RECENT ADVANCES IN THE DEVELOPMENT AND SCALABILITY OF SUSTAINABLE AVIATION FUELS

Sustainable aviation fuels (SAFs) present a viable alternative to fossil-derived jet fuels, offering significant reductions in greenhouse gas emissions while maintaining compatibility with existing aviation infrastructure. This review examines key SAF feedstocks, including algae-based lipids, waste biomass, and power-to-liquid (PtL) fuels, and explores their respective conversion pathways such as hydroprocessed esters and fatty acids (HEFA), alcohol-to-jet (ATJ) conversion, and Fischer-Tropsch (FT) synthesis. The discussion highlights advances in catalyst optimization, process intensification, and hybrid production approaches aimed at improving fuel yield and reducing costs. Key challenges, including feedstock availability, scalability, and economic feasibility, are analyzed alongside strategies such as advanced biorefineries, high-efficiency catalysts, and policy-driven incentives to facilitate widespread SAF adoption. Emerging research in electrochemical CO_2 reduction and biocatalytic synthesis is also explored as a future avenue for achieving carbon-neutral fuel production.

1. Introduction

Sustainable aviation fuels (SAFs) are derived from biomass, organic waste, and carbon dioxide, offering an alternative to traditional aviation fuels composed of fossil fuels and hydrocarbons. The primary goal of SAF utilization in the modern day is to decrease carbon emissions in the aviation industry while maintaining traditional aviation fuels' unique chemical properties, consistent with improved resistance to temperature fluctuations, freezing, and high-temperature explosions. Recent efforts to achieve this goal include initiatives led by the International Air Transport Association (IATA) to achieve net-zero carbon emissions in the aviation industry by 2050. Nevertheless, the aviation industry accounts for approximately 2% of greenhouse gas emissions internationally, highlighting the importance of SAFs in mitigating the effects of global warming by implementing normal and isomeric alkenes to mimic the properties of traditional fuels [1].

Various materials have been proposed as feedstock for SAF production. Among the most prevalent production pathways include hydro-processed esters and fatty acids (HEFAs), derived from vegetable oils, algae-based oils, and animal fats refined through the two-phased process of hydrogenation. Alcohol-to-jet (AJT) technologies have also been used to alter the carbon structure of alcohols, such as ethanol and isobutanol, through molecular bonding and deoxygenation. Additionally, power-to-liquid (PtL) has shown promise in converting carbon-containing materials, renewable electricity, and non-fossil carbon dioxide to produce refinable synthetic liquid hydrocarbons and crude oils by combining hydrogen synthesized from water electrolysis with carbon dioxide (CO_2) captured through Fischer-Tropsch (FT) synthesis [2]

However, significant barriers remain preventing large-scale SAF production. Although HEFA has already shown promise as a commercially viable SAF pathway, ATJ, PtL, and FT technologies are still in early development. Moreover, many sustainable feedstocks used for these processes have also raised biodiversity and deforestation concerns, are limited in supply, and often compete with other industries that heavily depend on these materials, such as biodiesel production [3]. Additionally, global infrastructure facilitating SAF refinement, transportation, and storage is scarce, rendering production logistically challenging.

This paper will evaluate recent advances in the development and scalability of SAF technologies. With an emphasis on identifying efficient and cost-effective producing methods using various feedstocks like algae, biowaste, and renewable electricity to reduce carbon emissions within aviation while meeting growing industrial demands, this review will also discuss research into blending ratio optimization, life cycle analysis, and policy frameworks to incentivize large-scale SAF adoption despite recent challenges in the field.

2. Feedstocks for Sustainable Aviation Fuels

2.1 Algae-Based SAF

Algae-based sustainable aviation fuel (SAF) production relies on microalgae and cyanobacteria, which can efficiently convert CO_2, water, and sunlight into lipids suitable for biofuel conversion. As illustrated in Figure 1, algae accumulate high lipid contents under optimized conditions, making them a promising alternative to conventional oil crops [35]. The process typically involves cultivation in open ponds or photobioreactors, followed by lipid extraction and hydroprocessing to generate hydrotreated esters and fatty acids (HEFA), the most widely accepted SAF pathway [4].

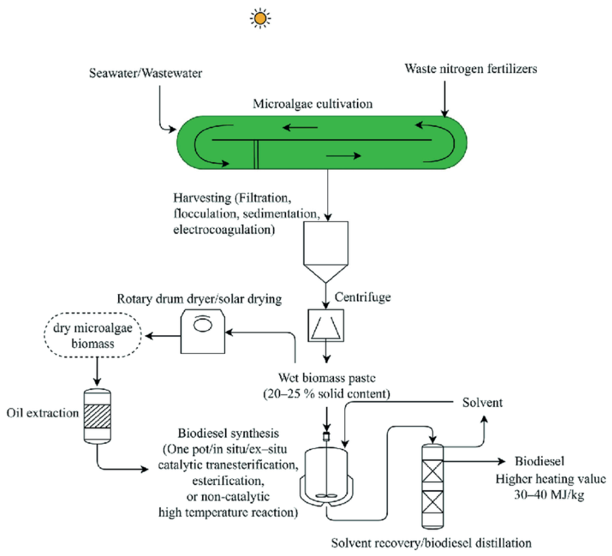

Figure 1. Process flow diagram for biodiesel production from microalgae [31]

One of the primary advantages of algae-derived SAF is its high biomass yield and minimal land-use impact, allowing for production without competing with food supply chains. Furthermore, microalgae can be cultivated using non-arable land, saline water, and industrial waste streams rich in CO_2, enhancing sustainability [5]. However, scalability remains challenging due to the high costs associated with cultivation, harvesting, and lipid extraction. Improvements in genetic engineering and strain selection have led to enhanced lipid accumulation and growth rates, with recent studies demonstrating lipid contents exceeding 50% of dry biomass in optimized conditions [6].

Despite its potential, commercial viability depends on reducing energy-intensive processing steps. Current research focuses on integrated biorefineries that utilize residual biomass for biochar, biogas, or high-value co-products to offset costs. Additionally, advancements in direct catalytic conversion of whole algae biomass—bypassing lipid extraction—are being explored to improve process efficiency and economic feasibility [7].

2.2 Waste Biomass and Residual Feedstocks

Waste biomass-derived SAF leverages agricultural residues, forestry waste, municipal solid waste (MSW), and industrial byproducts to create drop-in fuels while reducing landfill waste and emissions. The most common conversion methods include thermochemical processes such as gasification-Fischer-Tropsch (FT) synthesis and pyrolysis, which break down biomass into synthesis gas (syngas) or bio-oil, respectively, before upgrading into aviation-compatible hydrocarbons [8].

Agricultural residues, including corn stover, wheat straw, and sugarcane bagasse, are rich in cellulose and lignin, making them ideal for biofuel production through enzymatic hydrolysis or catalytic depolymerization. Forestry residues, such as sawdust and bark, have also been utilized in bio-oil production through fast pyrolysis, with upgraded biofuels showing promising fuel properties comparable to conventional jet fuel [9]. Additionally, MSW conversion provides a scalable alternative by repurposing plastic waste and organic fractions into liquid hydrocarbons through hydrothermal liquefaction (HTL) and catalytic cracking [10].

Challenges in waste biomass utilization include heterogeneous feedstock composition, which affects conversion efficiency and fuel quality. Advanced pretreatment methods, such as steam explosion and torrefaction, have been employed to enhance biomass reactivity and improve overall process yields. Recent studies indicate that blending bio-based intermediates with petroleum-derived fractions can improve SAF compatibility and cost-effectiveness, supporting wider industry adoption [11].

2.3 Renewable Electricity and Power-to-Liquid (PtL) Fuels

Power-to-liquid (PtL) technology enables synthetic fuel production from CO_2 and renewable electricity, offering a fully decarbonized alternative to conventional aviation fuels. The process involves electrolytic hydrogen (H_2) production via water electrolysis, followed by FT synthesis or methanol-to-jet (MTJ) conversion, where hydrogen reacts with captured CO_2 to form liquid hydrocarbons suitable for aviation applications [12].

One key advantage of PtL fuels is their potential for carbon-neutral operation, as the CO_2 used in production can be sourced from direct air capture (DAC), industrial flue gases, or biogenic emissions. When coupled with wind, solar, or hydroelectric power, PtL fuels achieve near-zero lifecycle emissions while ensuring fuel security and scalability independent of biomass availability [13]. However, high energy input requirements and electrolyzer efficiency limitations currently hinder large-scale deployment.

Advancements in high-temperature co-electrolysis using solid oxide electrolysis cells (SOECs) have demonstrated higher conversion efficiencies and lower operational costs than conventional alkaline or PEM electrolysis. Additionally, catalysts optimized for selective CO_2 hydrogenation are improving hydrocarbon yield and product selectivity, making PtL fuels more commercially viable [14]. However, recent techno-economic assessments indicate that PtL fuels currently have higher production costs compared to fossil jet fuel, with projections suggesting that cost parity may not be achieved in the near term. Factors such as the high energy requirements for electrolysis, limited availability of low-cost renewable electricity, and the nascent state of carbon capture and storage (CCS) infrastructure contribute to these challenges. For instance, a 2023 study reported that the production costs for e-kerosene are higher than recent fossil jet fuel prices, ranging from approximately $340 to $1,370 per ton, depending on various factors including electricity costs and plant scale [15]. These findings suggest that significant technological advancements and policy interventions will be necessary to make PtL fuels economically competitive with traditional jet fuels.

2.4 Comparison of SAF Feedstocks: Benefits, Challenges, and Maturity

As evidenced by section 2.1, 2.2, and 2.3, SAFs can be derived from various feedstocks, each with unique advantages and challenges. Algae-based SAF offers high lipid yields and can be grown on non-arable land, but its commercial viability is limited by high production and extraction costs. Waste biomass and residual feedstocks, including agricultural and municipal waste, provide a scalable and cost-effective SAF pathway, though feedstock variability and pretreatment costs pose challenges. This pathway is already commercially viable. PtL fuels, produced using renewable electricity and captured CO_2, present a fully decarbonized alternative, independent of biomass availability. However, high energy demands and infrastructure costs currently limit widespread adoption. As summarized in Table 1, waste biomass-based SAF is the most commercially mature, while algae and PtL fuels hold long-term potential with continued advancements in cost reduction, technology scaling, and policy support.

Table 1. Summary of advantages, challenges and maturity levels of primary SAF feedstocks

Feedstock	Advantages	Challenges	Maturity Level
Algae-Based SAF	- High lipid yield per unit area - Uses non-arable land - Can utilize CO_2-rich waste streams	- High cultivation and extraction costs - Energy-intensive processing	Early commercial
Waste Biomass & Residuals	- Abundant feedstock availability - Utilizes agricultural and municipal waste - Existing FT and pyrolysis infrastructure	- Feedstock variability affects fuel quality - Pretreatment costs - Logistics and collection challenges	Commercially viable
Power-to-Liquid Fuels	- Fully decarbonized pathway - No reliance on biomass - Scalable with renewable energy expansion	- High electricity demand - Expensive electrolyzers - Limited infrastructure	Demonstration & early commercial

3.Production Pathways and Optimization Strategies

3.1 Hydroprocessed Esters and Fatty Acids (HEFA)

Hydroprocessed esters and fatty acids (HEFA) represent the most commercially viable pathway for sustainable aviation fuel (SAF) production, accounting for the majority of current SAF supply. The process involves hydrotreatment of renewable lipid feedstocks, such as vegetable oils, waste fats, and algal lipids (primarily in the forms of cooking oil or animal fats), to produce drop-in biofuels that meet conventional jet fuel specifications. Observable in Figure 2, HEFA fuels undergo hydrodeoxygenation, hydrocracking, and isomerization to remove oxygen and adjust hydrocarbon chain length, resulting in a fuel with high energy density and compatibility with existing aviation infrastructure [16].

One of the key advantages of HEFA-based SAF is its low sulfur content and improved combustion characteristics, leading to reduced particulate emissions compared to petroleum-derived jet fuel. However, feedstock availability and cost remain primary constraints to large-scale adoption. While waste fats and used cooking oils provide cost-effective alternatives, their limited supply necessitates the expansion of dedicated oilseed crops, such as camelina and carinate, or advancements in high-lipid algae cultivation [17].

Recent research has focused on catalyst optimization and process integration to improve HEFA yield and reduce hydrogen consumption. Studies on NiMo and CoMo catalysts have demonstrated improved deoxygenation efficiency, while novel bifunctional catalysts incorporating zeolites enhance selectivity for jet-range hydrocarbons [18]. Additionally, co-processing HEFA intermediates in petroleum refineries is emerging as a cost-effective strategy, leveraging existing infrastructure to scale SAF production [17].

3.2 Alcohol-to-Jet (ATJ) Conversion

The alcohol-to-jet (ATJ) pathway utilizes fermentation-derived alcohols, such as ethanol, butanol, and isobutanol, as precursors for SAF production. The process involves dehydration, oligomerization, hydrogenation, and distillation to convert short-chain alcohols into branched and cyclic hydrocarbons that meet jet fuel specifications [19].

A key advantage of ATJ fuels is their feedstock flexibility, as alcohols can be produced from lignocellulosic biomass, municipal solid waste, and syngas fermentation. However, the pathway is less mature than HEFA and requires higher processing energy due to the additional chemical steps involved [19]. Additionally, selectivity and catalyst efficiency play crucial roles in determining overall fuel yield and economic feasibility.

Recent advancements include improved dehydration catalysts, such as zeolite-based materials, which enhance conversion efficiency and minimize byproduct formation. Additionally, genetically engineered microbial strains have been developed to increase alcohol titers in fermentation, reducing downstream processing costs [19]. In a recent study, an optimized ATJ process using butanol from biomass fermentation achieved a conversion efficiency of 84% with a jet fuel yield exceeding 50% by weight—a significant improvement over earlier designs [19].

Despite its potential, ATJ SAF remains more expensive than HEFA-derived fuels, with production costs largely dependent on feedstock sourcing and process energy requirements. Ongoing research into integrated biorefineries and process intensification is expected to improve the pathway's commercial viability [20].

3.3 Gasification and Fischer-Tropsch Synthesis

Gasification followed by FT synthesis is a thermochemical pathway for SAF production, converting solid biomass, municipal solid waste (MSW), and other carbonaceous feedstocks into liquid hydrocarbons via syngas ($CO + H_2$). The process consists of high-temperature gasification, syngas cleaning, FT synthesis, and hydrocracking to generate aviation-compatible fuels [20].

The FT pathway is particularly attractive due to its feedstock versatility and ability to produce a wide range of hydrocarbons, including diesel and jet fuel. Additionally, FT-derived SAF has excellent combustion characteristics, featuring a high hydrogen-to-carbon ratio and near-zero sulfur content, resulting in reduced particulate emissions compared to conventional jet fuel [20].

Despite these advantages, FT SAF faces significant economic barriers due to high capital investment requirements and relatively low process efficiency. One of the primary challenges is syngas purification, as contaminants such as tars, ammonia, and sulfur compounds can poison FT catalysts and reduce overall conversion efficiency [20].

Recent advancements in biomass pretreatment, catalyst development, and process intensification have led to improved FT SAF yields. For instance, Co-based and Fe-based FT catalysts have been optimized for higher selectivity towards jet-range hydrocarbons, while hybrid gasification approaches incorporating plasma-enhanced and catalytic gasification have shown promise in reducing syngas cleaning costs [20].

A key area of research focuses on blending FT SAF with conventional fuels to improve fuel properties and emissions performance. Recent trials indicate that a 50/50 FT-blended fuel can achieve CO_2 lifecycle reductions of up to 80% compared to conventional jet fuel, supporting regulatory approval and industry adoption [20].

3.4 Emerging Catalytic and Electrochemical Approaches

Beyond conventional SAF pathways, emerging catalytic and electrochemical conversion technologies are being explored to enhance process efficiency and reduce carbon intensity. These

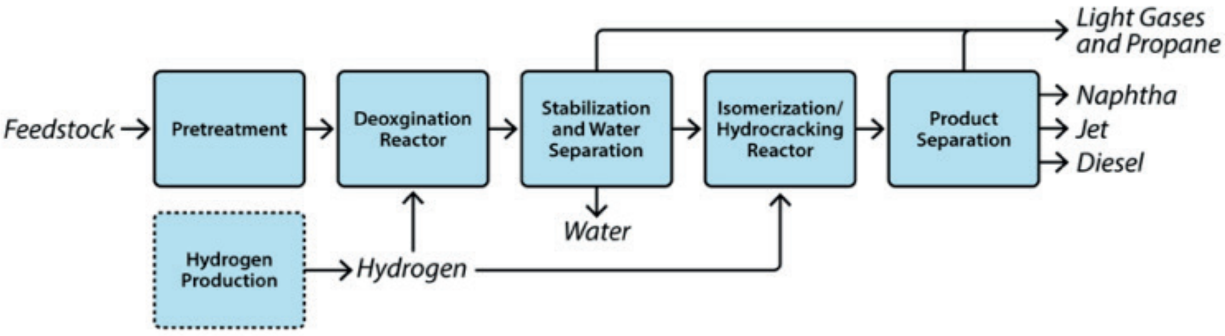

Table 2. Lifecycle carbon footprint reductions of SAF pathways

SAF Pathway	Lifecycle GHG Reduction (%)	Key Assumptions
HEFA	**50 – 80%**	**Based on waste oils and fats; lower emissions for used cooking oil, higher for virgin oils**
ATJ	**60 – 85%**	**Depends on fermentation efficiency and feedstock source (e.g., sugarcane vs. corn)**
PtL	**Near-zero**	**Assumes 100% renewable electricity for electrolysis and CO_2 sourced from direct air capture (DAC)**

include direct CO_2 hydrogenation, electrochemical CO_2 reduction, and biocatalytic routes that utilize engineered microbes for hydrocarbon synthesis [20]. One promising approach is high-temperature co-electrolysis, where solid oxide electrolysis cells (SOECs) are used to convert CO_2 and H_2O into syngas, which can then be processed into SAF via FT synthesis. This method has demonstrated higher conversion efficiencies and lower energy penalties compared to traditional electrolysis and gasification routes [20].

Another innovative pathway involves heterogeneous catalytic hydrogenation of CO_2, utilizing metal-organic frameworks (MOFs) and single-atom catalysts to selectively produce liquid hydrocarbons. Recent studies have reported conversion efficiencies exceeding 60% with low-temperature, low-pressure operation, making this approach attractive for distributed SAF production [20]. Biotechnological advancements are also contributing to SAF development, with genetically engineered microbes capable of directly converting CO_2 into hydrocarbons via engineered metabolic pathways. For example, engineered Clostridium strains have demonstrated continuous biofuel production from industrial CO_2 waste streams, providing a sustainable and scalable alternative to fossil-based aviation fuels [20].

While still at the early TRL (Technology Readiness Level) stages, these emerging technologies hold long-term potential for cost-effective, carbon-neutral SAF production. Future research will focus on scaling these approaches, integrating them with renewable energy sources, and improving catalyst longevity and process stability [20].

4. Optimizing SAF Blending and Lifecycle Analysis

4.1 SAF Blending Ratios for Performance and Emissions

Sustainable aviation fuel is designed to be compatible with existing aircraft engines and infrastructure through blending with conventional jet fuel. The American Society for Testing and Materials (ASTM) has established specifications under ASTM D7566, which currently permit blending ratios of up to 50% with conventional jet fuel, depending on the production pathway [21]. These specifications ensure that the blended fuel meets the necessary performance and safety standards for aviation operations while maintaining engine reliability and fuel efficiency. While most commercial operations use SAF blends up to 50%, certain SAF pathways, such as Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) and Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK), have been approved for 100% SAF use in test flights. Recent trials conducted by Boeing, Airbus, and commercial airlines have demonstrated that 100% SAF can be used without engine modifications, showcasing its potential for full replacement of fossil-based jet fuel in the future [22]. However, full regulatory approval for commercial 100% SAF use is still under review, requiring further studies on long-term engine performance, emissions impact, and fuel supply scalability.

Higher blending ratios have been shown to improve combustion efficiency and reduce emissions. Studies indicate that increasing the proportion of sustainable fuel in the blend leads to lower particulate matter and sulfur oxide emissions, primarily due to the absence of aromatics and sulfur compounds in alternative fuel sources [22]. This reduction in particulate emissions also decreases the formation of contrails, which contribute to radiative forcing and climate impact. Research has demonstrated that using 100% alternative fuel can reduce ice crystal formation in contrails by up to 50%, significantly mitigating its environmental effects [22].

Despite these benefits, challenges remain in achieving higher blending percentages beyond current regulatory limits. Studies suggest that blends exceeding 50% may require modifications to fuel systems, seals, and combustion dynamics, necessitating further research and certification efforts before widespread adoption [22]. Additionally, fuel composition variability across different production pathways may impact overall engine performance and material compatibility [22].

4.2 Lifecycle Carbon Footprint and Sustainability Metrics

Assessing the environmental impact of sustainable fuels requires a comprehensive life cycle analysis (LCA), often referred to as a "well-to-wake" assessment. This evaluation considers all stages of the fuel's production and use, including feedstock cultivation, refining, distribution, and combustion in aircraft engines [23]. LCA studies suggest that well-established production pathways, such as hydroprocessed esters and fatty acids (HEFA), can reduce lifecycle greenhouse gas (GHG) emissions by 50–80% compared to conventional fossil fuels [23]. However, the actual carbon savings depend heavily on the type of feedstock used. For instance, HEFA fuels derived from used cooking oil (UCO) or animal fats result in higher emission reductions than those sourced from palm or soybean oil, which have greater land-use change impacts [24].

Beyond carbon dioxide (CO_2) emissions, the impact of sustainable fuel on non-CO_2 emissions, such as nitrogen oxides (NO_x) and water vapor emissions, is a crucial consideration. Research indicates that using sustainable aviation fuel reduces soot particle emissions, leading to fewer contrail ice crystals and a lower overall climate-warming effect [22]. Since contrails contribute significantly to aviation-induced climate change, reducing their formation is a major advantage of shifting to higher blending ratios [23].

However, the effectiveness of different production pathways varies. While PtL fuels can theoretically achieve near-zero lifecycle emissions when produced using renewable electricity and carbon capture, their actual impact depends on the energy source for electrolysis and CO_2 sourcing method. If 100% renewable electricity (e.g., wind, solar, or hydropower) is used, and CO_2 is sourced from direct air capture (DAC) or biogenic emissions, PtL fuels can approach full carbon neutrality. In contrast, if the electrolysis process is powered by fossil-fuel-based electricity, the overall emissions can be significantly higher, reducing the climate benefits of PtL fuels [25]. Similarly, the ATJ pathway exhibits a wide range of carbon reduction potential (60–85%), largely dependent on the feedstock source. ATJ fuels derived from sugarcane-based ethanol tend to have lower emissions, whereas corn-based ethanol—which requires higher land and energy inputs—results in higher associated emissions [26]. To provide a comparative overview, Table 2 summarizes the lifecycle carbon footprint reductions of different SAF pathways, highlighting their potential GHG savings under optimal conditions.

5. Scaling Challenges and Economic Concerns

The scalability of SAF production is significantly constrained by the availability and sustainability of suitable feedstocks. Current primary feedstocks, such as waste oils and fats, are limited in supply and face competition from other industries, leading to potential supply chain bottlenecks. For instance, the finite availability of used cooking oil and animal fats restricts the volume of SAF that can be produced through the HEFA pathway. Additionally, the cultivation of energy crops raises concerns regarding land use, water consumption, and potential impacts on food security, necessitating careful consideration to avoid adverse environmental and social effects [27]. To mitigate these challenges, research is focusing on alternative feedstocks, such as lignocellulosic biomass, municipal solid waste, and algae, which offer greater abundance and sustainability. However, the development of efficient and cost-effective technologies to convert these feedstocks into SAF remains a significant hurdle. Advancements in biochemical and thermochemical conversion processes are essential to unlock the potential of these alternative feedstocks and enable large-scale SAF production [28].

SAF's economic viability is another critical factor influencing its adoption in the aviation industry. Currently, SAF production costs are substantially higher than those of conventional jet fuel, primarily due to the high costs associated with feedstock procurement, processing technologies, and the scale of production facilities. Estimates suggest that SAF can be two to three times more expensive than traditional jet fuel, posing a significant barrier to widespread adoption [29]. Economies of scale play a pivotal role in reducing production costs. As production volumes increase, unit costs are expected to decrease, making SAF more competitive with conventional fuels. Policy interventions, such as subsidies, tax incentives, and carbon pricing mechanisms, are also crucial in bridging the cost gap and encouraging investment in SAF production infrastructure. For example, government initiatives that provide financial support for SAF producers can enhance economic feasibility and stimulate market growth.

The existing fuel infrastructure is predominantly designed for fossil-based jet fuels, presenting challenges for the integration of SAF. Modifications to transportation, storage, and refueling systems may be necessary to accommodate SAF's unique properties and ensure compatibility with current aviation operations. Additionally, the geographic distribution of SAF production facilities relative to major airports can impact logistics and supply chain efficiency. Establishing a robust distribution network is essential to facilitate the widespread adoption of SAF [27]. Collaborative efforts among stakeholders, including fuel producers, airlines, airport operators, and policymakers, are vital to address these infrastructure challenges. Developing standardized protocols and investing in infrastructure upgrades can streamline SAF integration into the existing fuel supply chain, thereby supporting the scaling of SAF utilization in the aviation sector [28]. Additionally, policy and regulatory frameworks can significantly influence the development and deployment of SAF. Supportive policies, such as blending mandates, tax credits, and research funding, can create a favorable environment for SAF advancement. For instance, the European Union has implemented the ReFuelEU Aviation Regulation, which sets a minimum supply mandate for SAF in Europe, starting with 2% in 2025 and increasing to 70% by 2050 [31]. However, policy uncertainty and inconsistent regulations across different regions can pose challenges for investors and producers. Coordinating policies and establishing long-term regulatory commitments are essential to providing the stability needed for substantial investments in SAF production capacity [32].

6. Future Works

Advancing SAF necessitates addressing current limitations in catalyst efficiency, feedstock sustainability, and interdisciplinary collaboration. Enhancing catalyst performance is pivotal for improving SAF production efficiency. Emerging materials, such as metal-organic frameworks (MOFs) and single-atom catalysts, have shown promise in increasing reaction rates and selectivity in processes like FT synthesis and ATJ conversion. For instance, MOFs with tailored pore structures facilitate better access to active sites, thereby improving hydrocarbon yield. However, challenges related to catalyst stability and scalability under industrial conditions persist. Current research focuses on doping strategies and support modifications to enhance catalyst durability and performance [33].

In bioengineering, genetically modified microorganisms are being developed to optimize metabolic pathways for higher lipid production, serving as efficient feedstocks for SAF. For example, engineered strains of Yarrowia lipolytica have demonstrated increased lipid accumulation through the overexpression of specific genes involved in fatty acid biosynthesis. Despite these advancements, issues such as genetic stability and process scalability remain. Ongoing studies aim to refine genetic constructs and fermentation conditions to achieve consistent, high-yield lipid production suitable for industrial applications [34].

Optimizing the entire SAF production process is crucial for economic viability and environmental impact reduction. Integrating advanced pretreatment methods, such as steam explosion and torrefaction, can enhance biomass reactivity, leading to higher conversion efficiencies. Additionally, process intensification techniques, including the use of reactive distillation and membrane reactors, are being explored to streamline production steps and reduce energy consumption. However, challenges in process integration and control need to be addressed to fully realize these benefits [35].

Diversifying feedstock sources is essential to ensure a sustainable and resilient supply chain for SAF production. Non-edible oilseed crops, such as camelina and carinata, are gaining attention due to their low agricultural input requirements and compatibility with existing farming practices. For instance, field trials of camelina have shown its potential as a rotation crop, providing both economic and soil health benefits. Nevertheless, considerations regarding land use change and indirect environmental impacts must be carefully managed. Research is ongoing to assess the lifecycle emissions of these feedstocks and develop best practices for their cultivation and harvesting [36].

Lastly, securing adequate funding is critical to supporting the research, development, and commercialization of SAF technologies. Government grants, private investments, and public-private partnerships play vital roles in financing these initiatives. Policy instruments, such as tax incentives and carbon pricing, can further stimulate investment by improving the economic competitiveness of SAFs. For instance, the implementation of a carbon offset and reduction scheme for international aviation (CORSIA) aims to incentivize the adoption of lower-carbon fuels. Nonetheless, uncertainties in policy frameworks and market dynamics pose risks to sustained funding. Continuous engagement with policymakers and stakeholders is necessary to develop stable and supportive financial mechanisms [37].

7. Conclusion

SAFs provide a promising pathway for reducing aviation-related carbon emissions while maintaining compatibility with existing fuel infrastructure. This review explored key SAF feedstocks, including algae, waste biomass, and PtL fuels, as well as major conversion pathways such as HEFA, ATJ, and FT synthesis. While SAF technologies have demonstrated viability, challenges related to feedstock availability, production scalability, and economic feasibility persist. Advancements in catalyst optimization, process integration, and emerging electrochemical approaches offer potential solutions to improve fuel yield and reduce costs. Additionally, policy frameworks and financial incentives will play important roles in accelerating SAF adoption. Continued research into novel feedstocks, improved conversion processes, and infrastructure development is necessary to support the widespread implementation of SAFs as a long-term solution for decarbonizing the aviation industry.

References

[1] Wang, Bofan, et al. "Sustainable Aviation Fuels: Key Opportunities and Challenges in Lowering Carbon Emissions for Aviation Industry." Carbon Capture Science & Technology, vol. 13, Aug. 2024, p. 100263. https://doi.org/10.1016/j.ccst.2024.100263.

[2] "The Essentials of Sustainable Aviation Fuel." Sia Partners. https://www.sia-partners.com/en/insights/publications/essentials-sustainable-aviation-fuel.

[3] Shah, Raj, et al. "Advancements and Challenges in Sustainable Aviation Fuel Production." Petro Online, www.petro-online.com/article/analytical-instrumentation/11/koehler-instrument-company/advancements-and-challenges-in-sustainable-aviation-fuel-production/3428.

[4] Singh, Anoop, et al. Renewable fuels from algae: An answer to debatable land-based fuels. Bioresource Technology, 102(1), 10-16. https://doi.org/10.1016/j.biortech.2010.06.032

[5] Mata, T. M., Martins, A. A., & Caetano, N. S. (2010). Microalgae for biodiesel production and other applications: A review. Renewable and Sustainable Energy Reviews, 14(1), 217-232. https://doi.org/10.1016/j.rser.2009.07.020

[6] Griffiths, M. J., & Harrison, S. T. L. (2009). Lipid productivity as a key characteristic for choosing algal species for biodiesel production. Journal of Applied Phycology, 21(5), 493-507. https://doi.org/10.1007/s10811-008-9392-7

[7] Lari, Z., & Abedi, J. (2012). Production of bio-jet fuel from algae oil via direct catalytic hydrodeoxygenation. Fuel Processing Technology, 109, 145-153. https://doi.org/10.1016/j.fuproc.2012.09.040

[8] Bridgwater, A. V. (2012). Review of fast pyrolysis of biomass and product upgrading. Biomass and Bioenergy, 38, 68-94. https://doi.org/10.1016/j.biombioe.2011.01.048

[9] Mohan, D., Pittman Jr, C. U., & Steele, P. H. (2006). Pyrolysis of wood/biomass for bio-oil: A critical review. Energy & Fuels, 20(3), 848-889. https://doi.org/10.1021/ef0502397

[10] Melligan, F., Dussan, K., Auccaise, R., Novotny, E. H., Leahy, J. J., & Hayes, M. H. B. (2011). Pressurised pyrolysis of Miscanthus using a fixed bed reactor. Bioresource Technology, 102(3), 3466-3470. https://doi.org/10.1016/j.biortech.2010.10.124

[11] Wright, M. M., Daugaard, D. E., Satrio, J. A., & Brown, R. C. (2010). Techno-economic analysis of biomass fast pyrolysis to transportation fuels. Fuel, 89, S2-S10. https://doi.org/10.1016/j.fuel.2010.07.029

[12] Schmidt, P. R., & Weindorf, W. (2016). Power-to-Liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel. German Environment Agency (UBA). https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/161005_uba_hintergrund_ptl_barrierrefrei.pdf

[13] Fasihi, M., & Breyer, C. (2020). Baseload electricity and hydrogen supply based on hybrid PV-wind power plants. Journal of Cleaner Production, 243, 118466. https://doi.org/10.1016/j.jclepro.2019.118466

[14] Schemme, S., Samsun, R. C., Peters, R., & Stolten, D. (2017). Power-to-fuel as a key to sustainable transport systems–An analysis of diesel fuels produced from CO_2 and renewable electricity. Fuel, 205, 198-221. https://doi.org/10.1016/j.fuel.2017.05.061

[15] Schmidt, Patrick & Weindorf, Werner & Failer, Sandra & Astono, Yanni & Ullmann, Alexandra. (2023). E-SAF: Techno-Economics of PtL and PtH2 – Focus North America and Europe.

[16] National Renewable Energy Laboratory. (2023). Hydroprocessed Esters and Fatty Acids Pathway. Retrieved from https://www.nrel.gov/docs/fy24osti/87803.pdf

[17] U.S. Department of Energy. (2024). Sustainable Aviation Fuel: Pathways to Commercial Liftoff. Retrieved from https://liftoff.energy.gov/sustainable-aviation-fuel-2/

[18] Geleynse, S., Brandt, K., Garcia-Perez, M., Wolcott, M., & Zhang, X. (2018). The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation. ChemSusChem, 11(21), 3728-3741. https://doi.org/10.1002/cssc.201801690

[19] Geleynse, S., Brandt, K., Garcia-Perez, M., Wolcott, M., & Zhang, X. (2018). The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation. ChemSusChem, 11(21), 3728-3741. https://doi.org/10.1002/cssc.201801690

[20] U.S. Department of Energy. (2024). Sustainable Aviation Fuel: Pathways to Commercial Liftoff. Retrieved from https://liftoff.energy.gov/sustainable-aviation-fuel-2/

[21] International Air Transport Association. Sustainable Aviation Fuel (SAF) Handbook. 2023. https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-handbook.pdf

[22] Voigt, Christian, et al. "Powering Aircraft with 100% Sustainable Aviation Fuel Reduces Ice Crystal Number in Contrails." Atmospheric Chemistry and Physics 24, no. 6 (2024): 3813–3829. https://doi.org/10.5194/acp-24-3813-2024

[23] Congressional Research Service. "Sustainable Aviation Fuel (SAF): Production Pathways." 2024. https://crsreports.congress.gov/product/pdf/IF/IF12847

[24] Zemanek, Debrah, Pascale Champagne, and Warren Mabee. "Review of Life-Cycle Greenhouse-Gas Emissions Assessments of Hydroprocessed Renewable Fuel (HEFA) from Oilseeds." Biofuels, Bioproducts and Biorefining, vol. 14, no. 5, 2020, pp. 748–774. https://doi.org/10.1002/bbb.2112.

[25] International Air Transport Association (IATA). Sustainable Aviation Fuel (SAF) Handbook. 2023. https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-handbook.pdf.

[26] U.S. Department of Energy. Sustainable Aviation Fuel: Pathways to Commercial Liftoff. 2024. https://liftoff.energy.gov/sustainable-aviation-fuel-2/.

[27] World Economic Forum. Scaling Sustainable Aviation Fuel Supply: Overcoming Barriers. 2024. https://www3.weforum.org/docs/WEF_Scaling_Sustainable_Aviation_Fuel_Supply_2024.pdf

[28] Resources for the Future. Sustainable Aviation: Challenges, Strategies, and Policies for Greener Aviation. 2024. https://www.rff.org/publications/reports/sustainable-aviation-challenges-strategies-policies-for-greener-aviation/

[29] Resources for the Future. Promoting Sustainable Aviation Fuels: Considerations for Policymakers. 2024. https://www.resources.org/common-resources/promoting-sustainable-aviation-fuels-considerations-for-policymakers/

[30] Center for Climate and Energy Solutions. Scaling Sustainable Aviation Fuel: Recommendations to Federal Policymakers from Washington State. 2024. https://www.c2es.org/wp-content/uploads/2024/07/Scaling-Sustainable-Aviation-Fuel-Recommendations-to-Federal-Policymaker-From-Washington-State.pdf

[31] European Union Aviation Safety Agency. Sustainable Aviation Fuels. 2024. https://www.easa.europa.eu/en/domains/environment/eaer/sustainable-aviation-fuels

[32] Chooose. Benefits and Considerations of Sustainable Aviation Fuel. 2024. https://www.chooose.today/resources/learning-resources/benefits-and-considerations-of-sustainable-aviation-fuel

[33] Khan, Shoyeb, et al. "Microalgal Feedstock for Biofuel Production: Recent Advances, Challenges, and Future Perspective." Fermentation, vol. 9, no. 3, Mar. 2023, p. 281. https://doi.org/10.3390/fermentation9030281.

[34] Calderon, Oscar Rosales, et al. Sustainable Aviation Fuel State-of-Industry Report: Hydroprocessed Esters and Fatty Acids Pathway. 30 July 2024, https://doi.org/10.2172/2426563.

[35] Lee, S. Y., et al. "Engineering Microbial Lipid Production for Biofuels: Advances and Challenges." Biotechnology Advances, vol. 46, 2024, p. 107894. https://doi.org/10.1016/j.biotechadv.2024.107894

[36] U.S. Department of Energy. "Sustainable Aviation Fuel Grand Challenge Roadmap Implementation Framework." 2024. https://www.energy.gov/eere/bioenergy/articles/sustainable-aviation-fuel-grand-challenge-roadmap-implementation-framework

[37] U.S. Department of Energy. "SAF Implementation Framework." 2024. https://www.energy.gov/sites/default/files/2024-11/SAF-Implementation-Framework-Nov-2024.pdf

About the Authors

Dr. Raj Shah is a Director at Koehler Instrument Company in New York, where he has worked for the last 25 plus years. He is an elected Fellow by his peers at IChemE, ASTM,AOCS, CMI, STLE, AIC, NLGI, INSTMC, Institute of Physics, The Energy Institute and The Royal Society of Chemistry. An ASTM Eagle award recipient, Dr. Shah recently coedited the bestseller, "Fuels and Lubricants handbook", details of which are available at ASTM's Long-awaited Fuels and Lubricants Handbook https://bit.ly/3u2e6GY

He earned his doctorate in Chemical Engineering from The Pennsylvania State University and is a Fellow from The Chartered Management Institute, London. Dr. Shah is also a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute and a Chartered Engineer with the Engineering council, UK. Dr. Shah was recently granted the honorific of "Eminent engineer" with Tau beta Pi, the largest engineering society in the USA. He is on the Advisory board of directors at Farmingdale university (Mechanical Technology), Auburn Univ (Tribology), SUNY, Farmingdale, (Engineering Management) and State university of NY, Stony Brook (Chemical engineering/ Material Science and engineering). An Adjunct

Professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical Engineering, Raj also has over 680 publications and has been active in the energy industry for over 3 decades. More information on Raj can be found at https://shorturl.at/JDPZN

Contact: rshah@koehlerinstrument.com

Dr. Vikram Mittal, PhD is an Associate Professor in the Department of Systems Engineering at the United States Military Academy. His research interests include energy modeling, technology forecasting, and Alternative fuels. Previously, he was a senior mechanical engineer at the Charles Stark Draper Laboratory. He holds a PhD in Mechanical Engineering from MIT, an MS in Engineering Sciences from Oxford, and a BS in Aeronautics from Caltech. Dr. Mittal is also a combat veteran and a major in the U.S. Army Reserve.

Vikram Mittal

Mr. Michael Lotwin is part of a thriving internship program at Koehler Instrument company in Holtsville, and is a student of Chemical Engineering at Stony Brook University, Long Island, NY where Dr.'s Shah and Mittal are on the external advisory board of directors

Michael Lotwin

Dr. Raj Shah, Koehler Instrument Company

Holtsville, NY11742 USA

Email: rshah@koehlerinstrument.com

Web: www.koehlerinstrument.com