatible with existing airport and aircraft infrastructure, making it a critical near-term pathway for decarbonizing aviation. Consequently, SAF is widely regarded as the most important lever for achieving net-zero emissions in aviation by

2050 [14]. Beyond its environmental role, SAF offers a broad range of additional benefits [15]. SAFs promise a marked reduction in CO_2 emissions, overshadowing conventional jet fuels (CJFs) [16]. They also produce fewer particulates, contributing to cleaner air and decreased health risks associated with aviation emissions [17]. Economically, SAFs provide a buffer against the fickleness of oil prices and could stimulate job creation and economic rejuvenation in areas producing biofuel feedstocks [18,19]. This harmonious blend of economic and environmental advantages makes SAFs an alluring option for stakeholders, from airlines to governments, eyeing a greener aviation future [20].

On the global stage, the momentum behind SAFs is accelerating [21,22]. Major international organizations and governments are actively supporting SAF, signaling a paradigm shift in aviation fuel policy [23,24]. The International Air Transport Association (IATA), for example, has set the ambitious target of SAF accounting for 10% of global jet fuel consumption by 2030 [25]. This commitment is echoed by countries such as the United States and blocs such as the European Union, which are promoting SAF production through incentives, mandates, and funding programs [26]. At a higher level, the International Civil Aviation Organization (ICAO) is spearheading efforts to establish global sustainability benchmarks and frameworks to facilitate SAF adoption [27]. Industry is also mobilizing. Airbus, for instance, announced at its 2025 Airbus Summit plans to scale up SAF use in its operations, a commitment reaffirmed at the inaugural SAF Asia-Pacific Summit held in Melbourne (16–17 July 2025). These collective endeavors highlight a growing global consensus: SAF is central to aviation's sustainable transition. Compared with conventional fossil-based Jet A fuel, SAF can substantially reduce lifecycle greenhouse gas emissions, making it a key decarbonization pathway. SAF can be produced from a wide range of feedstocks, including bio-based sources such as tallow and municipal solid waste, as well as via advanced technologies like PtL, which synthesizes fuel from CO_2 and water using renewable electricity [25]. Despite its promise, SAF currently represents only a small share of total aviation fuel. Widespread deployment will require overcoming significant technological, economic, and regulatory challenges [28–30].

SAF manufacture has recently advanced beyond conventional methods. Notably, a noteworthy recent advancement that may further lessen carbon intensity and dependency on biomass feedstocks is the conversion of collected CO_2 to aviation fuel via PtL and other synthetic methods [26]. These developments are becoming more important as the aviation industry looks for all viable paths to sustainability, such as using electrification techniques and hydrogen propulsion for short-haul travel as substitutes for carbon-cutting methods. But there are still significant obstacles in the way of SAF development, even with its growth. There are constant hurdles in ensuring feedstock availability, establishing cost-competitive manufacturing, and adhering to stringent certification criteria, such those set out by ASTM International for the use of SAF in commercial aircraft [27]. These issues have been thoroughly reviewed in recent evaluations along with some possible fixes. The purpose of this study is to discuss the difficulties and prospects for SAF in the future, with an emphasis on the latest advancements in fuels generated from CO_2 and the changing technological and legal environment.

Numerous review articles have scrutinized the development of SAF from various analytical frameworks. For instance, Watson et al. delivered an exhaustive review encompassing SAF technologies, associated costs, emissions profiles, policy frameworks, and market dynamics [31], while Wandelt et al. undertook a meta-review, synthesizing existing scholarly works and elucidating persistent deficiencies within the literature [13]. In a similar vein, researchers evaluated the production pathways of SAF and their significance in attaining net-zero objectives, and recent investigations have analyzed life cycle assessment results, certification protocols, and environmental trade-offs [32–34]. Nonetheless, most

of these reviews tend to be either focused on specific technologies, isolate economic or policy considerations, or concentrate on restricted geographical contexts such as the United States or the European Union. Thorough evaluations that amalgamate technical, economic, environmental, and policy dimensions within a global framework while simultaneously addressing emerging CO_2 derived synthetic fuels are markedly scarce. This deficiency accentuates the originality of the current review, which aspires to furnish a comprehensive understanding of the opportunities and challenges associated with SAF to guide future inquiries, policy formulation, and international cooperation.

The annual distribution of documents reflects the development in research in any field of study. To understand the trends in using e-fuel of SAF research, Figure 2 provides a snapshot of the annual publication across the years in this study. There was a total of 50 publications exported from the databases, with publication dates from January 2020 to September 2025. There was a slight increase in publications from 2020 to 2025, and total citation is mentioned in the graph from publication date to July 2025. Citation analysis is used to measure a document, author, source, or organization's influence in a field.

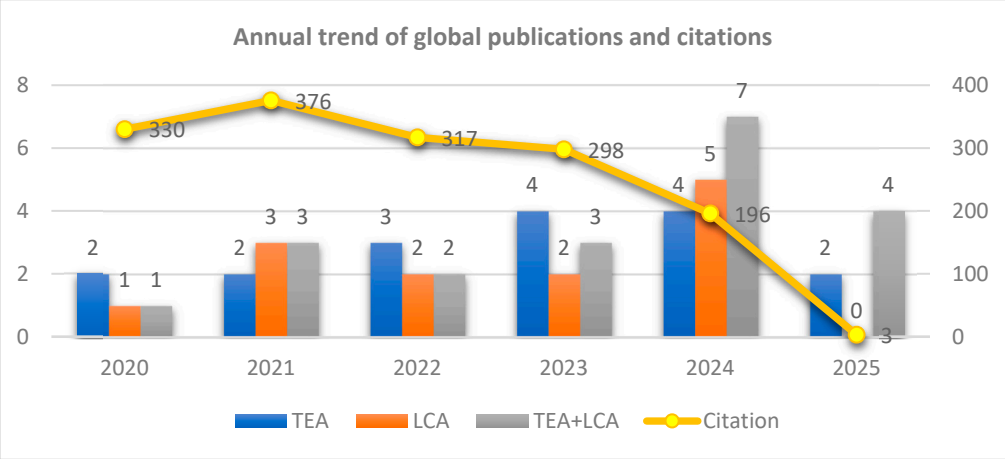

Figure 2. Annual publication and citations in the period of 2020–2025 (30 September 2025).

To enhance the contextual understanding of the merits and drawbacks of sustainable aviation fuels in relation to traditional jet fuels, a comparative analysis is presented in Table 1 amalgamates contemporary research findings and elucidates essential aspects including feedstock provenance, lifecycle greenhouse gas emissions performance, compatibility, pollutant output, energy density, economic implications, scalability, and regulatory environments drawing on recent comprehensive reviews and techno-economic evaluations. By contrasting traditional jet fuels with SAFs, the table accentuates the imperative of sustainability: although SAFs exhibit significant ecological and operational advantages, enduring issues related to cost, availability of feedstock, and regulatory inconsistency persistently hinder widespread implementation. This analytical viewpoint emphasizes the critical need for coordinated research initiatives, enabling policies, and interdisciplinary collaboration to expedite the deployment of SAFs.

As shown in Table 1, SAFs stand out as a near-term, drop-in solution with clear sustainability advantages over fossil-based jet fuels, yet their widespread adoption hinges on overcoming cost, scalability, and policy alignment barriers issues that frame the subsequent discussion in this review. This paper endeavors to unravel the challenges surrounding SAFs. Objective is twofold: to amalgamate existing insights on SAFs, presenting a unified view of the present scenario, and to delve deep into the multifaceted challenges technical, economical, and environmental that they present. By illuminating these facets, this article's aim to spark a nuanced dialogue on SAFs' future trajectory, especially in a global context.

The paper also ventures into diverse regional strategies, underscoring the variegated challenges and solutions in SAF adoption and goals to pave the way for discerning research and policy evolution in this crucial realm of sustainable aviation. The extant body of research has mostly concentrated on discrete elements of sustainable agriculture, such as feedstock analysis and production techniques.

Table 1. Comparative Analysis of SAFs and CJF Properties with critical perspective.

Property	Conventional Jet Fuel (Jet A/Jet A-1)	Sustainable Aviation Fuels (SAFs)	Critical Sustainability Perspective
Lifecycle GHG Emissions	89 kg CO_2-eq/GJ (well-to-wake)	20–30 kg CO_2-eq/GJ (70–80% reduction)	Aviation contributes 2–3% of global CO_2 emissions; SAFs offer the only viable near-term pathway to achieve ICAO's net-zero 2050 targets while maintaining existing infrastructure [35,36].
Energy Density	~43 MJ/kg (Higher Heating Value)	42–44 MJ/kg (comparable performance)	SAFs maintain operational performance while delivering environmental benefits—no trade-off between efficiency and sustainability [37,38].
Production Cost	\$0.50–0.80/L	\$1.20–2.00/L (1.5–2.5 × higher)	High costs currently limit adoption, but carbon pricing and policy incentives are narrowing the gap; projected cost parity by 2030–2035 with scale-up [39–41].
Feedstock Sources	Crude oil (finite fossil resource)	Biomass waste, algae, municipal solid waste, CO_2 + renewable electricity (PtL) [11]	Diversified renewable feedstocks reduce dependence on volatile fossil fuel markets and geopolitically sensitive regions [11,12]
Infrastructure Compatibility	Standard (baseline compatibility)	100% compatible as drop-in fuel (ASTM D7566) [13]	No infrastructure modification required enables immediate implementation across existing fleet and fuel systems [13]
Certification Requirements	ASTM D1655, DEF STAN 91-91 [13,14,16]	ASTM D7566 (blend components), ongoing 100% SAF certification [13,14]	Rigorous standards ensure safety while enabling sustainable transition; 100% SAF approval expected by 2030 [14]
Policy & Regulation	Long-established global standards; low regulatory risk	ASTM D7566-certified for seven pathways; supported by CORSIA, EU Fit-for-55, US SAF Grand Challenge	Policy support is accelerating SAF adoption; however, regulatory heterogeneity and lack of harmonized LCA criteria hinder global deployment [27,31,33].
Supply Chain Resilience	Centralized, geographically concentrated	Distributed, regionally producible from local feedstocks [18]	Local production enhances energy security and reduces transportation-related emissions [18]
Job Potential	Limited (mature industry)	High (emerging sector): 1 million jobs projected by 2030 [19]	SAF industry development stimulates rural economies and creates high-skilled green jobs [19,20]
Pollutant Emissions	Higher particulate matter (PM) and SOx/NOx emissions	Lower PM, sulfur, and aromatic compounds → improved air quality and reduced contrail formation	Demonstrated air-quality benefits; however, real-world emission reductions vary depending on production pathway and blending ratio [13,16,17].

However, integrated evaluations that consider the interplay between technological, economic, and environmental concerns are still lacking. By synthesizing recent research on

SAF challenges and providing crucial insights into cutting-edge technologies like carbon capture and power-to-liquid, which have the potential to dramatically reduce carbon intensity and improve the sustainability of aviation fuels, this work makes a unique contribution to the field. Additionally, this research seeks to offer a road map for removing obstacles to SAF adoption and promoting innovation in the aviation industry by emphasizing the significance of industry-academia collaboration and regulatory frameworks.

2. Major Types of Sustainable Aviation Fuel

Based on the SAF production pathways, there are eleven ASTM approved pathways [42], which can be grouped into three categories: bio-based, synthetic, and hybrid [43]. In this study we focus on the major pathways. Bio-based SAFs, often termed "biomass-based SAFs," originate from biological materials like agricultural waste, algae, and used cooking oil, converting these feedstocks through processes like pyrolysis and gasification [44]. They are carbon-neutral, as the CO_2 released during combustion is balanced by the amount absorbed by the feedstock during its lifecycle. Synthetic SAFs, created via chemical processes, use renewable energy to transform CO_2 and hydrogen into hydrocarbons [45]. They can capture and utilize industrial CO_2 emissions, presenting a compatible alternative to traditional jet fuels. Hybrid SAFs combine the best of both worlds, blending bio-based and synthetic elements to optimize sustainability and performance [46].

The HEFA process epitomizes the most advanced commercially viable pathway for SAF, employing well-established hydroprocessing methodologies to transform renewable lipid sources such as vegetable oils, animal fats, used cooking oils, and tallow into paraffinic hydrocarbons [47]. Achieving a Technology Readiness Level (TRL) of 9 and witnessing extensive commercial implementation, HEFA-SPK was the inaugural SAF pathway to receive certification from ASTM in 2011 for a 50% blend with conventional jet fuel [48]. This pathway demonstrates an energy efficiency ranging from 65% to 70% and a potential reduction in greenhouse gas (GHG) emissions of 40% to 70%, contingent upon the practices employed in sourcing feedstock [49–51]. Nonetheless, the HEFA process encounters considerable challenges regarding the availability of feedstocks, as the supplies of sustainable waste oils and animal fats are inadequate to fulfill the anticipated demand for aviation fuel [52,53], thereby necessitating the exploration of supplementary pathways for extensive large-scale implementation [52–55].

Fischer–Tropsch (FT) technology presents a remarkable degree of feedstock flexibility and superior fuel quality, facilitating the conversion of a variety of carbonaceous substrates such as biomass, municipal solid waste, and natural gas via gasification and catalytic synthesis into hydrocarbons that are compatible with aviation fuels [56,57]. FT-SPK demonstrates elevated energy density (42–44 MJ/kg) and minimal sulfur content, with the potential to achieve greenhouse gas reductions ranging from 50% to 90% contingent upon the choice of feedstock [58–60]. There are two certified formulations available: FT-SPK and FT-SPK/A, which incorporate synthetic aromatics. Notwithstanding its technological advancement (TRL 6–8), FT technology encounters obstacles stemming from substantial capital expenditures ($300–500 million for commercial facilities) and energy-intensive operational processes that adversely affect its overall economic viability [61,62].

AtJ pathways facilitate the conversion of renewable alcohols predominantly ethanol, isobutanol, and the emergent methanol methodologies into jet-range hydrocarbons via processes of dehydration, oligomerization, and hydrogenation [63,64]. The Ethanol-to-Jet (EtJ) process attained ASTM certification in 2018, permitting a blend limit of 50%, and is recognized as the most commercially developed AtJ route, with LanzaJet's facility in Georgia, capable of producing 10 million gallons annually, representing the inaugural commercial-scale deployment anticipated in 2024. The Isobutanol-to-Jet (IBtJ) pathway

provides superior energy density benefits with a 30% blend approval achieved in 2016, whereas the Methanol-to-Jet (MtJ) process emerges as a viable synthetic route that employs captured CO_2 alongside green hydrogen [65–67]. AtJ pathways realize energy efficiencies ranging from 40% to 50% and reduce greenhouse gas emissions by 50% to 80%, albeit confronting challenges related to feedstock competition with alternative sectors and constraints on commercial-scale production [68].

PtL signifies the most ecologically advantageous pathway for SAF, demonstrating the capability for greenhouse gas (GHG) reductions in the range of 90–95% when harnessed with renewable electricity and employing captured CO_2 [69–75]. The comprehensive process integrates water electrolysis for the generation of green hydrogen, CO_2 capture (either via direct air capture or from point sources), the reverse water-gas shift (RWGS) reaction, and Fischer–Tropsch synthesis to produce entirely synthetic jet fuel. PtL effectively tackles the inherent scalability limitations associated with biomass-derived SAFs, exhibiting a theoretically limitless production capacity that is merely contingent upon the availability of renewable electricity [76–78]. Nevertheless, the current production expenses are 4–8 times greater than those of conventional jet fuel, attributable to elevated capital expenditures and energy intensity (ranging from 20 to 30 MWh per metric ton of SAF); however, anticipated reductions in renewable energy costs indicate a potential for achieving cost parity within the forthcoming decade [79,80].

Biomass-to-Liquid (BtL) pathways harness the extensive availability of lignocellulosic materials through processes such as gasification or advanced biological conversion, thereby presenting significant scalability potential while avoiding direct competition with food resources [69–72]. The Catalytic Hydrothermolysis Jet (CHJ) signifies a transformative technology that facilitates the direct conversion of lipid-rich biomass into Sustainable Aviation Fuel (SAF), concurrently yielding integrated aromatics and achieving conversion efficiencies of 60–70% [71]. Algal biofuels present distinctive advantages, including the capability for cultivation on non-arable land and remarkably high productivity rates (ranging from 10,000 to 20,000 gallons per acre annually); however, they continue to face limitations due to technical and economic challenges associated with their cultivation, harvesting, and conversion methodologies [81–83].

Co-processing pathways, wherein bio-feedstocks are simultaneously processed with fossil crude within conventional refinery settings, present a transitional mechanism. Although blend limits are presently restricted to 5–10% in accordance with ASTM D1655, co-processing constitutes a pragmatic short-term strategy for scaling SAF without necessitating significant infrastructure modifications. Table 2 delineates the comparative advantages and disadvantages of various SAF pathways categorized by feedstock, technology, and performance metrics.

The landscape of SAF technology displays considerable disparities in terms of commercial maturity, scalability potential, and sustainability performance, as delineated in Table 2. The selection of strategic pathways is contingent upon a multitude of interrelated factors, encompassing regional feedstock availability, renewable energy resources, technological infrastructure, and prevailing policy frameworks. Adopting a diversified portfolio approach that leverages the synergies of complementary SAF pathways represents the most effective strategy for fulfilling the decarbonization objectives of the aviation sector while concurrently mitigating technical, economic, and supply chain risks. Immediate deployment priorities concentrate on the expansion of HEFA capacity and the commercial scaling of AtJ processes, whereas medium to long-term strategies prioritize the development of PtL technology and the optimization of advanced biomass pathways.

Table 2. Merits and Drawbacks of different SAF production from origins.

Type of SAF	Feedstock	Details	TRL/FRL	Blend Limit	Merits	Drawbacks
Hydroprocessed Esters and Fatty Acids (HEFA) [54]	Vegetable oils, animal fats, used cooking oil, and tallow	Hydroprocessing technology to convert fats and oils into LCHs.	9/9	Up to 50%	• Derived from renewable feedstocks like vegetable oils and animal fats [55]. • Drop-in replacement for conventional jet fuels. • Well-established and certified for aviation use.	• Competition with food resources and land use change concerns [56]. • Limited reduction in greenhouse gas emissions [57].
Fischer–Tropsch (FT) Synthetic Kerosene [58,59]	Biomass, coal, natural gas	Via FT, converting CO and H_2 into LCHs.	6–8/6–7	Up to 50%	• Can be produced from a variety of feedstocks, including biomass and natural gas [60]. • High energy density and compatible with existing aviation infrastructure [61]. • Lower sulfur content, reducing sulfur emissions [62].	• High production costs and energy-intensive processes [63]. • Greenhouse gas emissions highly dependent on feedstock [64].
Alcohol-to-Jet (ATJ) [65,66]	Alcohols like ethanol or isobutanol	Converts alcohols to LCHs through dehydration, oligomerization, hydrogenation.	7–8/7–8	Up to 50%	• Derived from alcohols (e.g., ethanol and methanol), which can be produced sustainably [67]. • Reduced particulate emissions [68].	• Potential feedstock competition with other applications [69]. • Limited commercial-scale production [70].
Biomass-to-Liquid (BtL) [71,72]	Biomass (e.g., waste, sugarcane, corn, etc.)	Produced through biological fermentation into LCHs	4–7/5–8	Up to 50%	• Utilizes biomass feedstocks, including lignocellulosic materials [73]. • High energy density and lower sulfur content [74].	• Complex production processes, often requiring significant energy inputs [75]. • Limited commercial-scale availability [76].
Power-to-Liquid (PtL) [77,78]	Water, CO_2	electrolysis, CO_2	6–8/6–7	Up to 50%	• Utilizes renewable electricity (e.g., from wind or solar) to produce synthetic fuels [79]. • Potential for low GHG emissions when using renewable energy [80].	• High production costs and energy requirements [81]. • Limited scalability and availability [82].
Algal Biofuels [83,84]	Biomass (e.g., oilseeds, algae, microalgae, macroalgae, etc.)	Converts lipids di-rectly into SAF through catalytic hydrother-molysis	3–5/4–6	Up to 50%	• Algae can be grown in various environments, including non-arable land and wastewater [85]. • High growth rates and potential for sustainable production [86]. • Reduced competition with food resources [87].	• Technical and economic challenges in algae cultivation and conversion [88]. • Limited commercial-scale production [89].
Co-processing [87]	Bio-feedstocks	Blending bio-feedstocks with conventional crude oil in refineries	6–7/6–7	≤5–10%	• Near-term option; uses existing refineries	• Bio-oils blended with crude oil in refineries

The successful transition to sustainable aviation necessitates the coordinated advancement of various SAF pathways, each providing distinct advantages that contribute to the overarching decarbonization strategy. Although no singular pathway can fulfill all aviation fuel requirements, the integrated portfolio of bio-based, synthetic, and hybrid SAFs establishes a comprehensive foundation for achieving net-zero aviation emissions by the year 2050.

3. Challenges of Sustainable Aviation Fuel

SAF represents a beacon of hope for the aviation industry's green transition. While it promises a reduction in carbon emissions and a step towards an eco-friendlier aviation future, the journey to widespread SAF adoption is not without its hurdles. From technical constraints to economic considerations, the path to fully realizing SAF's potential is laden with challenges that require collaborative and innovative solutions. As industry moves forward, understanding these obstacles is crucial to effectively addressing them and harnessing the true potential of SAF in modern aviation. As shown in Figure 3, they might serve as a cornerstone in the next phase of our global energy transformation.

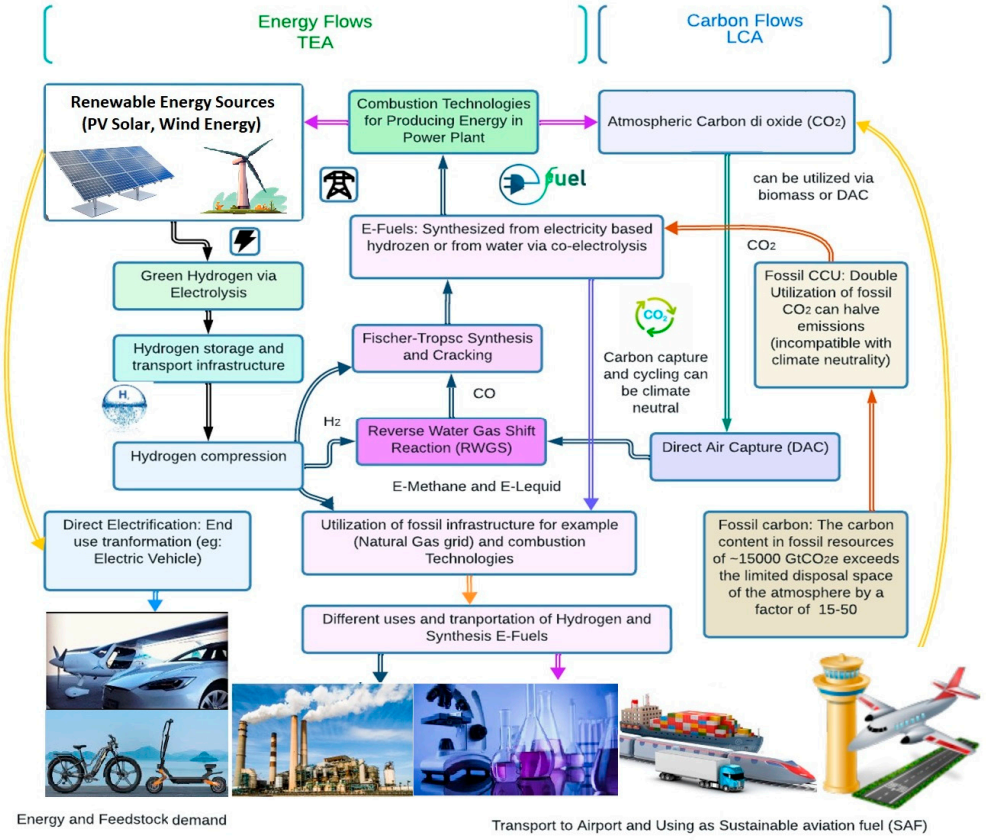

Figure 3. Production process and different uses of H_2 and Synthesis e-fuels.

3.1. Technical Challenges of Sustainable Aviation Fuel

The production of SAF confronts various technological obstacles that need to be addressed to boost its feasibility as a replacement for fossil-based jet fuel. Variability in feedstock is a major problem that can impact on the quality and uniformity of the final SAF. The content and attributes of various feedstocks, including tallow, maize ethanol, and municipal solid waste, vary, impacting the fuel's characteristics and the procedures involved in manufacturing [72]. This fluctuation may make it difficult to scale up production and guarantee that the SAF satisfies strict requirements for aviation fuel. Feedstocks are essential for making SAF. Examples include biomass, council waste, and industrial

emissions. But there is a problem: these materials are not always available in steady supplies. Their quality and amount can fluctuate, making SAF production uncertain [90]. On top of that, other industries also want these feedstocks for their products, creating a competitive environment [91]. Hence, a constant and varied feedstock supply is crucial for SAF's uninterrupted production.

The industrial procedures used to transform feedstock into SAF provide another significant difficulty. Existing methods frequently encounter obstacles with catalyst development, including Fischer–Tropsch synthesis and hydrotreatment. Catalyst performance can deteriorate with time, affecting production and efficiency. Researchers are striving to produce more durable and efficient catalysts, but major effort is still needed to solve challenges including catalyst poisoning and selectivity for desired products. There are various methods to turn feedstocks into SAFs. Each method has its pros and cons. For example, the FT method is effective but requires a lot of energy because of its high temperature and pressure conditions [92]. Meanwhile, using algae for biofuel production is environmentally friendly but might be hard to produce on a large scale without high costs [93]. Therefore, when choosing a production technique, it is important to think about factors like the type of feedstock, how energy-efficient it is, and if it makes economic sense.

SAFs need to be as efficient as regular aviation fuels to stand a chance in the market. Producing SAFs demands a lot of energy, especially when converting feedstocks [94]. The challenge is to find methods that do not use too much energy but can also be scaled up to meet the huge demands of the airline industry. Both energy savings and large-scale production are key for SAF's success [95]. Catalysts speed up the SAF production process and determine its efficiency. But creating good, affordable catalysts is not easy. Take the Fischer–Tropsch (FT) method; it needs catalysts to turn gas into liquid fuel. Designing the perfect catalyst for this is complex, and researchers are still trying to find ways to make them better and cheaper [96]. The process involves knowledge from different fields like chemistry and engineering.

Moreover, energy efficiency in SAF production is a major concern. Many current processes require significant energy inputs, which can negate the environmental benefits of using renewable feedstocks. Integrating renewable energy sources into the production process can help improve overall efficiency, but this necessitates advancements in energy management and system integration. To ensure the success of SAF technologies, it is crucial to delve deeper into these technical challenges, exploring innovative solutions and conducting rigorous studies that can provide a clearer understanding of the pathways to more sustainable and efficient SAF production. Even though SAFs are designed to fit right into the current aviation system, they still need to be as good as or better than traditional fuels. This means they should have the same or better energy content and work well in cold temperatures [97]. Aircraft engine makers and aviation authorities are testing SAFs to make sure they work safely and efficiently in engines. Ongoing research aims to ensure SAFs can be smoothly used in the existing aviation setup. To navigate through these technical roadblocks, research and innovative thinking are crucial. It is also vital that experts from universities, businesses, and regulatory organizations work together to solve these challenges [69].

3.2. Economic Challenges Sustainable Aviation Fuel

The journey to popularizing SAF is riddled with economic hurdles. The transition to SAF poses several economic challenges that require critical examination. One significant aspect is the impact of SAF adoption on the aviation industry. The high production costs of SAF, often higher than traditional Jet A fuel, can strain airline profitability, potentially leading to increased ticket prices for consumers [80]. This economic burden may hinder

widespread adoption, particularly in a highly competitive industry sensitive to fuel price fluctuations. Making SAFs often carries a steeper price tag than traditional aviation fuels. This discrepancy arises from the intricacies of obtaining the right feedstocks, undergoing advanced conversion techniques, and adhering to rigorous sustainability norms. Simply put, SAFs are pricey to produce, and this can deter their widespread use in the aviation sector. A consensus among various studies emphasizes the urgency to reduce SAF production costs to match, or even undercut, those of conventional jet fuels [98].

Capital is the lifeblood of SAF advancements. From preliminary research to erecting large-scale production hubs, every facet demands significant monetary influx. Hence, it is imperative to cultivate a fertile ground for investment—both from private pockets and public coffers. Funds diverted towards refining conversion methods can further streamline costs. The onus falls not just on individual investors but also on governmental bodies and global organizations to underpin SAF initiatives financially [99].

Governments can indeed be game-changers in the SAF equation [100]. By rolling out attractive incentives and subsidies, they can level the economic playing field. Countries worldwide have proactively introduced measures, from tax breaks and grants to low-interest loans, all aimed at propelling SAFs forward. For instance, U.S. authorities have extended both tax reliefs and grant schemes to budding SAF producers, thus galvanizing the sector [101]. Echoing this sentiment, the European Union, through its Renewable Energy Directive, not only prescribes the use of SAFs but also sweetens the deal with fiscal rewards. Such state-backed measures are invaluable in making SAFs financially palatable. The market dynamics around SAF are complicated and impacted by various aspects, including oil prices, feedstock supply, and technological improvements. The competitiveness of SAF can change in response to changes in fossil fuel costs, making it more difficult for producers to enter the market [102]. Additionally, the scarcity of feedstocks, especially sustainable ones, might raise costs and reduce the amount that can be produced.

However, SAFs do not just have to be sustainable; they need to be competitive [103]. SAFs, despite their eco-credentials, are pitted against traditional jet fuels in the market arena. Price oscillations in crude oil can skew this competition, affecting SAFs' allure and the aviation sector's eagerness to embrace them. Furthermore, for SAFs to truly shine, they need to be as readily available as their conventional counterparts, demanding widespread distribution networks. Reaching a critical mass in production and ensuring ample market presence are pivotal for SAFs to rival, and perhaps surpass, conventional fuels [104]. In essence, the economic roadmap for SAFs is multifaceted: it requires cost reductions, robust investments, supportive governmental policies, and a formidable market presence. Harmonizing these elements is crucial for SAFs to ascend as the fuel of choice in aviation.

Government interventions constitute the paramount determinant of the viability of SAF markets; however, the efficacy of the associated policy instruments exhibits considerable variability. TEA indicate that no SAF pathway can attain commercial viability in the absence of substantial policy backing, with projected policy expenditures ranging from $35 to $337 million per facility (approximately $0.07 to $0.71 per liter) [105]. Fiscal incentives such as tax credits and subsidies (for instance, the U.S. Inflation Reduction Act) directly diminish minimum selling prices and enhance the net present value of projects, potentially reducing production expenditures by up to one-third for specific pathways [106]. Nonetheless, these supply-side incentives necessitate sustained temporal commitment and scale to effectively attract private capital while incurring significant public financial implications. Mandates and blending quotas (such as the EU ReFuelEU Aviation initiative) provide assurances for market demand and facilitate scaling; however, they may elevate fuel prices if the incentives for supply are found to be inadequate [107]. Mechanisms such as carbon pricing and emissions trading (e.g., the EU Emissions Trading System, ICAO's

Carbon Offsetting and Reduction Scheme for International Aviation) extend long-term decarbonization signals but necessitate carbon pricing levels exceeding $100 to $200 per tonne of CO_2 to effectively bridge the cost disparity associated with SAF [108]. Empirical evidence suggests that an integrated, "stacked" policy framework—incorporating tax credits (to mitigate risks for initial projects), mandates (to guarantee demand certainty), and robust carbon pricing (to incentivize low-carbon fuel utilization) represents the most efficacious approach [109]. The success of such an approach is contingent upon multi-year policy commitments, stringent sustainability safeguards to mitigate competition for feedstocks, and cross-jurisdiction collaboration to avert market fragmentation while ensuring adequate scale for commercial implementation.

3.3. Environmental Challenges Sustainable Aviation Fuel

SAFs come to the forefront mainly due to their potential in slashing greenhouse gas (GHG) emissions. They are formulated from renewable sources and advanced technological processes, allowing them to significantly undercut the carbon dioxide (CO_2) emissions of traditional jet fuels. The magic lies in the carbon-friendly lifecycle of SAFs: their feedstocks often are either carbon-neutral (they absorb as much carbon as they release) or even carbon-negative (they absorb more carbon than they release). The numbers speak for themselves SAFs can reduce CO_2 emissions by a whopping 80% over their lifecycle compared to regular jet fuels [110]. This is not just about reducing a carbon footprint; it is about the aviation industry playing a pivotal role in global climate change mitigation efforts [111].

But carbon is not the only environmental concern. Aviation also releases particulate matter the tiny, harmful particles, often termed 'black carbon,' that emerge during fuel combustion. These particles do not just harm the environment; they jeopardize human health, contributing to local air pollution. Enter SAFs: especially those derived from high-purity feedstocks, they burn cleaner, drastically cutting down on particulate matter emissions. This means clearer skies around airports and cleaner air for communities under flight paths [112]. The world's dependency on fossil fuels is a double-edged sword economically and environmentally. The aviation industry, largely dependent on conventional jet fuels extracted from crude oil, faces not only environmental challenges but also economic vulnerabilities like price instability. SAFs offer an escape route. By diversifying aviation's fuel palette, SAFs can diminish the sector's fossil fuel dependence, making it more resilient to both price shocks and environmental repercussions associated with fossil fuel logistics [113].

The environmental issues surrounding SAF are complex and involve more than just carbon emissions; thus, a thorough assessment using life cycle assessment (LCA) techniques is required. Although the main emphasis of conventional LCA is greenhouse gas emissions, it is important to acknowledge the wider environmental effects of various feedstocks and production processes, including changes in land use, water use, and biodiversity loss. LCA frequently encounters obstacles, such as the temporal scale of emissions reductions, assumptions about technical developments, and uncertainty in data quality. The indirect impacts of changing land use, which might have unforeseen implications like increasing deforestation or habitat damage, may not be sufficiently considered by these techniques. For example, if feedstocks like corn and palm oil are not handled responsibly, the production of these crops can cause serious ecological devastation [89].

A few interrelated obstacles with technological, financial, and environmental implications impede the shift to SAF. Technically, it is difficult to achieve consistent fuel properties and match aviation criteria due to the variety in feedstock quality, which includes tallow, maize ethanol, and municipal solid waste. Additionally, supply uncertainties make it difficult to scale up production. Since many conversion processes need significant energy

inputs, which might negate the environmental benefits of SAF, they are crucial obstacles to overcome. These procedures include catalyst development and energy efficiency. SAF's high manufacturing costs in comparison to conventional Jet A fuel pose an economic risk to airline profitability and impede its wider adoption in a sector that is highly competitive. Research and large-scale manufacturing need significant financial investment, and government incentives are required to level the economic playing field. Environmentally, while SAFs can significantly reduce greenhouse gas emissions, their broader ecological impacts such as particulate matter emissions and land use changes must be carefully evaluated using comprehensive life cycle assessments. Addressing these challenges requires innovative solutions and collaboration among researchers, industry stakeholders, and regulatory bodies to ensure SAFs can effectively replace fossil fuels in the aviation sector while meeting sustainability goals.

3.4. Regulatory Challenges of Sustainable Aviation Fuel

Fuel certification and market uptake are impacted by major regulatory obstacles that must be overcome to establish and implement SAF. The regulatory regimes in different countries differ significantly, which frequently results in discrepancies in SAF certifications and standards. This might impede the business' capacity to scale globally. To guarantee that SAFs fulfill the same performance and safety requirements as traditional Jet A fuels, for example, thorough testing is mandated by the ASTM D7566 standard, which controls the certification of alternative jet fuels [90]. Potential investors and producers may be discouraged by this procedure because it can be costly and time-consuming. Additionally, the absence of well-defined, globally standardized laws breeds uncertainty among aviation sector players, making SAF infrastructure investment and planning more difficult. To ensure that SAFs do not jeopardize performance or safety requirements, regulatory organizations must also address fuel quality issues, including as the fuel's compatibility with current engines and aviation infrastructure. It is imperative that regulatory frameworks adjust and make it easier for SAF to be integrated into the current aviation fuel supply chain while upholding strict safety and quality requirements as the SAF industry continues to grow [91].

To truly gauge SAFs' environmental credentials, one must look beyond combustion. It is about assessing their entire life from production to consumption. This is where LCA comes into play. LCA digs deep into SAFs' environmental impacts, covering everything from GHG emissions to energy utilization and even broader environmental markers. To ensure SAFs are genuinely sustainable, it is vital to set and adhere to rigorous sustainability metrics, like carbon intensity, water and land consumption, and effects on ecosystems. These metrics serve as a compass, guiding stakeholders from policymakers to industry players, in navigating the sustainability terrain of SAFs [114]. In essence, SAFs present a multifaceted solution, but a comprehensive evaluation is essential to ensure they stand up to their promise of a sustainable future. Here is a list of ASTM-approved pathways for SAF production under the ASTM D7566 specification. This specification outlines the requirements for blending SAF with conventional jet fuel (Jet A or Jet A-1) for use in aircraft.

These ASTM approved pathways provide a foundation for drop-in SAFs that can be blended with traditional jet fuels and demonstrate the industry's gradual shift toward enabling higher SAF blends, eventually up to 100% SAF for some future technologies. This Table 2 offers a concise overview of each pathway, their feedstocks, blend limits, and a brief description of their production processes. It is crucial to consider alternative advances in addition to SAF, including hydrogen propulsion and electrification techniques, given the quickly changing environment of sustainable aviation. This mini review places these alternative systems in the larger framework of aviation sustainability to offer a thorough

assessment of the difficulties and potential for the future of SAF. Through a comparison of the many uses of SAF in short-, medium-, and long-haul flights, can pinpoint the precise situations in which SAF works best and the situations in which other methods could be more suitable [82–86].

While SAF presently shows promise for decarbonizing medium-haul routes, its limited availability and the energy density of existing technologies pose hurdles for long-haul flights. The strategic deployment of the previously restricted amounts of SAF is called into question in this context, highlighting the importance of carefully evaluating where these resources may have the biggest impact on lowering emissions [87–89]. Table 3 summarizes the major challenges and possible solutions.

Table 3. Key challenges of sustainable aviation fuels (SAFs) and possible solutions.

Challenges	Key Areas	Descriptions	Possible Solutions
Technical	• Feedstock variability • Feedstock supply uncertainty • Catalyst development issues • Energy efficiency concerns • Fuel performance standards	• Variability and limited availability of feedstocks (biomass, MSW, tallow, algae, etc.) • Inconsistent availability and quality of biomass, municipal waste, and industrial emissions; competition from other industries • High energy demand for conversion (FT, ATJ, hydroprocessing) • Catalyst degradation, poisoning, and cost issues • Need to meet strict ASTM standards for aviation fuels	• Diversify and secure sustainable feedstock supply chains • Invest in feedstock storage and preservation technologies • Improve energy efficiency through process optimization and renewable integration • Develop more robust, selective, and low-cost catalysts • Strengthen collaboration between academia, industry, and regulators for certification and engine testing
Economic	• High Production Costs • Capital Investment Requirements • Market Competitiveness • Limited Government Support	• SAF production cost significantly higher than Jet A fuel • High capital expenditure for large-scale plants • Market competitiveness affected by fossil fuel price fluctuations • Limited investment and infrastructure	• Scale up production to achieve economies of scale • Increase public and private investment in SAF R&D • Government incentives (tax credits, subsidies, grants, low-interest loans) • Establish long-term offtake agreements with airlines
Environmental	• Indirect Land Use Effects • Water and Resource Consumption • Lifecycle Assessment Complexity • Particulate Matter Emissions	• Risk of indirect land use change (ILUC), deforestation, and biodiversity loss • High water and energy use in some feedstock pathways • Uncertainty in LCA results and system boundaries • Particulate matter emissions still possible in some processes	• Conduct rigorous and standardized Life Cycle Assessments (LCA) • Prioritize non-food, waste-based, and CO_2-derived feedstocks • Integrate renewable energy (solar/wind/green hydrogen) in SAF production • Establish sustainability certification frameworks for feedstock and processes
Regulatory	• Complex Certification Process • Inconsistent Global Standards • Fuel Quality and Safety Requirements • Infrastructure Integration	• Complex and time-consuming ASTM certification (D7566) • Lack of harmonized global standards • Regulatory uncertainty discouraging investors • Compatibility with existing infrastructure needs rigorous validation	• Streamline and harmonize international certification standards • Fast-track approvals for proven SAF pathways • Create clear long-term policy frameworks to reduce investor risk • Encourage global collaboration via ICAO, IATA, and regional alliances

Table 3. *Cont.*

Challenges	Key Areas	Descriptions	Possible Solutions
Aviation-Sectoral (Broader Context)	• Pandemic • Cybersecurity threats • Aircraft trading • Manpower limitation • ATC system • Geopolitics • Digital transformation	• Demand recovery and capacity misalignment post-COVID • Emerging cybersecurity threats to aviation systems • Aircraft delivery delays and aging fleets • Workforce shortages across aviation functions • ATC system modernization and safety oversight • Increasing geopolitical instability affecting supply chains • Digital transformation disparities in adoption	• Develop flexible demand–supply alignment strategies for SAF adoption • Strengthen aviation cybersecurity frameworks • Modernize fleets and integrate SAF-compatible technologies • Train and expand skilled workforce for SAF-related operations • Upgrade ATC systems with SAF readiness in mind • Build resilient supply chains to withstand geopolitical shocks • Bridge digital transformation gaps in SAF adoption and aviation systems

4. Future Perspective of Sustainable Aviation Fuel

Although the impediments to the adoption of SAF are multifaceted encompassing technological, economic, environmental, and regulatory challenges the solutions outlined in Table 3 demonstrate that these barriers are not insurmountable. Ongoing progress in feedstock diversification, renewable integration, and advanced conversion technologies, combined with strong policy incentives and international collaboration, is steadily narrowing the gap between SAF and conventional jet fuels. Rather than hindering progress, these challenges define a framework for targeted interventions that can accelerate commercialization. Building on this foundation, the following section explores prospective developments in SAF, highlighting how technological innovation, policy support, and partnerships across industry and academia can transform aviation into a more sustainable and resilient sector.

SAF has a bright future, but it also depends on overcoming a few significant obstacles that might prevent it from being widely used. Although there are still many obstacles to overcome, recent advancements in SAF technology, such as the utilization of novel feedstocks and sophisticated manufacturing techniques, appear promising [90]. Technologically, the scalability of SAF manufacturing processes and the integration of renewable energy sources are important challenges that require substantial investment and innovation. Regulatory frameworks are also very important; uneven rules throughout areas may lead to uncertainty, which discourages investment and stifles market expansion [91]. To level the playing field, government incentives and market interventions are required due to the high cost of SAF production in comparison to conventional fuels. Additionally, industry-academia cooperation is essential for research and development; for example, alliances such as Boeing and MIT have significantly advanced alternative fuel technologies, illustrating how focused partnerships can address challenges in the SAF landscape. So, to direct future research and policy choices, a balanced approach that acknowledges both the promise and the limitations of SAF is necessary [92]. The future of aviation lies in its capacity to evolve and adapt to the growing environmental challenges, and at the forefront of this evolution is SAF. Delving into the prospective horizon of SAF provides insight into the innovative advancements, collaborative opportunities, and market dynamics that promise to reshape the landscape of aviation for a greener tomorrow.

4.1. Potential Advancements in SAF Technology

The horizon for Sustainable Aviation Fuels (SAFs) is luminous with forthcoming technological breakthroughs. There is fervent exploration by researchers and industry experts into pioneering methods to make SAFs even more sustainable and cost-effective [115]. One remarkable stride is the shift towards optimized production techniques, which encompass the use of avant-garde catalysts and state-of-the-art electrochemical modalities for efficient carbon capture and conversion. In line with this, a growing body of research is also turning towards non-edible biomass sources for SAF generation, signifying a move towards truly carbon-neutral synthetic fuels. Parallelly, SAF technology is evolving to be fully compatible with current aircraft engine designs. Aircraft engine manufacturers are immersed in R&D, tailoring engines to operate efficiently on SAFs. This ensures that transitioning to SAFs will not jeopardize engine efficacy, safety standards, or reliability a critical step to fostering wider SAF adoption in aviation [116].

4.2. Collaborative Efforts Between Industry and Academia

The evolution and mainstreaming of SAFs demand a robust collaboration between the industrial sector and academia. Recognizing the invaluable insights academic research offers, industry magnates are forming alliances with universities and research hubs to kindle innovation. Such cooperative ventures, buoyed by both governmental funding and private capital, aim to tackle the inherent technical and economic intricacies of SAF production and integration [117]. This confluence of industry and academia has already borne fruit. Breakthroughs in catalyst design, optimizing feedstocks, and enhancing processing efficiency owe their genesis to these partnerships. Beyond the tangible results, academia channels talent, chemists, engineers, environmental scientists, bolstering the human capital needed for SAF's upward trajectory [118].

4.3. Commercialization Prospects and Market Growth

As the dawn of commercializing SAFs approaches, the market's potential growth trajectory appears robust. Both governmental bodies and global aviation consortiums are rallying behind SAFs, recognizing their potential in trimming down aviation-induced carbon emissions. Policy tools, ranging from carbon pricing schemes to tax reliefs, are slated to galvanize the SAF market. With such robust backing, a surge in SAF production is foreseeable, ushering in economies of scale and consequent cost efficiencies, positioning SAFs as genuine competitors to traditional jet fuels [119].

This burgeoning interest is also piquing the curiosity of private investors and venture capitalists, leading to heightened innovation and product commercialization. Testament to the growing confidence in SAFs, numerous airlines are heralding their commitment to SAF inclusion, signifying a palpable market momentum towards sustainable aviation [120]. The ensuing expansion of the SAF market augurs well for both economic rejuvenation and greener aviation practices. As the aviation sphere embarks on a transformative phase, it is clear that SAFs are central to its sustainable metamorphosis. Technoeconomic (TEA) and life cycle assessment (LCA) by Technological innovations, synergistic academic-industry collaborations, and promising commercial avenues collectively hint at SAFs being the fulcrum for the industry's eco-conscious pivot.

Economic competitiveness of SAF depends on feedstock cost, process scale, co-product credits, and policy instruments; this section assesses TEA findings, market viability, and policy influences [121]. Studies consistently find feedstock and hydrogen/electricity cost dominates minimum fuel selling price (MFSP) and that policy (quotas, mandates, incentives) materially alters market viability [32]. PtL cost drivers are dominated by green hydrogen and electrolyzer capital costs; reports modeling e-SAF supply chains stress that

renewable electricity availability and low-cost hydrogen are prerequisites for competitive PtL [122]. Policy effects such as blending mandates, quotas, and carbon pricing materially change MFSP thresholds and market entry; dedicated demand signals (quotas/long-term offtake) are repeatedly advised to mobilize investment [123].

The extensive commercialization of Sustainable Aviation Fuel (SAF) will be profoundly shaped by the formulation and enactment of conducive policy frameworks. Policies can function as formidable facilitators by alleviating cost impediments, generating demand certainty, and promoting international cooperation. Initially, financial incentives such as tax deductions, subsidies, and loan guarantees can effectively decrease production expenses and mitigate investment risks associated with large-scale SAF facilities. Prominent illustrations of this include the U.S. Inflation Reduction Act and the European Union's Renewable Energy Directive, both of which provide incentives for SAF production and blending. Moreover, carbon pricing instruments (e.g., EU Emissions Trading System, ICAO's CORSIA) can establish competitive parity by elevating the costs of conventional jet fuels in comparison to SAF, thus incentivizing airlines to shift towards low-carbon alternatives. Additionally, blending mandates and quotas can generate reliable demand signals, ensuring that producers are assured of markets for their products.

Furthermore, support for research and development (R&D) is crucial for enhancing feedstock diversification, refining catalysts, and scaling innovative pathways such as PtL. Government supported R&D initiatives, in conjunction with academic institutions and industry stakeholders, can expedite technological readiness while maintaining cost-effectiveness. Lastly, the international standardization of certification protocols through organizations such as ICAO is essential to prevent regional disparities that obstruct global adoption. Explicit sustainability criteria, consistent certification regulations (e.g., alignment with ASTM D7566), and cross-border collaboration will mitigate uncertainty for investors and producers.

A well-balanced amalgamation of incentives, carbon pricing mechanisms, mandates, R&D funding, and regulatory alignment will be crucial to establishing SAF as a commercially feasible and universally recognized aviation fuel. Achieving commercial-scale SAF integration necessitates a comprehensive, coordinated policy framework that addresses market deficiencies, diminishes investment risks, and cultivates sustainable demand. The proposed policy architecture provides multiple, interdependent mechanisms to expedite SAF implementation while safeguarding environmental integrity and economic viability. The success of this initiative will hinge on sustained political resolve, sufficient funding, and adaptive execution that responds to advancements in technology and market dynamics. The transition to SAF embodies both a pressing climate necessity and a substantial economic opportunity. With appropriate policy backing, the aviation sector can fulfill its decarbonization objectives while sustaining growth and competitiveness within the global economy.

Integration model: co-processing within petroleum refineries or integrated biorefineries reduces incremental capex and uses existing logistics infrastructure, improving economics in some scenarios [103]. Dedicated plants with offtake: projects relying on long-term airline purchase agreements or mandate-driven markets are more bankable given current cost gaps [101,102]. Export supply chains: studies examining Australian e-SAF export to off-takers highlight transport, certification alignment, and contractual certainty as prerequisites for export viability [124]. TEA results vary with assumptions on scale, feedstock price, hydrogen/electricity price, and co-product value; cross-study comparisons require normalization of LCOE, hydrogen cost, and allocation rules because differing boundaries (plant gate vs. delivered fuel) produce divergent MFSP estimates [125].

Lifecycle and prospective LCA studies show wide variation in climate benefits depending on feedstock, land use assumptions, and energy inputs; this section summarizes LCA outcomes and methodological caveats. High-resolution and prospective LCAs underscore that feedstock choice and future decarbonization of electricity/hydrogen systems determine net GHG reductions. Feedstock and land use dominate GHG results: perennial and high-yield energy crops (e.g., miscanthus in scenario modeling) frequently show lower carbon intensity than first-generation feedstocks once indirect land use change is accounted for [126]. PtL/e-SAF offers potential for very low lifecycle emissions if powered by low-carbon electricity and using low-carbon CO_2 sources, but current pathways incur large upstream energy penalties without cheap renewable electricity and electrolyzers [104]. Methodological sensitivity: allocation choices, temporal system boundaries, and treatment of indirect land use change create substantial variability across studies; prospective LCA approaches that model future technology adoption and grid decarbonization are recommended to reduce static-scenario bias [106]. Land use and biodiversity risks arise for crop-based SAF unless high-yield or waste/residue feedstocks are prioritized; several studies recommend using microbial oils, wastes, or non-food energy crops to limit displacement effects [127]. Energy system interactions: scaling PtL or algae routes places large new demands on renewables, implying synergies and competition with other sectors for green electricity and low-carbon hydrogen [128]. Many LCAs in the literature use different default carbon accounting (e.g., allocation, co-product handling, ILUC factors). Robust policy and procurement criteria must require transparent LCA methods and prospective scenario analysis to avoid overstating near-term GHG benefits [129].

Figure 4 shows the concept of SAF derived from renewable sources such as CO_2 and hydrogen (H_2). These SAF have gained attention for their potential to reduce the carbon footprint of aviation while also addressing other critical environmental and socio-economic aspects. Through the integration of these topics, this analysis aims to provide a nuanced outlook on sustainable aviation's future, emphasizing the complimentary roles that SAF and upcoming propulsion technologies will play in the industry's shift toward greater sustainability. Emphasizing SAF's potential, recent studies elucidate its manifold benefits [130]. SAFs stand out as environmentally congenial, emitting significantly fewer greenhouse gases than their traditional counterparts [131]. Preliminary research posits that SAFs can curtail CO_2 emissions by a staggering 80% compared to orthodox jet fuels [132]. They are in alignment with global benchmarks like those outlined by the International Civil Aviation Organization (ICAO) and resonate with the United Nations Sustainable Development Goals (UNSDGs) on climate activism [133]. Moreover, SAFs bolster energy resilience, curtailing the aviation sector's over-reliance on petroleum, thereby insulating it from supply shocks, price volatilities, and geopolitical intrigues [134]. The versatile feedstock options for SAFs from urban waste to farm remnants foretell a stable and region-centric supply matrix [135]. Furthermore, SAFs stand at the forefront of aviation's sustainability endeavors [136]. This article seeks to provide a thorough understanding that can help to ongoing research and initiatives aimed at transitioning the aviation sector towards a more sustainable and environmentally friendly future.

In the context of feasibility, the imminent implementation of SAF is most achievable through established methodologies such as HEFA and Fischer–Tropsch synthesis fuels, which are both technologically advanced and equipped with the necessary infrastructure. Nevertheless, advanced alternatives such as Power-to-Liquid technologies and algal biomass-derived fuels, while significantly promising, are constrained by elevated production expenses, high energy requirements, and challenges related to scalability. From an economic perspective, SAF continues to incur higher costs compared to conventional fossil jet fuel, thus rendering widespread adoption contingent upon financial incentives, carbon

pricing mechanisms, and blending regulations; however, co-processing techniques and economies of scale may enhance commercial viability. It is imperative that policy support and the international standardization of regulations are prioritized to facilitate global acceptance, while environmental evaluations consistently indicate that SAF pathways derived from waste materials and renewable energy sources yield the greatest sustainability advantages. In summary, the commercialization of SAF is plausible in the short-term utilizing current technologies, yet long-term success will be contingent upon ongoing technological advancements, cost mitigation strategies, comprehensive policy frameworks, and the sustainable management of feedstock resources.

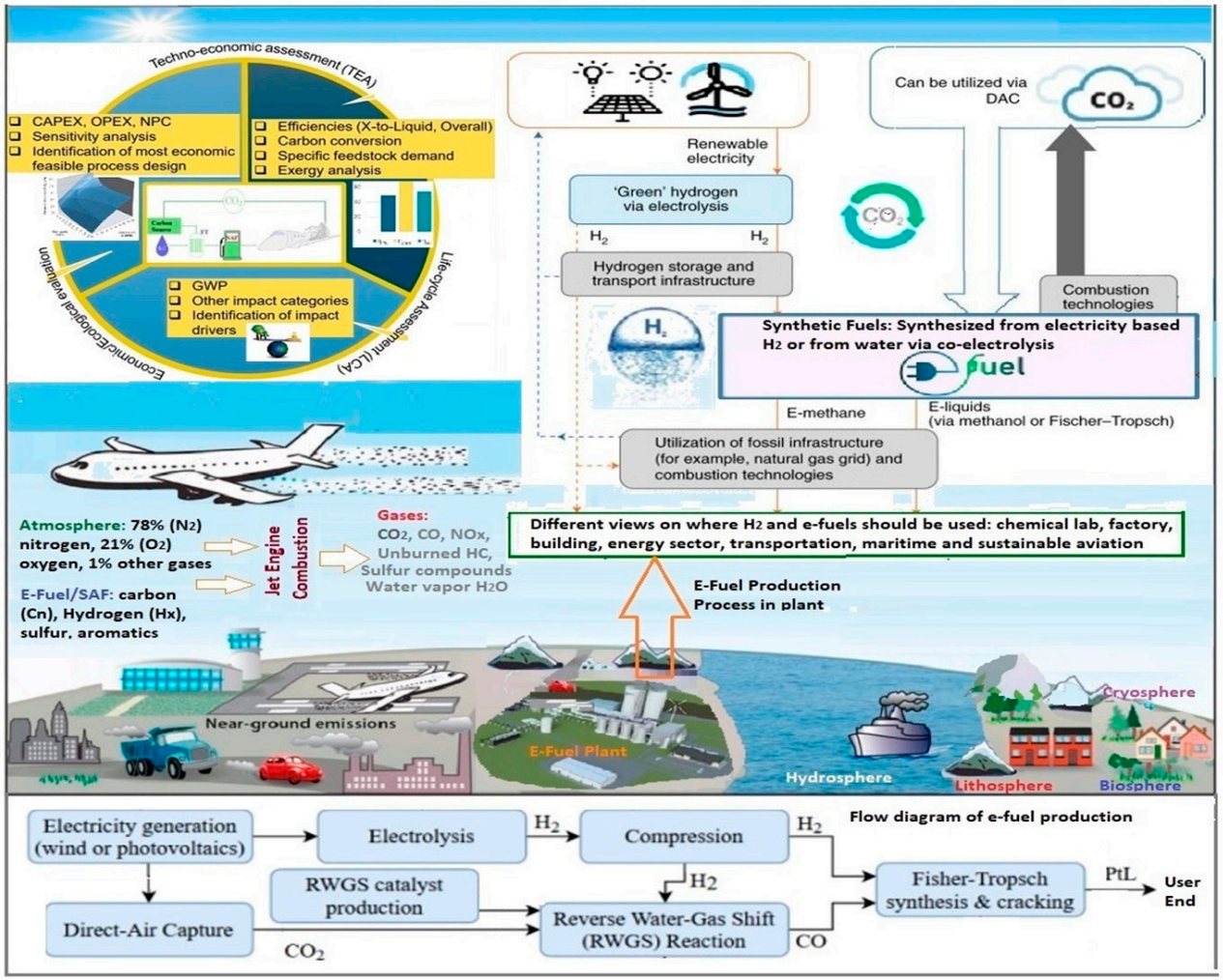

Figure 4. TEA and LCA of SAF plant with FT process.

5. Conclusions

This review has examined the multifaceted challenges surrounding the global adoption and integration of SAFs. Technical hurdles include feedstock variability, energy efficiency, engine compatibility, production costs, financing, and market competitiveness. Environmental ambitions such as reducing greenhouse gas emissions and particulate matter further add complexity, while regional regulatory differences underscore the need for international coordination. Despite these challenges, SAFs hold immense promise. They can substantially reduce the aviation industry's environmental footprint, helping to meet international climate commitments and net-zero targets. Realizing this potential, however, will require significant investment, innovation, and supportive policy frameworks.

Coordinated regulations and global collaboration are critical to align stakeholders and accelerate deployment.

Future research should focus on TEAs that compare alternative production pathways, scalable feedstock sources, and novel synthesis methods. Critical research gaps include cost-reduction pathways for green hydrogen/electrolysers, scale-up of microbial/photochemical conversions, harmonized LCA/certification frameworks, and regional feedstock assessments tied to land use planning. Concerted policy signals (mandates, carbon price or offtake guarantees) are recommended to bridge current economic gaps Complementary strategies including improved air traffic and advanced aircraft design should also be considered to further reduce aviation's climate impact. By addressing these interconnected challenges, the aviation sector can position itself as a leader in sustainability and move decisively toward its net-zero aspirations.

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Abbreviations

The following abbreviations are used in this manuscript:

A	Acidification
ARENA	Australian Renewable Energy Agency
ASEAN	Association of Southeast Asian Nations
BNG	Bio-natural gas
$C_6H_{12}O_5$	Cellulose
CA	Cellulose acetate
CE	Contemporary era
CH_3COOH	Acetic acid
CH_4	Methane
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CNG	Compressed natural gas
E	Eutrophication
EPA	Environmental Protection Agency Victoria
FT	Fischer Tropsc
GIE	Gas Infrastructure Europe
GWh	Gigawatt hours
H_2	Hydrogen
HT	Human toxicity
LCA	Life-cycle assessment
LNG	Liquified natural gas
MW	Megawatt
N_2	Nitrogen
NH_3	Ammonia
O_2	Oxygen
PTL	Power to Liquid
RGF	Renewable "Green" Fuels
WE	Waste Energy
TEA	Techno-economic analysis/assessment
TJ	Terajoule
AbD	Abiotic depletion

AS	Amine scrubbing
bcm	Billion cubic meters
C&SAmerica	Central and South America
$C_6H_{12}O_6$	Glucose
CAGR	Compound annual growth rate
CH_3CH_2OH	Ethanol
CH_3OH	Methanol
CHP	Combined heat and power
SUPRA	Swinburne University Postgraduate Research Award
CO_2	Carbon dioxide
EBA	European Biogas Association
EU	European Union
GHG	Greenhouse gases
GJ	Gigajoule
GWP	Global warming potential
H_2O	Water
IEA	International Energy Agency
LCC	Lifecycle costing
WWTP	Waste Water treatment plant
MWh	Megawatt hours
NCf	Net cash flow
NPV	Net present value
CO	Carbon monoxide
RES	Renewable energy source(s)
SO_2	Sulfur dioxide
STP	Standard temperature and pressure
TE	Thermal energy
TRL	Technological readiness level

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