

Review

Recent Advances in Sustainable Aviation Fuel from Renewable Feedstocks: A Biobased Perspective

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Abstract

Decarbonizing the aviation sector remains one of the most challenging aspects of the global energy transition because commercial aviation relies on high-energy-density liquid hydrocarbon fuels that cannot be readily replaced by electrification or hydrogen in the near term. Sustainable Aviation Fuel (SAF) has emerged as a viable solution for reducing lifecycle greenhouse gas (GHG) emissions while maintaining compatibility with existing aircraft, engines, and fuel infrastructure. This review presents an assessment of renewable biomass, waste-derived feedstocks, and captured CO₂ as sustainable carbon resources for SAF production. This study compares biological, thermochemical, electrochemical, and catalytic routes. Comparative evaluation indicates that no single technology can independently satisfy future aviation fuel demand; instead, integrated, feedstock-flexible circular-carbon biorefineries combining complementary conversion technologies provide the most promising route toward large-scale SAF deployment. Finally, this review identifies key research gaps and commercialization barriers, highlighting feedstock availability, renewable hydrogen integration, standardized sustainability assessment, and integrated biorefinery development as critical priorities for advancing scalable, ASTM-compliant, low-carbon aviation fuels and supporting the transition toward net-zero aviation.

Keywords: Sustainable Aviation Fuel (SAF); ASTM; volatile fatty acids (VFAs); acidogenic fermentation; CO₂ utilization



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1. Introduction

The global aviation industry is one of the most critical pillars of modern economic development, enabling international trade, tourism, logistics, scientific collaboration, and

geopolitical connectivity [1]. However, aviation remains among the most difficult sectors to decarbonize because of its strict energy-density requirements, safety constraints, long-haul operational demands, and reliance on liquid hydrocarbon fuels [2,3]. Currently, aviation contributes approximately 2.5–3% of global anthropogenic greenhouse gas (GHG) emissions and nearly 12% of transportation-related carbon emissions, while global jet fuel demand is projected to exceed 500 million tonnes annually by 2050 if no major interventions are implemented. Conventional aviation fuels such as Jet A and Jet A-1 are derived from petroleum refining processes and consist predominantly of C8–C16 paraffins, isoparaffins, cycloalkanes, and aromatics optimized for high gravimetric energy density, low freezing point, thermal stability, and combustion efficiency [4]. Despite continuous improvements in aircraft efficiency and operational optimization, the aviation sector’s growing demand trajectory continues to intensify concerns regarding fossil fuel dependency, climate change, and long-term energy security.

Unlike ground transportation, where electrification is rapidly progressing, full electrification of long-distance aviation remains technologically constrained due to limitations in battery energy density and aircraft weight penalties [5]. Similarly, although hydrogen-powered aviation presents long-term promise, major barriers related to cryogenic storage, infrastructure development, safety, and volumetric energy density continue to hinder immediate deployment. SAF has emerged as the most technologically mature and practically deployable pathway for near- and medium-term aviation decarbonization [6–8]. SAFs are considered “drop-in” fuels because they can be integrated into existing aircraft engines, fuel distribution systems, and airport infrastructure without substantial modifications. Importantly, SAFs derived from renewable biomass and waste feedstocks can reduce lifecycle GHG emissions by 50–90% relative to conventional jet fuel while maintaining equivalent aviation performance characteristics [9]. The significant rise in SAF-related publications over the past two decades reflects a growing commitment to SAF technologies and strategies for decarbonizing the aviation industry (Figure 1).

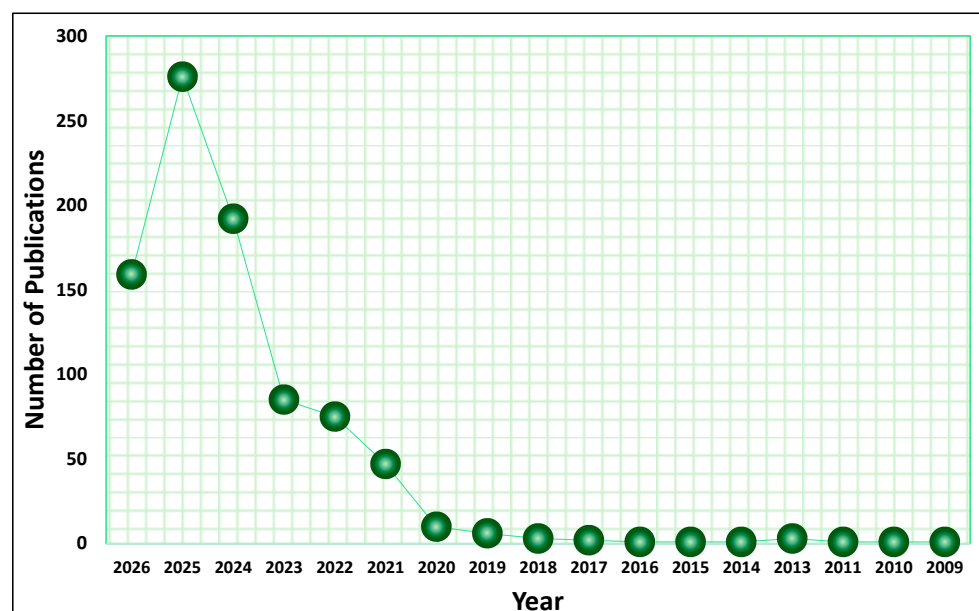


Figure 1. Year-wise distribution of publications related to SAF retrieved from the Web of Science database using the keyword “Sustainable Aviation Fuel (SAF)”.

At present, the hydroprocessed ester and fatty acid (HEFA) pathway dominates commercial SAF production and accounts for more than 99% of global SAF output [10,11]. HEFA primarily utilizes lipid-based feedstocks including used cooking oil (UCO), fats, oils,

greases (FOGs), animal fats, vegetable oils, and algal lipids [12]. Although HEFA technology is technologically mature and ASTM-certified, the limited availability of sustainable lipid feedstocks, increasing competition with food and cosmetic industries, and concerns regarding indirect land-use change significantly constrain its scalability. Consequently, expanding the renewable carbon pool for SAF production has become a global research priority. In this context, second- and third-generation feedstocks—including lignocellulosic biomass, agricultural residues, forestry waste, municipal solid waste (MSW), food waste, wastewater sludge, volatile fatty acids (VFAs), spent coffee grounds, pyrolysis oils, and waste plastics—have emerged as promising alternative carbon sources capable of supporting large-scale SAF deployment while simultaneously advancing circular economy principles [12–15]. Among renewable feedstocks, lignocellulosic biomass (LCB) represents one of the most abundant and sustainable organic carbon reservoirs on Earth. Agricultural residues such as corn stover, rice husks, wheat straw, sugarcane bagasse, and forestry by-products possess enormous potential for SAF production because they do not directly compete with food production and are widely distributed globally. Agricultural residues and lignocellulosic waste could provide billions of liters of SAF annually, fulfilling 10–20% of aviation demand and promoting waste valorization and a circular bioeconomy [8].

The conversion of lignocellulosic biomass into aviation-grade hydrocarbons employs thermochemical, biochemical, and catalytic methods. Key thermochemical processes include gasification/Fischer–Tropsch (FT) synthesis, pyrolysis, and hydrothermal liquefaction (HTL), which transform biomass into syngas, bio-oils, and biocrudes [15]. FT synthesis stands out for producing high-quality synthetic paraffinic kerosene (SPK) with superior thermal stability and combustion properties. Additionally, fast pyrolysis, when paired with hydrodeoxygenation (HDO) and hydrocracking, shows significant promise for generating aviation-range hydrocarbons from bio-oils derived from agricultural waste, enhancing the sustainability of aviation fuels [16]. Biochemical conversion routes, particularly anaerobic fermentation and arrested methanogenesis, have garnered significant attention for their potential in sustainable fuel production. Organic wastes—such as food waste, wastewater sludge, and animal manure—can be transformed into volatile fatty acids (VFAs), which are crucial intermediates for producing jet-fuel-range hydrocarbons [12]. Advanced membrane-assisted anaerobic digestion systems enhance carbon redirection towards butyrate- and acetate-rich VFAs while minimizing methane emissions. The catalytic ketonization of these VFAs, using industrial oxides like ZrO_2 , yields aviation-relevant ketones, such as 6-undecanone, which can be further processed into n-alkanes for SAF blending [17,18]. Catalyst engineering is integral to the advancements in SAF production, influencing selectivity, carbon retention, fuel quality, and process economics. The development of advanced bifunctional catalysts that combine acidic, metallic, mesoporous, and redox-active sites has demonstrated exceptional effectiveness across various reactions, including hydrodeoxygenation and hydrocracking [19]. Key catalysts such as $\text{Co}/\text{H-ZSM-22}$, $\text{Ni}/\text{ZSM-22}$, Pd/CeZrO_x , $\text{Pt}/\text{Al}_2\text{O}_3$, Nb_2O_5 , $\text{CoMo}/\text{Al}_2\text{O}_3$, $\text{Ni-Mo}/\text{Al}_2\text{O}_3$, H-MCM-22 , and Al-SBA-15 enable the selective generation of paraffins, isoparaffins, cycloalkanes, and aromatics, essential for achieving optimal aviation fuel properties. Furthermore, innovations in nanoscale catalyst-interface engineering, particularly through atomic layer deposition (ALD) of TiO_2 onto Pt catalysts, have shown that oxygen-vacancy-rich interfaces can enhance n-alkane selectivity significantly while minimizing precious metal usage, underscoring the transformative potential of atomic-scale catalyst design in SAF development [19–21]. Waste valorization through catalytic upgrading has broadened SAF feedstock options beyond biomass, incorporating waste plastics, municipal solid waste, tire pyrolysis oils, and hydrothermal liquefaction biocrudes as renewable carbon sources. Notably, the thermochemical upgrading of waste polypropylene via catalytic oligomerization and hydrogenation yields

aviation-grade hydrocarbons with favorable ASTM properties. Furthermore, hydroprocessing tyre pyrolysis oil produces cycloalkanes and aromatic-rich fuel fractions, highlighting the dual benefit of addressing waste management issues while contributing to aviation decarbonization goals.

Despite significant advancements in SAF technology, challenges persist in achieving widespread commercialization. Key obstacles include feedstock heterogeneity, hydrogen demand, catalyst deactivation, oxygen removal efficiency, carbon losses, and infrastructure limitations, which impede industrial-scale deployment. Currently, global SAF production accounts for less than 1% of total aviation fuel demand, highlighting the urgent necessity for enhanced technology development, supportive policies, and investment in low-carbon fuel systems. International initiatives like ICAO's CORSIA, the U.S. SAF Grand Challenge, and the EU's ReFuelEU Aviation aim to accelerate SAF deployment through blending mandates, carbon reduction targets, and sustainability certification frameworks. This review article examines the evolving landscape of SAF production from renewable biomass and waste-derived feedstocks, highlighting the interconnected roles of biological conversion, catalytic upgrading, reactor engineering, feedstock sustainability, lifecycle carbon mitigation, and circular carbon utilization. Integrating advances in anaerobic fermentation, thermochemical conversion, catalyst-interface engineering, hydroprocessing, and systems-level optimization, it proposes a robust framework for scalable, economically viable, and environmentally sustainable SAF technologies supporting aviation decarbonization and net-zero transitions.

Methodology

This review was carried out through a comprehensive literature survey of peer-reviewed articles obtained from Scopus, Web of Science, ScienceDirect, and Google Scholar. The focus was primarily on studies published between 2015 and 2026, although seminal works prior to this period were included when relevant to the topic. Key search terms encompassed SAF, lignocellulosic biomass, waste-to-jet pathways, Hydroprocessed Esters and Fatty Acids (HEFA), Fischer–Tropsch synthesis, Alcohol-to-Jet processes, hydrothermal liquefaction, volatile fatty acids, algae, catalytic systems, life-cycle assessment, and techno-economic evaluations. Publications were meticulously selected based on their scientific rigor, relevance, novelty, and direct contributions to SAF production, sustainability assessments, catalyst advancements, and commercialization efforts. The analysis aimed to critically integrate findings to reveal technological innovations, identify research gaps, and outline future research directions in the field.

2. Alternative Fuels in Aviation

Decarbonizing aviation requires energy carriers that meet high standards for energy density, safety, and operational performance [22]. Key alternatives under consideration include SAF, hydrogen propulsion, battery-electric systems, and synthetic electro fuels. Hydrogen can achieve near-zero carbon emissions but faces challenges such as cryogenic storage and infrastructure needs, hindering widespread adoption [23]. Battery-electric propulsion is limited by low energy density and weight, making it suitable mainly for short-haul flights [24]. Power-to-Liquid (PtL) fuels, produced from renewable electricity and CO₂, show promise for decarbonization but depend on affordable renewable energy and efficient carbon capture for commercialization [25]. Among these options, SAFs stand out as the most viable solution, functioning as drop-in fuels compatible with existing aircraft and infrastructure. Derived from renewable biomass and waste carbon, SAFs can significantly reduce lifecycle greenhouse gas emissions while meeting aviation performance standards. Thus, SAFs can serve as a crucial bridge between traditional aviation and future

zero-emission flight technologies, positioning it as a pivotal element in the industry's transition towards sustainability [5].

Sustainable Aviation Fuel: Production Routes and Specifications

SAF represents a range of certified production pathways aimed at creating aviation-grade hydrocarbons from renewable sources. Currently, eight production routes and three co-processing methods are approved under ASTM D7566, allowing SAF to blend with conventional Jet A/Jet A-1 fuels while adhering to ASTM D1655 performance standards. The leading pathway is Hydroprocessed Esters and Fatty Acids (HEFA-SPK), which transforms lipid-rich feedstocks, such as used cooking oils and animal fats, into synthetic paraffinic kerosene. Other approved methods include Fischer–Tropsch (FT), Alcohol-to-Jet (ATJ), and Catalytic Hydrothermolysis (CH), among others (Figure 2). Emerging technologies increasingly leverage second-generation feedstocks like agricultural residues and municipal solid waste, enhancing circular carbon utilization and minimizing reliance on food-based resources. SAF production focuses on generating essential hydrocarbon classes—paraffins, isoparaffins, cycloalkanes, and controlled aromatic fractions—that dictate fuel performance attributes such as energy density and combustion stability. Key factors in this process include catalyst design and hydrocarbon selectivity, which are crucial for producing ASTM-compliant fuels that support the aviation industry's long-term decarbonization goals.

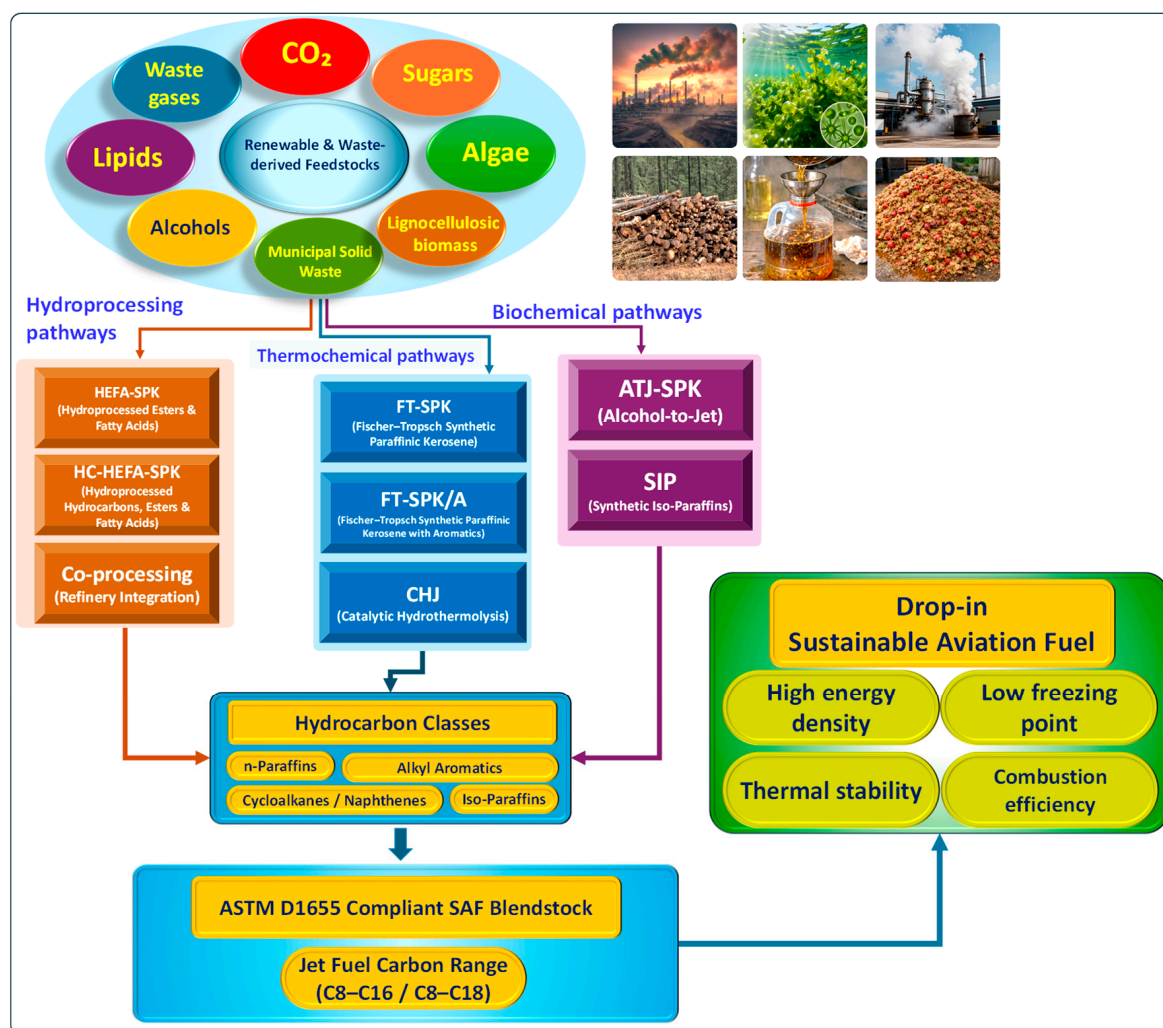


Figure 2. ASTM D7566-certified SAF pathways (8 ASTM-approved), corresponding renewable feedstocks, conversion technologies, and resulting hydrocarbon classes.

3. Waste to Sustainable Aviation Fuels

Waste-to-SAF production employs a combination of biological, thermochemical, and catalytic upgrading technologies to transform heterogeneous waste carbon into aviation-grade hydrocarbons. The selection of technology is influenced by factors such as feedstock composition, moisture content, and desired fuel characteristics. Biological methods, including anaerobic digestion and acidogenic fermentation, convert organic waste into volatile fatty acids (VFAs) and other intermediates, which are then upgraded through various chemical processes to produce jet-fuel-range hydrocarbons. Thermochemical approaches, such as gasification and pyrolysis, convert waste into syngas or bio-oils, which require catalytic hydroprocessing to enhance fuel stability and energy density. Catalytic upgrading is crucial across all waste-to-SAF pathways, involving processes like hydrodeoxygenation and oligomerization that dictate carbon-chain growth and hydrocarbon selectivity. The effectiveness of these catalysts—determined by properties such as acidity and metal dispersion—affects carbon retention and conversion efficiency. Successful waste-to-SAF production necessitates the integration of efficient carbon recovery, selective catalytic upgrading, and energy optimization to produce fuels that meet ASTM specifications while maximizing carbon efficiency and minimizing lifecycle greenhouse gas emissions. This holistic approach positions waste-to-SAF as a viable solution for SAF production.

3.1. Lignocellulosic Biomass Valorization for Sustainable Aviation Fuel Production

Lignocellulosic biomass (LCB) has emerged as one of the important renewable carbon platforms for SAF production because of its global abundance, renewable carbon availability, and molecular compatibility with aviation fuel chemistry (Figure 3). Composed primarily of cellulose, hemicellulose, and lignin, LCB represents the largest reservoir of sustainable organic carbon on Earth and includes agricultural residues, forestry by-products, municipal biowaste, paper sludge, spent coffee grounds, and food-processing residues. Unlike lipid-based SAF feedstocks, lignocellulosic resources avoid direct competition with food systems while simultaneously supporting circular bioeconomy principles through waste valorization and carbon recovery. Traditionally, lignin-rich biomass fractions generated from pulp and paper industries have been treated as low-value residues and predominantly combusted for process heat or utilized in low-grade materials such as fiberboards and oriented strand boards [26]. However, harsh pulping conditions generate stable C–C linkages that increase lignin recalcitrance and limit downstream monomer recovery. Consequently, the “lignin-first” biorefinery has emerged as a transformative strategy that selectively extracts, depolymerizes, and stabilizes lignin while preserving cellulose and hemicellulose fractions for integrated fuel and chemical production. Reductive catalytic fractionation (RCF) has become one of the most promising lignin-first approaches because it enables simultaneous lignin solubilization, depolymerization, and stabilization under reductive catalytic environments [27]. During RCF, lignin is converted into refined lignin oil (RLO), a phenolic-rich bio-oil containing substituted C6 aromatic monomers, dimers, and oligomers with average carbon numbers close to aviation fuel aromatics and naphthenes [28]. The relevance of lignin-derived intermediates for SAF production is particularly important because aviation fuels require controlled aromatic and cycloalkane fractions to regulate energy density, freezing point, viscosity and thermal stability [29–31]. However, lignin-derived bio-oils exhibit high oxygen content and therefore require catalytic hydrodeoxygenation (HDO) prior to utilization as aviation fuel blendstocks [32]. Recent studies have demonstrated that lignin extracted through RCF possesses superior physicochemical characteristics for HDO upgrading compared with lignins generated from conventional Organosolv processing. Combining RCF with hydrodeoxygenation can enable efficient production of cycloalkanes, naphthenes, and aromatics suitable for aviation applications while improving overall

carbon efficiency and reducing refinery severity [27,28]. The effectiveness of RCF strongly depends on catalyst, solvent system, biomass composition, and reaction conditions. Bi-functional catalysts such as Pd/C, Pd/CNx, Ni/C, and Ru/Al₂O₃ can cleave β -O-4 ether linkages while hydrogenating unstable intermediates, thereby preventing repolymerization and improving monomer stabilization [33]. Furthermore, metal nanoparticle size and dispersion directly govern hydrodeoxygenation selectivity and removal of residual aliphatic hydroxyl groups, ultimately improving fuel stability and hydrocarbon quality [34].

Beyond lignin valorization, the carbohydrate fraction of LCB provides additional SAF precursor routes through biochemical and thermochemical conversion. Zhu, Lingjun et al. (2023) developed a hydrothermal conversion platform integrating dilute H₂SO₄ hydrolysis with a highly stable resin-derived carbon solid acid catalyst to selectively produce furfural and levulinic acid from corn stover [35]. The system achieved near-complete carbohydrate conversion with furfural and levulinic acid yields of 68.7 mol% and 70.3 mol%, respectively. These intermediates serve as critical platform molecules for downstream synthesis of paraffins, cycloalkanes, and aromatic aviation hydrocarbons. The catalyst's intrinsic sulfonic acid functionalities, hydrothermal stability, and large-pore architecture significantly reduced humin formation while improving catalytic longevity over 28 cycles. Similarly, Li, Biomass-derived aldehydes and ketones can be selectively upgraded into aviation hydrocarbons through integrated aldol condensation and hydrodeoxygenation [36]. Using bifunctional Ni/Mg–Al–O/AC catalysts, the process coupled base-mediated carbon–carbon bond formation with metal-assisted hydrogenation can generate C₇–C₁₄ paraffins and cycloalkanes with approximately 79% condensate yields and 72% alkane selectivity [36]. Critically, catalyst acidity, reactant ratios, and thermal conditions govern carbon-chain growth and cycloalkane formation, directly influencing aviation fuel energy density and low-temperature operability.

The production of high-density cyclic SAF molecules from lignocellulosic intermediates has also advanced significantly. Li, Zhanchao et al. (2021) developed a selective route for transforming biomass-derived cyclopentanone into bi(cyclopentane)-based aviation hydrocarbons through one-pot condensation and hydrodeoxygenation over Pd/C catalysts [37]. The resulting SAF molecules exhibited exceptionally high densities (0.87–0.94 g cm^{−3}), volumetric heating values reaching 41.4 MJ L^{−1}, and freezing points below −80 °C, comparable to advanced aerospace fuels such as JP-10 and RJ-4. These findings demonstrate that lignocellulosic biomass can serve as a platform for synthesizing next-generation high-energy-density cyclic aviation fuels. Integrated lignocellulosic biorefineries can further strengthen SAF feasibility by maximizing carbon utilization across all biomass fractions. Klein, Bruno Colling et al. (2023) proposed a unified biorefinery integrating co-solvent-enhanced lignocellulosic fractionation (CELF), consolidated bioprocessing, and catalytic lignin valorization [38]. Through selective deconstruction of cellulose, hemicellulose, and lignin streams, the process generated alcohol, esters, adipic acid, and cycloalkane SAF blendstocks while achieving carbon utilization efficiencies exceeding 50%. Copper porous metal oxide catalysts operating in supercritical methanol selectively converted lignin into cyclic hydrocarbons critical for freezing-point control and fuel stability. Importantly, the system achieved SAF production costs as low as \$3.15/GGE while significantly reducing greenhouse gas emissions.

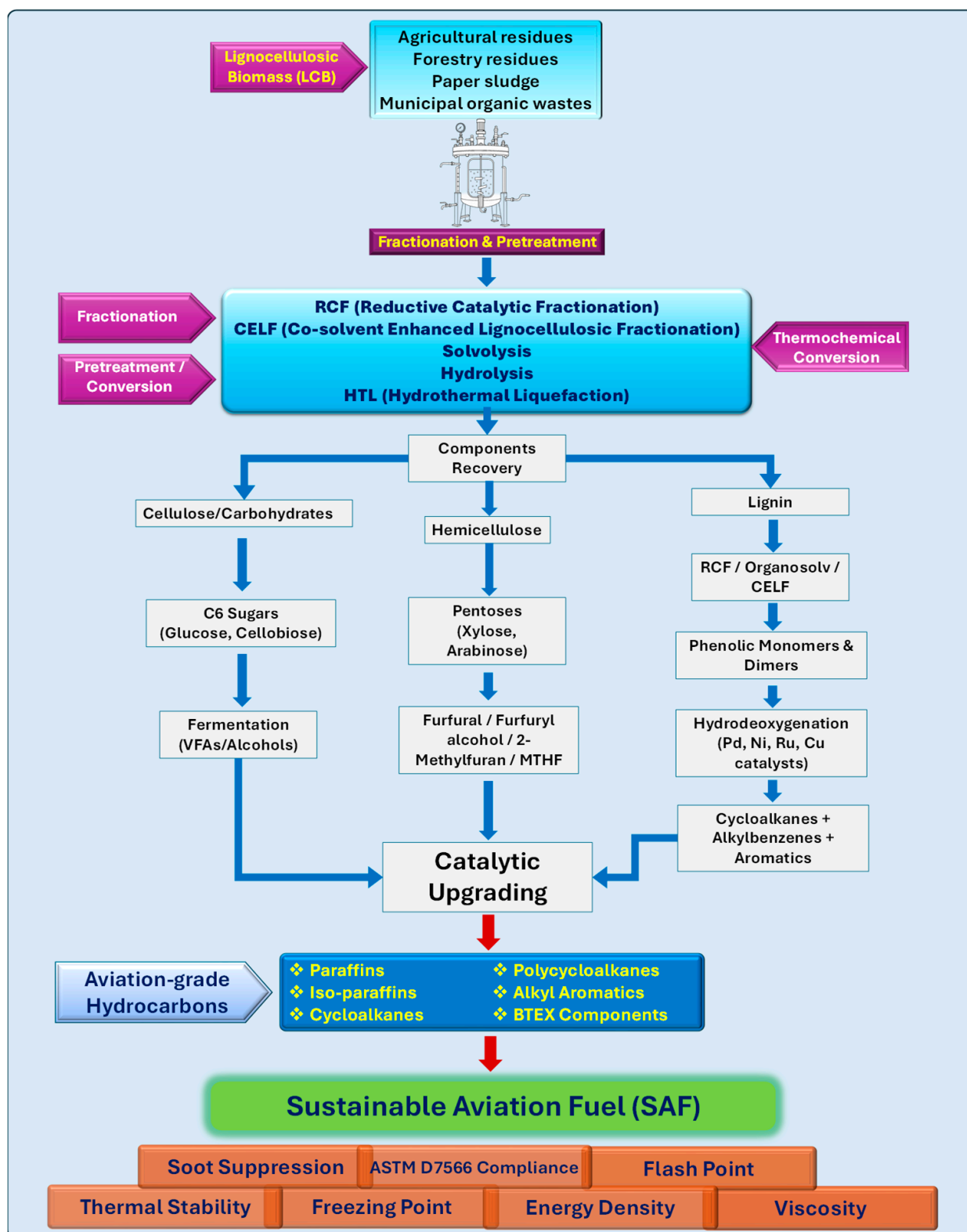


Figure 3. Biomass-derived cellulose, hemicellulose, lignin, and waste fractions are converted through biological fermentation, thermochemical processing, and advanced catalytic upgrading into aviation-grade paraffins, cycloalkanes, isoparaffins, and aromatic hydrocarbons compatible with ASTM-certified SAF specifications.

Recent studies also demonstrate the importance of unconventional lignocellulosic waste. Acquah, Christopher et al. (2026) developed a circular biorefinery strategy us-

ing spent coffee grounds (SCG) as an integrated SAF feedstock [13]. Through alcohol-based solvolytic fractionation with endogenous glycerol–ethanol solvent systems, the process simultaneously recovered carbohydrate-rich solids, lipid-derived oils, and lignin-rich fractions suitable for HEFA, alcohol-to-jet (ATJ), and HDO pathways. The process achieved > 98% glucan retention, >95% delipidification, and >67% delignification while reducing autogenous pressure by 59%. The resulting SAF precursors included fatty acid esters, lignin monomers, paraffinic intermediates, aromatics, and cycloalkane precursors critical for aviation fuel performance. The optimized ethanol/glycerol system further achieved minimum selling prices near \$1.43 kg^{−1}, highlighting the economic viability of integrated waste-derived lignocellulosic SAF systems.

Thermochemical valorization of lignocellulosic agricultural waste has similarly shown exceptional promise. Halimi NAN et al. (2025) demonstrated conversion of corn stover into aviation-grade hydrocarbons through fast pyrolysis followed by two-stage hydrotreatment over Ru/C and CoMo/Al catalysts [21]. The process selectively generated paraffins, isoparaffins, cycloalkanes, and controlled aromatic fractions while reducing undesirable oxygenates. Heat integration eliminated external heating demand and reduced cooling utilities by 55%, while lifecycle greenhouse gas emissions decreased by up to 76% relative to fossil jet fuel. Likewise, Lan Kai et al. (2024) developed a circular-carbon pathway utilizing high-ash paper sludge as feedstock [39]. Through deashing, enzymatic hydrolysis, dehydration, aldol condensation, and hydroprocessing, the process generated aviation-range C₈–C₁₆ hydrocarbons with lifecycle emissions as low as 5.1–11.1 gCO₂eq MJ^{−1} after ash recycling, representing up to 94% GHG reduction compared to petroleum jet fuel.

Lipid upgrading from lignocellulosic-associated feedstocks has also evolved beyond conventional HEFA. Hebish, Anas Ahmed et al. (2024) demonstrated hydrogen-free catalytic deoxygenation of triglycerides into paraffins, isoparaffins, cycloparaffins, and aromatics using Ni-, Co-, Pd-, and zeolite-supported catalysts [29]. By eliminating the substantial hydrogen demand associated with conventional hydroprocessing, the approach improved economic feasibility while maintaining aviation-grade hydrocarbon selectivity approaching 90%. Similarly, Liu, Junli et al. (2025) introduced ozone-assisted cracking of oleic-acid-rich lipids into nonanoate esters exhibiting ultra-low cloud points (−35 to −67 °C), exceptional oxidation stability, and up to 93% CO₂ reduction potential, demonstrating a highly energy-efficient route toward winter-grade SAF molecules [40]. Waste-derived thermochemical systems further broaden lignocellulosic SAF integration. Summers, Sabrina et al. (2025) combined hydrothermal liquefaction (HTL) of food waste with CoMo catalytic hydrotreating to generate ASTM-compliant aviation fuels [31]. The process achieved complete hydrodeoxygenation, near-complete desulfurization, and 87% denitrogenation while preserving carbon and energy recovery efficiencies above 85%. The resulting fuel was rich in n-alkanes, cycloalkanes, isoalkanes, and aromatics essential for combustion stability and freezing-point control.

3.2. Fermentation of Waste: VFA-Based SAF Pathway

Unlike conventional lipid-based SAF systems, fermentation-driven platforms transform heterogeneous wet organic wastes (food waste, municipal biowaste, wastewater sludge, agricultural residues, fats, oils, and greases) into volatile fatty acids (VFAs), alcohols, and oxygenated intermediates that subsequently serve as refinery-compatible SAF precursors (Figure 4). This biological catalytic integration establishes a circular-carbon framework capable of simultaneously reducing landfill methane emissions, valorizing waste streams, and generating aviation-grade hydrocarbons with significantly reduced lifecycle GHG emissions. Fermentation-derived VFA platforms establish a next-generation circular-carbon pathway for SAF, integrating biological waste valorization with advanced

catalytic upgrading. By converting heterogeneous wet waste streams into uniform intermediate molecules and subsequently upgrading them into paraffinic, cyclic, and aromatic hydrocarbons, this approach overcomes major limitations associated with feedstock variability and process complexity. A central route within fermentation-connected SAF production is acidogenic/acetogenic fermentation through arrested methanogenesis.

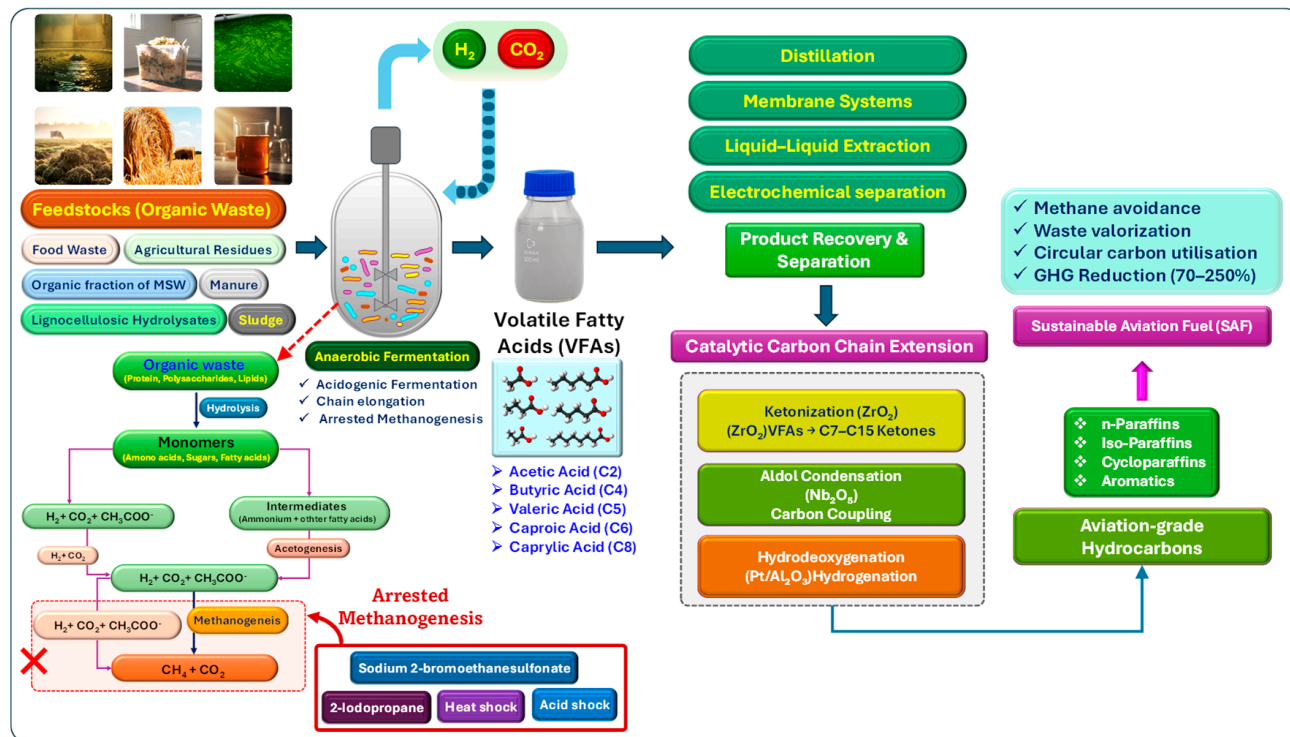


Figure 4. Integrated fermentation-based SAF production pathway illustrating the biological conversion of diverse organic waste streams into VFAs through arrested methanogenesis, followed by catalytic upgrading into aviation-grade hydrocarbons.

VFAs are key intermediate metabolites formed during anaerobic digestion, where complex organic matter is sequentially degraded by microbial consortia under anaerobic conditions [41]. Under conventional operation, VFAs are rapidly consumed by methanogenic archaea and ultimately converted into methane and carbon dioxide. However, by selectively arresting methanogenesis, the metabolic flux can be redirected from biogas production toward VFA accumulation [42,43]. This is typically achieved by regulating operational parameters such as pH (~5–6), organic loading rate (OLR), hydraulic retention time (HRT), temperature, and substrate availability, thereby suppressing methanogenic activity while maintaining acidogenic and acetogenic microorganisms [44]. Chemical inhibition of methanogenesis provides a highly selective strategy for maximizing VFA accumulation. 2-bromoethanesulfonate (BES/BESA) acts as a structural analogue of coenzyme M, competitively inhibiting methyl-coenzyme M reductase, the terminal and rate-limiting enzyme in methanogenesis that is unique to methanogenic archaea. Similarly, iodopropane functions as a corrinoid antagonist (restricts the functioning of the B12 enzyme which carries methyl group), disrupting methyl-group transfer reactions required for methanogenic metabolism [45,46].

Under methane-suppressed anaerobic conditions, complex organic substrates are biologically converted into short and medium-chain carboxylic acids (C₂–C₈ VFAs), including acetate, butyrate, valerate, and caproate, Heptanoate and Octanoate [41]. VFAs serve as versatile intermediates for catalytic carbon-chain upgrading, influencing chain elonga-

tion, oxygen removal, hydrocarbon structure, and overall fuel quality through established upgrading sequences [47]. The integration of acidogenic/acetogenic fermentation, ketonization, condensation chemistry, cyclization, and hydrodeoxygenation creates a flexible framework for optimizing fuel composition to align with aviation standards [48].

The catalytic ketonization stage is crucial in fermentation-derived SAF systems, influencing carbon-chain growth and hydrocarbon formation. This process effectively produces linear and branched ketones, paraffins, and cycloalkanes that meet the carbon distribution and energy density requirements for aviation fuel [19]. A biocatalytic–thermocatalytic strategy utilizing lignocellulosic biomass can be converted into mixed C₂–C₈ carboxylic acids via anaerobic fermentation. These acids are then transformed into ethyl esters and upgraded using bifunctional Pd/CeZrO_x catalysts, achieving over 90% selectivity for C₁₁+ aviation-range molecules [19]. The catalyst’s multifunctional active sites facilitate various reactions, including ketonization and hydrogenation, within a unified framework. Converting wet waste-derived VFAs into SAF highlights a transformative approach to decarbonizing the aviation sector. Utilizing a sequential catalytic process, VFAs undergo ketonization over ZrO₂, cyclization over H/ZSM-5, and hydrodeoxygenation over Pt/Al₂O₃ to produce aviation-grade hydrocarbons and BTEX compounds. This integrated method not only generates paraffins, cycloalkanes, and aromatics compatible with Jet A specifications but also achieves greenhouse gas reductions compared to traditional fossil jet fuels [49]. Further research by [12] highlighted the potential of VFAs as molecular precursors for SAF. Waste-to-fuel platform combining anaerobic digestion with advanced catalytic processes can yield hydrocarbons that enhance fuel properties such as freezing point and energy density. The ZrO₂ catalysts demonstrate significant stability, maintaining activity for over 100 h, while Pt/Al₂O₃ and Nb₂O₅ facilitated efficient carbon coupling and oxygen removal. Notably, blending strategies allow for up to 70% renewable fuel content, reducing soot formation by 34% relative to fossil fuels. Lifecycle assessments reveal a substantial greenhouse gas reduction potential of 165%, demonstrating VFA-derived SAF systems as a pivotal solution in the quest for sustainable aviation [12]. Recent advancements in biological conversion technologies have led to the development of membrane-assisted arrested methanogenesis for SAF precursor production [17]. Utilizing submerged membrane bioreactors (SubMBR) combined with resin-wafer electrodeionization (RW-EDI), the process effectively redirects carbon from high-strength wastewater and organic waste into butyrate- and acetate-rich VFAs, achieving concentrations over 113 g/L (Table 1). The optimized production costs for VFAs are \$0.60 kg^{−1}, with SAF selling prices at \$4.64 GGE^{−1}. Further upgrading through ketonization, aldol condensation, and hydrodeoxygenation yields aviation-grade hydrocarbons with improved freezing points and combustion stability. This approach results in a significant 71% reduction in greenhouse gas emissions compared to fossil Jet A, highlighting its techno-economic and environmental viability. Miller et al., 2022 showed that the ketonization of wet waste-derived VFAs using monoclinic ZrO₂ catalysts operates via a Langmuir–Hinshelwood mechanism, where coproduct water acts as a key inhibitor affecting reactor size and efficiency [18]. Implementing staged series-reactor configurations with interstage water removal can reduce reactor size by over 97% while achieving 98% conversion efficiency. The resulting C₉–C₁₅ ketones and n-alkanes align with aviation fuel specifications, ensuring optimal freezing point, viscosity, and energy density. Catalyst-interface engineering can improve fermentation-derived SAF. This approach minimizes precious-metal consumption while significantly improving durability and carbon efficiency, highlighting the transformative potential of nanoscale engineering in sustainable fuel production. McNeary W. Wilson et al. (2023) introduced a groundbreaking hydrodeoxygenation method utilizing atomic layer deposition (ALD) to fabricate TiO₂-coated Pt/Al₂O₃ catalysts featuring oxygen-vacancy-rich Pt–TiO₂ inter-

faces [20]. These Ti^{3+} -rich sites significantly boost carbonyl activation, alcohol dehydration, and hydrogen transfer for VFA-derived ketones. The enhanced catalyst achieved complete ketone conversion with 100% selectivity for n-undecane, while increasing n-alkane site-time yield eightfold compared to uncoated variants.

Table 1. Comparative overview of VFA production from different waste-derived feedstocks, highlighting VFA concentration, reported GHG reduction potential, and environmental performance relevant to SAF production.

Feedstock	VFA Concentration	GHG Reduction/Global Warming	Reference
High-strength wastewater	>113 g/L	71%	[17]
Fruit waste	>50 gCOD/L	Not reported	[50]
Food waste + biodiesel wastewater + brine	22.8 gCOD/L	NA	[51]
Slaughterhouse blood	100 g/L	NA	[52]
Food waste	25.77 g/L	−4.211 kg CO ₂ eq.	[53]

Although VFAs represent a promising intermediate for SAF production, several technical and economic challenges currently limit commercial deployment. First, VFA fermentation typically produces dilute acid streams, making downstream recovery and purification energy-intensive and costly. Conventional separation techniques, including distillation and solvent extraction, often account for a significant fraction of the overall process energy demand, while emerging approaches such as membrane separation, electrodialysis, and reactive extraction require further optimization for industrial application [47]. Second, upgrading VFAs into jet-range hydrocarbons through ketonization, hydrodeoxygenation, oligomerization, or catalytic condensation requires robust catalysts, renewable hydrogen, and efficient carbon management to minimize carbon losses and operating costs. Feedstock variability, process stability, catalyst deactivation, and integration of biological and thermochemical conversion steps remain additional scale-up challenges. Furthermore, comprehensive TEA and LCA studies are still limited, making it difficult to quantify commercial competitiveness relative to established SAF pathways such as HEFA, Fischer–Tropsch, and Alcohol-to-Jet. Future research should therefore prioritize integrated biorefinery designs, intensified product recovery, renewable hydrogen utilization, catalyst development, and pilot-scale demonstrations to improve both economic viability and environmental performance of VFA-derived SAF.

4. Sustainable Aviation Fuel from Algae

Microalgae have emerged as one of the most promising third-generation feedstocks for SAF production because they simultaneously combine carbon capture, wastewater remediation, and renewable fuel synthesis (Figure 5). Unlike terrestrial bioenergy crops, microalgae exhibit high photosynthetic efficiencies, rapid growth rates, elevated lipid accumulation, and the ability to utilize saline water, wastewater, and concentrated industrial CO₂ streams without competing for arable land or freshwater resources [54]. A unique advantage of microalgae is their metabolic versatility. They naturally produce triacylglycerols (TAGs), fatty acids, terpenoids, isoprenoids, and hydrocarbon-like molecules that serve as direct SAF precursors [55]. Among these, isoprenoid- and aromatic-derived hydrocarbons are particularly attractive because of their superior energy densities compared to conventional fatty-acid-derived fuels, making them highly suitable for aviation applications [56]. Species such as *Botryococcus braunii* are especially valuable due to their accumulation of botryococenes and other hydrocarbon-rich compounds that closely resemble aviation fuel molecules.

Currently, the HEFA pathway remains the dominant commercial route for converting algal lipids into aviation fuel. However, feedstock cost represents the major economic bottleneck, accounting for approximately 68–70% of the minimum fuel selling price (MFSP) [57]. Life-cycle assessment indicates that algal-HEFA pathways can achieve carbon intensities of approximately $36 \text{ g CO}_2\text{e MJ}^{-1}$ SAF, corresponding to nearly 60% lower greenhouse gas emissions than conventional jet fuel, while optimized waste-lipid HEFA systems can reduce emissions by up to 77% [58]. In integrated algal biorefineries, coproduct valorization can reduce production costs, resulting in MFSP values near $\$4.53 \text{ GGE}^{-1}$. The potential of scalability is substantial. Utilization of point-source CO_2 emissions could theoretically generate up to 235 million tonnes of algal biomass annually, corresponding to approximately 59 million tonnes of algal oil production [59]. Under favorable cultivation scenarios, algal oil production costs could decrease from $\$7\text{--}8 \text{ gallon}^{-1}$ to approximately $\$5\text{--}6 \text{ gallon}^{-1}$ when high-value coproducts are included. Consequently, advances in strain development, cultivation efficiency, carbon utilization, and integrated biorefinery concepts will determine the long-term contribution of algal SAF toward achieving global aviation decarbonization targets and the SAF Grand Challenge goal of 35 billion gallons by 2050.

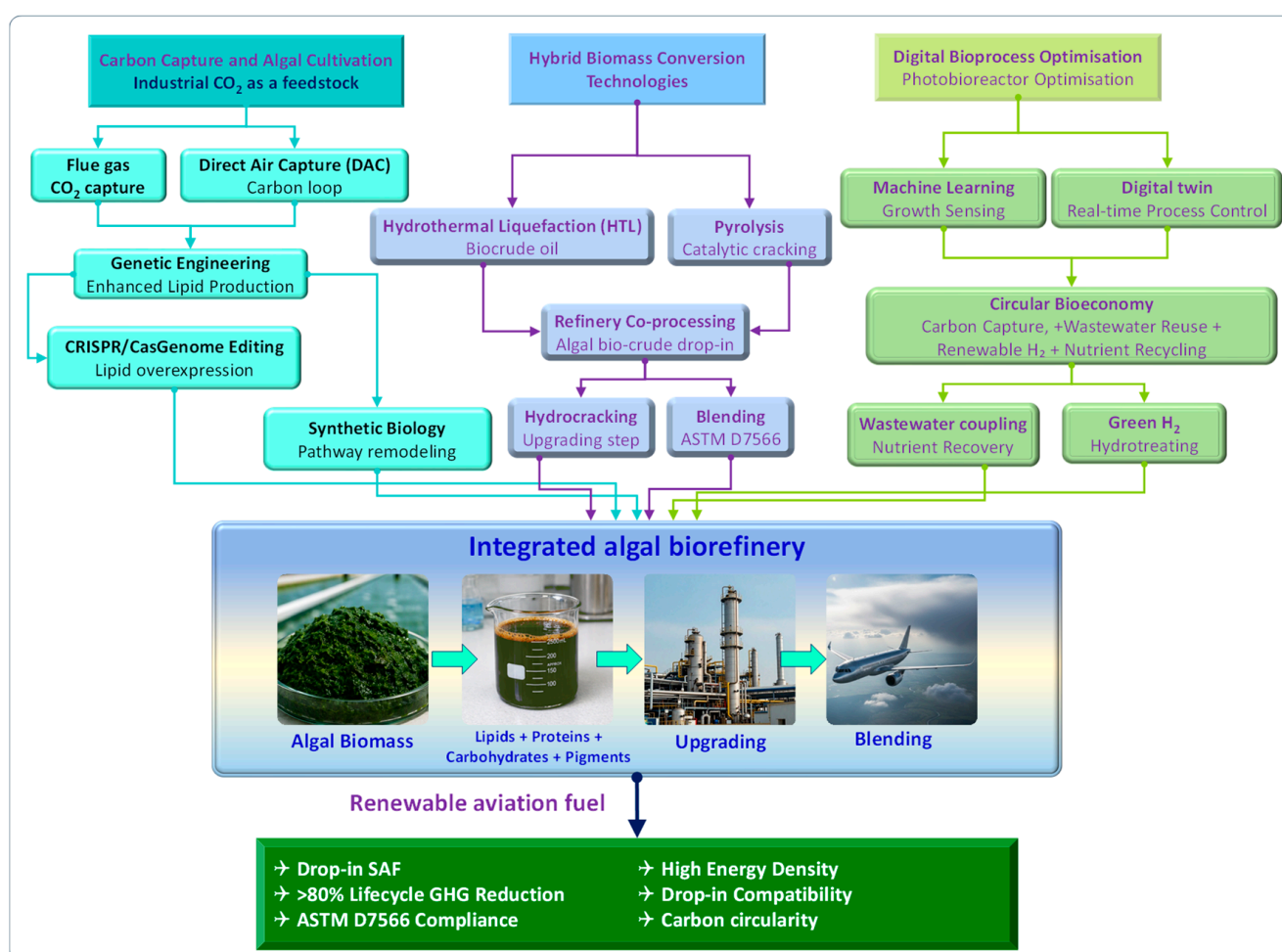


Figure 5. Algal biomass as a sustainable carbon-rich feedstock produced through microalgal cultivation, enabling CO_2 capture and conversion into lipids, proteins, and carbohydrates for biofuels, bioproducts, and circular bioeconomy applications.

4.1. Hybrid Bio-Thermochemical Pathways

Hybrid bio-thermochemical pathways maximize the value of algal biomass by integrating biological carbon fixation with thermochemical fuel production technologies, including hydrothermal liquefaction (HTL), pyrolysis-to-jet (PTJ), alcohol-to-jet (ATJ), and Fischer–Tropsch synthesis [58]. Unlike conventional HEFA systems that utilize only extracted lipids, these pathways convert the entire algal biomass, substantially improving carbon utilization efficiency and reducing residual waste generation.

Among these technologies, HTL is particularly advantageous because it directly processes wet algal biomass without energy-intensive drying, producing biocrude suitable for subsequent hydroprocessing into aviation-grade hydrocarbons [60]. Recent developments focus on integrating green hydrogen, advanced hydrodeoxygenation catalysts, and refinery co-processing strategies to improve fuel quality while lowering lifecycle greenhouse gas emissions. Co-processing algal biocrudes within existing hydroprocessing units, catalytic crackers, and refinery streams reduces capital investment requirements and accelerates industrial deployment. Consequently, hybrid pathways are increasingly recognized as one of the most commercially realistic routes for converting algal carbon into drop-in SAF while simultaneously improving refinery decarbonization and carbon efficiency.

4.2. Synbio Integration

Synthetic biology is transforming algae from passive biomass producers into programmable biofactories for SAF synthesis. Advanced genetic engineering, metabolic engineering, and CRISPR-based genome editing are being applied to strains including *Chlamydomonas reinhardtii*, *Nannochloropsis* spp., *Phaeodactylum tricornutum*, *Chlorella* spp., *Botryococcus braunii*, and *Synechocystis* to enhance photosynthetic efficiency, carbon fixation, lipid accumulation, and hydrocarbon biosynthesis [61,62]. Particular emphasis is placed on redirecting metabolic flux toward triacylglycerols (TAGs), isoprenoids, and aviation-compatible hydrocarbon precursors while reducing cellular energy losses associated with maintenance metabolism. Organelle-targeted engineering of chloroplasts and endoplasmic reticulum systems further improves conversion of solar energy and CO₂ into fuel molecules. Notably, engineered *Synechocystis* sp. PCC 6803 expressing an isoprene synthase gene from *Eucalyptus globulus* demonstrated direct biosynthesis of isoprene and jet-fuel precursors using only sunlight and carbon dioxide [63]. Design–Build–Test–Learn (DBTL) platforms combined with genome-scale metabolic models are accelerating strain optimization and reducing development cycles, creating next-generation algal biofactories capable of producing aviation fuel precursors with enhanced productivity and lower production costs in carbon-negative synthetic biology [64].

4.3. AI and ML-Based Approaches

Artificial intelligence (AI), machine learning (ML), and digitalization are transforming algae-based SAF production by enabling intelligent process optimization across the entire cultivation and downstream processing chain [65]. AI-driven platforms integrate Internet of Things (IoT) sensors, computer vision, predictive analytics, and automated control systems to continuously regulate light intensity, nutrient availability, CO₂ delivery, temperature, pH, and hydrodynamic conditions, thereby improving process stability and resource utilization [66]. Advanced ML algorithms, including artificial neural networks (ANNs), support vector machines (SVMs), random forests (RF), convolutional neural networks (CNNs), long short-term memory (LSTM) models, XGBoost, and reinforcement learning (RL), have demonstrated high predictive accuracy (R^2 values approaching 0.98) for biomass productivity, lipid accumulation, CO₂ fixation, and harvesting efficiency, while CNN-based image analysis has achieved approximately 98% accuracy in microalgal species

classification [67]. AI-assisted metabolic modelling further supports the identification of genetic targets for enhanced lipid and hydrocarbon biosynthesis, whereas digital twin technologies enable real-time process simulation, contamination detection, predictive maintenance, and energy-efficient operation of large-scale photobioreactors [68,69]. Collectively, these digital technologies improve cultivation efficiency, reduce operational uncertainty, and enhance the economic feasibility and scalability of algae-based SAF production within integrated circular biorefinery systems.

4.4. Carbon Capture and Utilization

Carbon Capture and Utilization (CCU) significantly strengthens the sustainability profile of algal SAF systems by transforming industrial CO₂ emissions into productive carbon feedstocks. Flue gases from cement plants, steel industries, thermal power stations, and refineries can be directly utilized to support algal growth, simultaneously reducing emissions and supplying renewable carbon for fuel synthesis. One of the most innovative developments is the Bicarbonate-Based Integrated Carbon Capture and Algae Production System (BICCAPS), where captured CO₂ is converted into bicarbonate-rich solutions that serve as transportable and biologically accessible carbon sources for algae and cyanobacteria. Amine-based capture systems employing monoethanolamine, diethanolamine, and triethanolamine further improve bicarbonate generation efficiency [70,71]. BICCAPS offers additional advantages through solvent recycling and coproduct generation, lowering overall carbon mitigation costs [72]. A mixed consortium of *Scenedesmus obliquus* and *Chlorella* spp. demonstrated bicarbonate fixation rates of 2.42 g HCO₃[−] per gram of algal biomass, highlighting the strong carbon-capture potential of biological systems [73]. Integration with Bioenergy with Carbon Capture and Storage (BECCS) further expands opportunities for achieving net-negative carbon emissions while supporting sustainable fuel production [74].

4.5. Industrial Flue Gas and Wastewater Systems

Industrial flue gases and wastewater represent low-cost resource streams that can substantially improve the economics and sustainability of algal SAF production. Typical industrial flue gases contain 10–25% CO₂ alongside NO_x, SO_x, fly ash, and particulate matter, creating challenging cultivation conditions that require robust microalgal strains [75]. Thermophilic and acidophilic species such as *Viridella* and *Galdieria* exhibit exceptional tolerance to elevated CO₂ concentrations and harsh industrial environments, making them attractive candidates for flue-gas-assisted cultivation. Simultaneously, wastewater streams provide water, nitrogen, phosphorus, and trace nutrients necessary for algal growth. Anaerobically digested sewage sludge, municipal wastewater, agricultural effluents, aquaculture discharges, food-processing wastewaters, and landfill leachates have all been successfully utilized for simultaneous phycoremediation and biomass production [76]. Oil and gas industry effluents have also demonstrated potential as cultivation media [77]. Integrating wastewater treatment, nutrient recovery, carbon capture, and algal biomass production within a single system substantially improves resource efficiency while lowering cultivation costs. Consequently, future algal SAF biorefineries are expected to evolve toward fully integrated circular bioeconomy platforms where waste carbon, nutrients, and water are simultaneously recovered and converted into aviation fuel precursors. The dynamics of various waste-based feedstocks for SAF are illustrated in Figure 6.

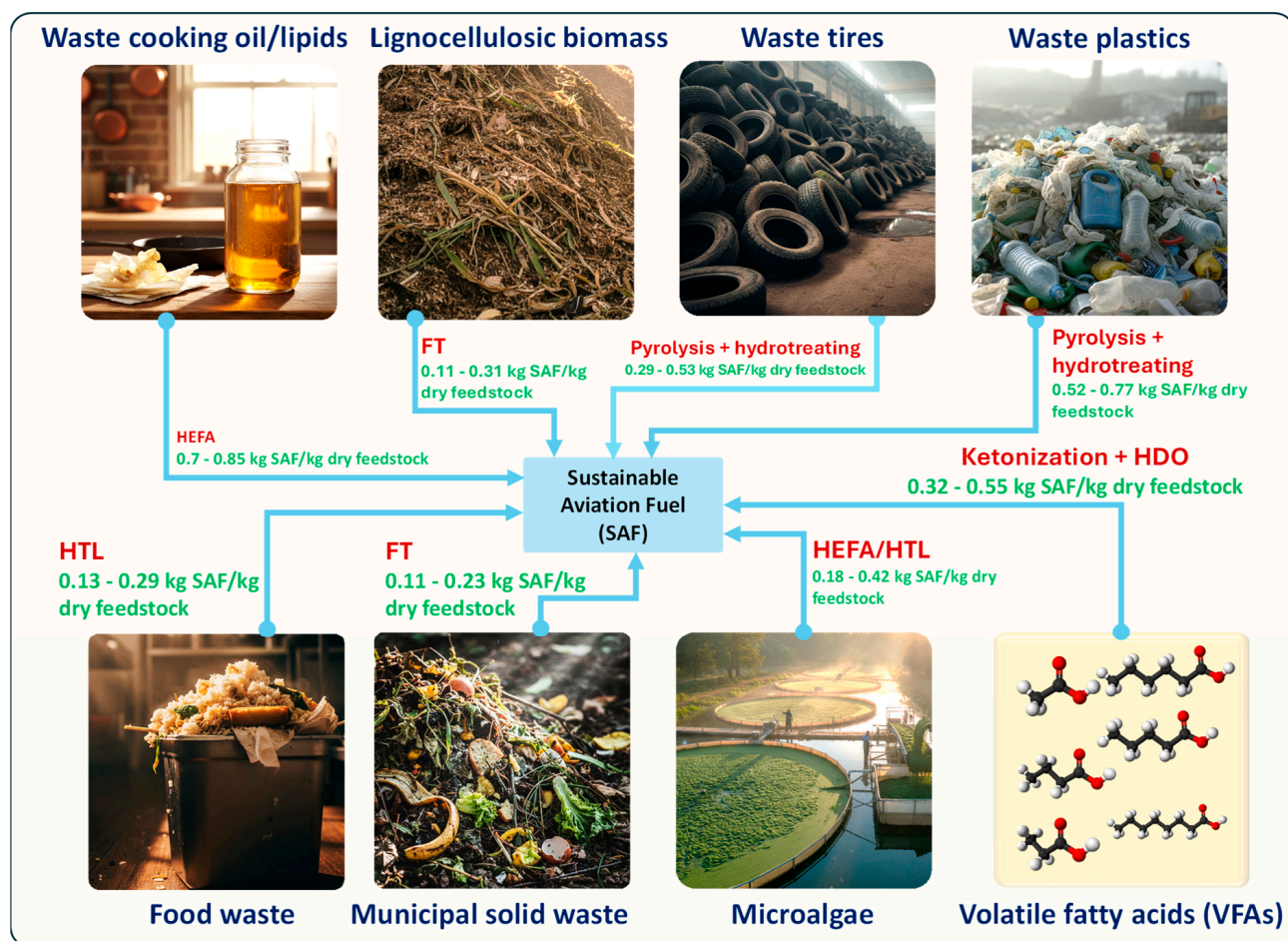


Figure 6. Comparative assessment of Sustainable Aviation Fuel yields from various waste-based feedstocks.

5. From CO₂ to SAF: Bioenergy Systems and Renewable Energy Integration

5.1. Biological Routes to SAF

Carbon-neutral liquid fuels synthesized from renewable sources are considered most sustainable and practical long-term strategies for achieving climate-neutral aviation [78,79]. Carbon-to-fuel approaches that integrate bioenergy systems, carbon capture, renewable electricity, and advanced catalytic platforms have recently emerged as highly promising pathways for converting CO₂ into SAF [80]. These integrated systems could establish a circular carbon economy in which CO₂ from industrial emissions, biomass processing, or direct air capture is recycled into hydrocarbon fuels instead of being directly released into the atmosphere [79]. The approaches simultaneously address greenhouse gas mitigation, renewable energy storage, carbon waste utilization, and sustainable transportation demands [81].

Carbon-to-fuel pathways rely heavily on the integration of renewable carbon sources with advanced thermochemical, biological, and electrochemical conversion technologies [82,83]. Biomass-derived carbon remains one of the most important feedstocks because biomass naturally captures atmospheric CO₂ during photosynthesis [84]. Agricultural residues, forestry waste, municipal solid waste, algae, and industrial organic wastes provide renewable carbon resources that can be converted into syngas, bio-oils, alcohols, and hydrocarbon intermediates suitable for aviation fuel synthesis [85]. Gasification technologies convert lignocellulosic biomass into syngas consisting primarily of carbon monoxide

and hydrogen, which can subsequently undergo catalytic Fischer–Tropsch synthesis to produce liquid hydrocarbons [86,87]. Similarly, pyrolysis and hydrothermal liquefaction processes generate bio-crude oils that may be upgraded into aviation-grade fuels through hydroprocessing and catalytic refining [5,83]. These bioenergy systems are increasingly integrated with carbon capture technologies to improve carbon utilization efficiency and minimize greenhouse gas emissions throughout the fuel production lifecycle [80].

Carbon capture and utilization (CCU) technologies development has significantly expanded the scope of SAF production beyond traditional biomass feedstocks. Industrial point-source emissions from cement plants, steel manufacturing, power generation facilities, and chemical industries contain concentrated streams of carbon dioxide that can be captured and redirected toward fuel synthesis pathways [88]. Direct air capture technologies are also gaining attention because they enable atmospheric carbon removal independent of industrial infrastructure [89]. Captured carbon dioxide may be combined with renewable hydrogen generated through water electrolysis to synthesize synthetic hydrocarbons through power-to-liquid (PtL) pathways [90]. These systems are particularly attractive because they establish nearly closed carbon cycles when powered entirely by renewable electricity. Renewable hydrogen functions as a key reducing agent during catalytic conversion processes and enables the production of synthetic paraffinic kerosene compatible with existing aviation turbines [91]. The integration of renewable electricity with carbon recycling systems therefore represents a transformative strategy for sustainable aviation decarbonization [92].

Biological carbon conversion systems are attracting considerable scientific interest because they enable CO₂ transformation under relatively mild operating conditions. Biological routes utilize microorganisms capable of converting CO₂ or syngas into alcohols or hydrocarbons, while electrochemical systems directly reduce CO₂ to fuel precursors [93]. Several autotrophic and acetogenic microorganisms naturally possess metabolic pathways capable of fixing carbon dioxide into organic compounds. Cyanobacteria, microalgae, methanogens, and acetogenic bacteria have demonstrated significant potential for converting CO₂ or syngas into alcohols, fatty acids, methane, and hydrocarbon precursors relevant to aviation fuel production [93,94]. Among these, acetogenic bacteria operating through the Wood–Ljungdahl pathway are particularly promising because they can utilize both carbon monoxide and carbon dioxide as carbon sources while producing ethanol, acetate, and butanol under anaerobic conditions [95]. Gas fermentation systems employing microorganisms such as *Clostridium ljungdahlii* and *Clostridium autoethanogenum* have been extensively investigated for industrial-scale ethanol production from syngas and industrial emissions [96]. The resulting alcohols can subsequently undergo alcohol-to-jet conversion pathways involving dehydration, oligomerization, and hydrogenation to produce aviation-grade hydrocarbons [94,95].

Microalgae-based systems provide another important biological platform for SAF synthesis [97,98]. Algae possess exceptionally high photosynthetic efficiency and can accumulate large quantities of lipids suitable for hydro-processed esters and fatty acids (HEFA) fuel production [99,100]. Unlike terrestrial crops, microalgae cultivation does not necessarily require arable land or freshwater resources, making algal biofuel systems attractive from a sustainability perspective [101]. Algae cultivation can also be integrated with wastewater treatment facilities and industrial carbon emissions to improve nutrient recycling and carbon capture efficiency. The lipid fractions extracted from algal biomass may be converted into renewable jet fuel through hydrotreating processes, while residual biomass can support anaerobic digestion, biohydrogen generation, or thermochemical conversion. Such integrated biorefinery approaches maximize resource utilization while reducing overall environmental impact.

Synthetic biology and metabolic engineering have further accelerated the development of biological SAF production systems by enabling precise manipulation of microbial metabolic pathways [102,103]. Advances in genetic engineering have enabled researchers to design microorganisms capable of producing long-chain hydrocarbons, terpenoids, fatty alcohols, and isoprenoid-based jet fuel molecules directly from renewable carbon sources [85]. Engineered strains of cyanobacteria and yeast are being optimized for enhanced carbon fixation efficiency, improved product yields, and increased tolerance to industrial operating conditions. Metabolic pathway optimization also enables improved electron utilization, redox balancing, and carbon flux distribution during fuel synthesis [104]. These developments are critical for improving the economic viability of biological carbon conversion technologies and expanding the range of fuel molecules accessible through microbial biosynthesis [105,106].

Commercialization and large-scale deployment of CO₂-derived SAF technology is principally determined by its maturity, energy demand, hydrogen availability, and economic viability [107]. Among existing pathways, biomass-based processes such as hydro-processed esters and fatty acids (HEFA) have achieved commercial maturity (TRL 9), whereas CO₂-based Power-to-Liquid (PtL) and electrofuel routes remain at pilot/demonstration stages (TRL 5–7) [108]. These emerging pathways integrate renewable electricity, green hydrogen by water electrolysis, and captured CO₂ through reverse water–gas shift and Fischer–Tropsch synthesis or methanol-mediated upgrading to generate drop-in jet fuels [16]. These technologies offer near-carbon-neutral fuel production, but their deployment is limited by the complexity of integrating multiple energy-intensive unit operations and maintaining continuous renewable power availability. Energy requirement of CO₂-to-SAF is considerably higher than the conventional refining routes, as renewable electricity is consumed during hydrogen generation, CO₂ capture, compression, and catalytic fuel synthesis [91]. Recent techno-economic analyses estimate that approximately 0.8 kg of renewable H₂ and ~3.1 kg of captured CO₂ are required to produce 1 kg of PtL-SAF, emphasizing the enormous demand for low-cost renewable electricity and electrolyzer capacity [108]. Consequently, the economic competitiveness of CO₂-derived SAFs strongly depends on declining renewable electricity prices, improved electrolyzer efficiencies, higher carbon utilization efficiencies, and economies of scale. At present, production costs remain substantially above those of fossil-derived jet fuel, necessitating policy incentives such as carbon pricing, production tax credits, contracts for difference, and long-term airline off-take agreements to accelerate commercialization. Despite these challenges, CO₂-to-SAF technologies possess significant long-term potential to produce fully compatible drop-in fuels without requiring modifications to existing aircraft or airport infrastructure. Future commercial deployment will therefore depend on expanding renewable hydrogen production, improving catalyst durability and carbon conversion efficiencies, integrating direct air capture with renewable energy systems, and establishing supportive regulatory frameworks that reduce investment risks while stimulating global SAF markets.

5.2. Electrochemical Routes to SAF

In parallel with biological systems, electrochemical carbon dioxide reduction technologies have emerged as powerful approaches for converting captured CO₂ into fuel intermediates using renewable electricity [109,110]. Electrochemical reduction systems utilize electrocatalysts capable of transferring electrons to carbon dioxide molecules, thereby producing carbon monoxide, formate, methanol, methane, ethylene, ethanol, and other hydrocarbon intermediates [94,111]. Product distribution depends strongly on catalyst composition, reactor configuration, electrolyte chemistry, and operating potential [112]. Copper-based catalysts are particularly important because they can facilitate multicar-

bon product formation, while silver and gold catalysts exhibit high selectivity toward carbon monoxide production [113]. Formate-producing catalysts based on tin, indium, and bismuth are also attracting interest because formate serves as an important chemical intermediate and hydrogen storage medium [114]. The integration of bioelectrochemical systems with renewable energy presents a promising pathway toward circular carbon utilization, aligning aviation fuel production with long-term climate neutrality goals. Bioelectrochemical reactors enable direct electron transfer between electrodes and microorganisms, facilitating microbial electrosynthesis of fuels and chemical intermediates from carbon dioxide (Figure 7). Renewable electricity derived from solar and wind power can drive cathodic CO_2 reduction while minimizing fossil energy dependence. Coupling renewable hydrogen production with microbial carbon fixation enhances fuel synthesis efficiency and enables continuous operation under variable renewable energy supply conditions [115]. Furthermore, integrating carbon capture technologies with electrochemical and biological conversion systems supports closed-loop carbon recycling by utilizing industrial emissions and atmospheric carbon as renewable feedstocks. Recent advances in nanostructured catalysts, enzyme-based electrodes, conductive biofilms, and synthetic metabolic engineering are improving conversion rates and product specificity in bioelectrochemical fuel systems. As renewable energy infrastructure expands globally, integrated carbon-neutral aviation fuel platforms may become essential components of future sustainable transportation networks, supporting both energy security and global decarbonization objectives.

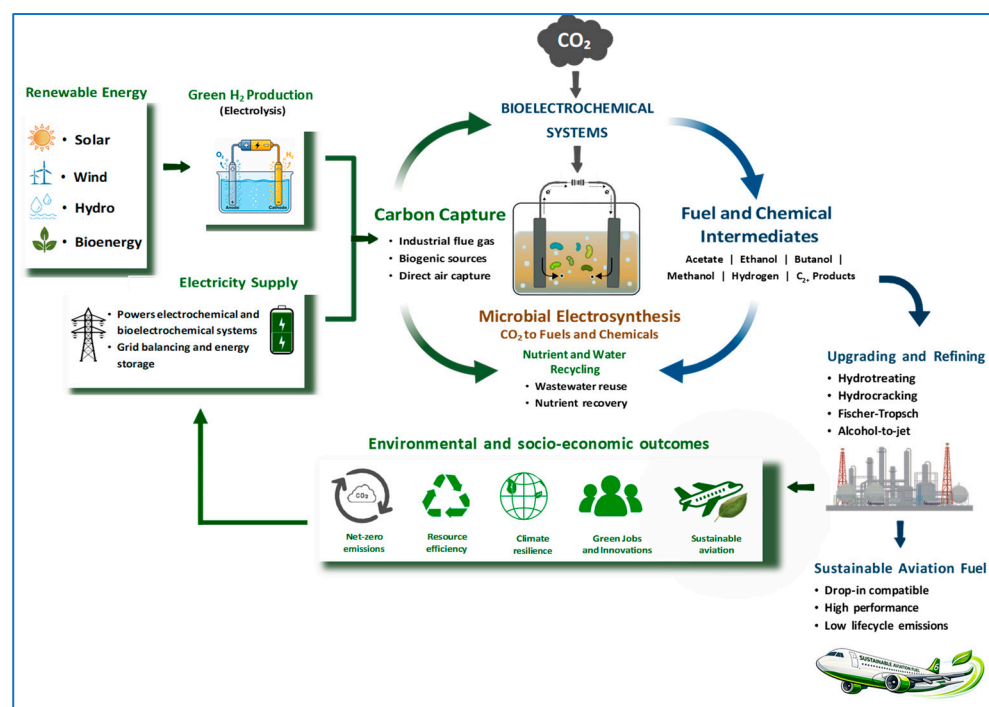


Figure 7. Bioelectrochemical systems and renewable energy integration depicting circular economy for SAFs.

Electrochemical CO_2 conversion systems offer several significant advantages for SAF production. First, they operate under relatively mild temperatures and pressures compared with thermochemical processes. Second, they can be directly powered by intermittent renewable electricity generated from solar and wind sources. Third, they enable decentralized fuel production systems capable of utilizing locally captured carbon dioxide streams. Furthermore, electrochemical reactors exhibit rapid operational flexibility, making them compatible with fluctuating renewable electricity supply [112]. However, several technical

challenges remain, including catalyst degradation, low energy efficiency, limited current density, and difficulties associated with downstream product separation. Significant research efforts are therefore focused on developing nanostructured catalysts, membrane electrode assemblies, gas diffusion electrodes, and advanced reactor architectures capable of improving conversion efficiency and product selectivity [85,113]. Renewable hydrogen production is another essential component of integrated carbon-to-fuel systems [81]. Hydrogen generated through renewable-powered water electrolysis acts as a reducing agent during hydrocarbon synthesis and hydro-processing operations. Green hydrogen can also be combined with captured carbon dioxide through reverse water-gas shift reactions followed by Fischer–Tropsch synthesis to generate synthetic aviation fuels [90,91].

The rapid expansion of renewable energy infrastructure has substantially improved the feasibility of hydrogen-mediated synthetic fuel pathways. Proton exchange membrane electrolysis, alkaline electrolysis, and solid oxide electrolysis technologies are increasingly being optimized for large-scale green hydrogen production. Coupling electrolysis systems with renewable electricity sources enables carbon-neutral hydrogen generation while supporting grid balancing and long-duration energy storage [5]. In integrated SAF production systems, renewable hydrogen can also enhance carbon conversion efficiency by improving hydrodeoxygenation and hydrocracking reactions during biomass upgrading.

Hybrid systems integrating biological and electrochemical processes represent a particularly promising frontier in SAF research. These systems combine the catalytic precision of biological pathways with the high electron transfer efficiency of electrochemical platforms. Microbial electrosynthesis systems, for example, utilize electroactive microorganisms capable of accepting electrons directly or indirectly from cathodes to reduce carbon dioxide into multi-carbon compounds. In such systems, renewable electricity drives cathodic reactions while microorganisms catalyze carbon fixation and product formation. This approach enables efficient coupling between renewable power generation and microbial fuel synthesis. Electroactive acetogenic bacteria can produce acetate, ethanol, and butyrate from carbon dioxide using electrons supplied through conductive surfaces or hydrogen intermediates generated electrochemically.

Bioelectrochemical systems offer several advantages compared with conventional catalytic approaches. Biological catalysts exhibit high substrate specificity and can operate under ambient conditions, reducing energy requirements and minimizing undesirable side reactions. Moreover, microorganisms possess self-regenerating catalytic capabilities that may improve long-term operational stability. Advances in electrode materials, conductive nanostructures, and biofilm engineering are improving extracellular electron transfer efficiency and enhancing microbial productivity. Carbon-based electrodes, graphene composites, conductive polymers, and metal–organic frameworks are being investigated for improving electrode biocompatibility and electron transport characteristics. These developments are expected to play a crucial role in advancing microbial electrosynthesis technologies toward industrial implementation (Table 2).

The integration of renewable energy systems with bioelectrochemical platforms is particularly important for establishing circular carbon utilization pathways aligned with long-term climate neutrality goals. Renewable electricity generated from solar photovoltaic systems, wind turbines, hydroelectric power, and bioenergy facilities can provide the electrical energy required for electrochemical carbon reduction, hydrogen generation, and microbial electrosynthesis. The intermittent nature of renewable electricity generation may also be addressed through flexible electrochemical reactor operation and hydrogen storage strategies. Excess renewable electricity generated during periods of low grid demand can be redirected toward carbon conversion systems, effectively transforming renewable power into storable liquid fuels suitable for aviation applications.

Table 2. CO₂-to-SAF, Bioenergy Systems, and Renewable Energy Integration.

Feedstock/Energy Source	Technology/Pathway	Main Product	Advantages	Limitations	Key Findings	Reference
Biomass, Waste oils, Renewable feedstocks	HEFA, FT, ATJ, PtL	SAF	Significant GHG reduction and fuel compatibility.	High production cost and feedstock limitations	SAF pathways can reduce greenhouse gas emissions by 27–87%; techno-economic barriers still exist	[116]
Green hydrogen, Renewable electricity, Captured CO ₂	Power-to-Liquid (PtL), electrofuels	Synthetic electrofuels	Near net-zero carbon emissions	High renewable electricity demand	Renewable-energy-based SAF systems may achieve near-net-zero emissions	[117]
Biomass and renewable feedstocks	AI-assisted catalytic conversion	Optimized biojet fuel	Improved process efficiency and predictive control	Requires large datasets and industrial validation	Machine learning improves fuel quality prediction and process optimization	[118]
Captured CO ₂ and renewable H ₂	CO ₂ hydrogenation and synthetic jet fuel production	Synthetic aviation hydrocarbons	Supports carbon recycling and CCU strategies	Expensive hydrogen production	CO ₂ -derived aviation fuels support carbon-neutral aviation goals	[119]
Waste oils, biomass, agricultural residues	ASTM-certified SAF pathways	Certified aviation biofuel	Commercial aviation compatibility	Regulatory and infrastructure challenges	Policy support is essential for commercial-scale SAF adoption	[120]
Multiple renewable feedstocks	HEFA, FT, ATJ, algae-based SAF	Biojet fuel blends	Diverse feedstock flexibility	Supply chain and feedstock availability issues	Feedstock availability and supply chain issues remain major bottlenecks	[121]
Agricultural residues, lignocellulosic biomass	Gasification and biorefinery systems	Syngas-derived aviation fuel	Utilizes agricultural waste effectively	Pretreatment and conversion complexity	Biomass offers sustainable routes for renewable fuel production	[122]
Algae oil, waste oils, alcohols	HEFA, FT, ATJ	Drop-in aviation fuel	Reduced emissions with engine compatibility	Large-scale algae cultivation challenges	SAF blends maintain engine compatibility while reducing emissions	[123]
Renewable electricity, CO ₂ , water	Electrolysis and electrofuel synthesis	Electro-SAF	Very low lifecycle carbon emissions	High electricity consumption and infrastructure costs	Electrified SAF production significantly lowers lifecycle carbon emissions	[124]
Lignocellulosic biomass and algae	Thermochemical and biochemical conversion	Biomass-derived SAF	Renewable and abundant feedstocks	Process scalability limitations	Biomass-derived SAF has strong potential for aviation decarbonization	[125]
Renewable biomass and bioresources	Integrated bioenergy systems	Bioenergy and aviation fuels	Supports circular bioeconomy	Complex system integration	Circular bioeconomy concepts improve sustainability and energy recovery	[126]
Municipal solid waste and food waste	Hydroprocessing and gasification	Waste-derived jet fuel	Reduces landfill burden and waste accumulation	Feedstock heterogeneity	Waste-derived SAF reduces landfill burden and supports circular economy	[127]
Atmospheric CO ₂ and renewable energy	DAC coupled with electrolysis	Carbon-neutral electrofuel	Direct atmospheric carbon utilization	High DAC operational costs	Integration improves carbon utilization efficiency and economic viability	[128]
Biomass and renewable carbon feedstocks	HEFA-SPK and ATJ pathways	Sustainable jet fuel	Up to 80% lifecycle emission reduction	Limited commercial-scale deployment	SAF can reduce lifecycle emissions by up to 80%	[129]
Synthetic aviation fuel blends	FTIR spectroscopy and ML modeling	Fuel quality prediction systems	Rapid and accurate fuel characterization	Model dependency on training data	AI tools enhance rapid fuel characterization and quality monitoring	[130]

Bioenergy systems themselves can contribute significantly to renewable electricity generation and carbon management [89]. Biomass combustion, anaerobic digestion, and gasification processes produce renewable electricity and heat while generating carbon-rich gas streams suitable for capture and utilization. Integrating carbon capture technologies with biomass energy systems creates bioenergy with carbon capture and storage (BECCS) configurations capable of achieving net-negative emissions. When captured biogenic carbon dioxide is redirected toward fuel synthesis rather than permanent storage, fully circular carbon utilization pathways become possible [92]. Such systems are increasingly recognized as essential components of future carbon-neutral energy infrastructure.

Thermochemical and electrochemical integration strategies are also expanding the technological diversity of SAF production pathways [94]. Reverse water–gas shift reactors can convert captured CO₂ into carbon monoxide using renewable hydrogen, thereby

generating syngas suitable for Fischer–Tropsch hydrocarbon synthesis. Plasma-assisted catalysis and photocatalytic reduction systems are additionally being investigated for direct solar-driven carbon conversion [131]. Semiconductor photocatalysts capable of utilizing sunlight to drive carbon dioxide reduction reactions may eventually enable low-energy fuel synthesis systems inspired by natural photosynthesis [132]. Although these technologies remain at relatively early stages of development, they represent important directions for future sustainable fuel research.

Biological, thermochemical, and electrochemical CO₂ conversion technologies are increasingly viewed as complementary components of an integrated carbon utilization framework for SAF production. Apart from possessing the individual benefits, the integration of these technologies enables each pathway to compensate for the limitations of the others. Electrochemical conversion addresses the need for renewable carbon activation, biological systems enhance product selectivity and carbon utilization while operating under low-energy conditions, and thermochemical upgrading provides the high productivity and process intensification necessary for commercial-scale fuel manufacture [82,94]. For example, electrochemically produced formate or syngas can serve as substrates for microbial fermentation, whereas biologically generated alcohols can subsequently undergo catalytic upgrading to jet-range hydrocarbons. Such hybrid platforms reduce dependence on single conversion technology, improve overall carbon efficiency, facilitate the utilization of intermittent renewable electricity, and enhance process flexibility [5,81]. Consequently, future CO₂-to-SAF biorefineries are expected to integrate electrochemical, biological, and thermochemical processes into a unified value chain, leveraging the strengths of each technology to achieve greater energy efficiency, improved carbon circularity, and economically viable production of SAFs [108].

Economic feasibility remains one of the most important challenges facing carbon-to-fuel technologies. The cost of renewable electricity, green hydrogen production, carbon capture infrastructure, catalyst materials, and reactor operation currently limits large-scale commercialization of many advanced SAF pathways [133]. Nevertheless, continuous declines in renewable electricity costs, advances in electrolyzer manufacturing, and increasing carbon pricing policies are improving the economic outlook for carbon-neutral aviation fuels [134,135]. Government incentives, low-carbon fuel standards, and international aviation decarbonization mandates are expected to accelerate technology deployment during the coming decades. Lifecycle assessment and techno-economic analysis are therefore becoming increasingly important tools for evaluating the sustainability and scalability of competing SAF pathways [81,136].

Lifecycle greenhouse gas reduction remains a central criterion for SAF evaluation. Integrated carbon-to-fuel systems can potentially achieve near-net-zero or even net-negative carbon emissions depending on feedstock origin, energy source, and process integration strategy. Biomass-derived carbon recycled through biological and electrochemical pathways contributes substantially lower lifecycle emissions compared with fossil-derived jet fuels. Furthermore, the use of renewable electricity eliminates indirect emissions associated with conventional hydrogen production and fuel refining processes. However, achieving true climate neutrality requires careful consideration of land use impacts, water consumption, nutrient requirements, and infrastructure-related emissions [137]. Future SAF deployment strategies must therefore emphasize holistic sustainability assessment frameworks incorporating environmental, social, and economic dimensions [138].

Recent advances in artificial intelligence, digital process optimization, and systems engineering are also contributing to the rapid evolution of SAF technologies [118,139]. Machine learning algorithms are increasingly being applied to catalyst discovery, metabolic pathway optimization, reactor control, and process integration analysis. Digital twins and

predictive modeling platforms enable real-time optimization of electrochemical reactors, biorefinery systems, and renewable energy integration strategies. Such computational tools may significantly accelerate technology development while reducing operational costs and improving process reliability [140]. The aviation industry's transition toward sustainable fuel systems will likely require a combination of complementary technological pathways rather than reliance on a single solution. Biomass conversion, electrochemical CO₂ reduction, microbial electrosynthesis, renewable hydrogen integration, and carbon capture technologies each offer distinct advantages and limitations depending on regional resource availability, infrastructure capacity, and policy frameworks. Hybrid systems integrating multiple technologies may ultimately provide the highest efficiency and flexibility for large-scale SAF deployment. For example, biological systems may be utilized for selective carbon fixation and alcohol production, while electrochemical platforms provide hydrogen generation and carbon monoxide synthesis. Thermochemical upgrading processes can subsequently convert intermediates into aviation-compatible hydrocarbons.

Integration of bioelectrochemical systems with renewable energy infrastructure therefore represents one of the most promising pathways toward circular carbon utilization and climate-neutral aviation. By transforming waste carbon dioxide into high-energy liquid fuels using renewable electricity and biological catalysis, these systems establish sustainable carbon cycles capable of reducing dependence on fossil resources. Continued advances in catalyst engineering, synthetic biology, electrochemical reactor design, renewable hydrogen production, and systems integration are expected to further improve process efficiency and economic feasibility. As global renewable energy capacity continues to expand, carbon-neutral aviation fuel production systems may become increasingly important for balancing energy supply, reducing greenhouse gas emissions, and supporting sustainable transportation networks. Ultimately, the successful implementation of carbon-to-fuel technologies will depend on coordinated collaboration among researchers, industry stakeholders, policymakers, and renewable energy developers. Strategic investments in renewable infrastructure, carbon capture systems, and advanced fuel synthesis technologies will be essential for scaling SAF production to meet future aviation demand. International climate agreements and carbon reduction policies are likely to further stimulate innovation and commercialization in this rapidly evolving field [134]. Through the integration of biological carbon fixation, electrochemical reduction, renewable electricity, and circular carbon management strategies, SAF systems have the potential to fundamentally transform the aviation industry and contribute substantially to global climate neutrality objectives.

6. Sustainability Assessment of SAF

SAF is increasingly recognized as critical near and medium-term option for reducing the climate impact of aviation. However, the term “sustainable” should not be reduced to renewable origin, technical compatibility, or life-cycle GHG reduction alone. A fuel classified as sustainable must demonstrate measurable environmental and resource-efficiency advantages across its complete value chain, including feedstock sourcing, land and water use, biomass logistics, process energy, conversion efficiency, hydrogen and electricity inputs, co-product management, fuel distribution, and final combustion. Therefore, SAF sustainability assessment requires an integrated framework combining life-cycle assessment (LCA), circular bioeconomy principles, life-cycle sustainability assessment (LCSA), resource-efficiency indicators, and multi-criteria decision analysis (MCDA) [141]. Recent literature has examined SAF sustainability primarily through certification and regulatory alignment, comparing frameworks like RED III and ReFuelEU Aviation with ICAO-CORSIA [141,142]. While these studies are crucial for defining feedstock eligibility, GHG limits, chain-of-custody, ILUC treatment, and policy recognition, regulatory compliance alone does not fully capture

sustainability. A pathway-level assessment is needed, addressing feedstock circularity, energy intensity, hydrogen use, land-use and water risks, soil-carbon and biodiversity impacts, co-product valorization, technology readiness, and scalability. This study adopts a broader LCA and circular-bioeconomy perspective, positioning certification as a supporting governance mechanism rather than the sole basis for sustainability claims (Figure 8).

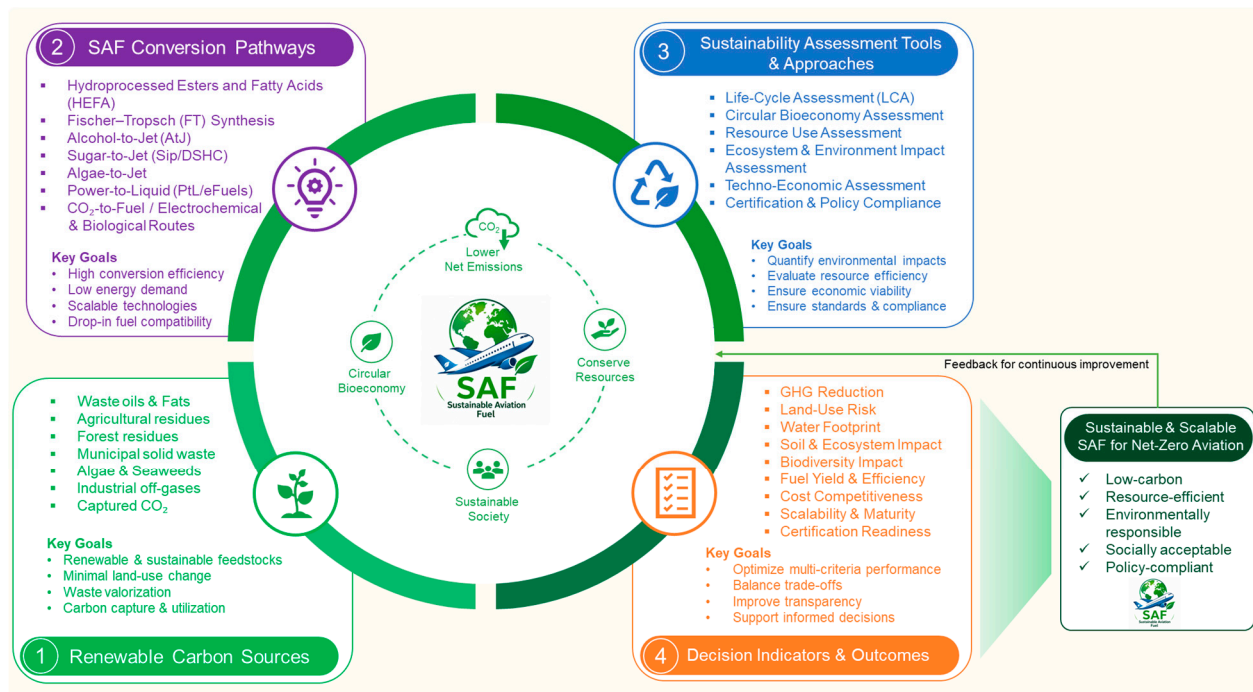


Figure 8. An integrated sustainability assessment of SAF pathways through feedstock selection, SAF conversion technologies, environmental evaluation, and performance-based decision indicators.

6.1. Role of Lifecycle Assessment (LCA)

LCA is one of the most widely used tools for quantifying the environmental performance of SAF. In conventional aviation fuel systems, emissions arise from crude oil extraction, transport, refining, fuel distribution, and aircraft combustion. In SAF systems, the emission profile is more pathway-specific and may include biomass cultivation or residue collection, feedstock transport, pretreatment, fermentation, gasification, hydrogenation, catalytic upgrading, electricity consumption, hydrogen production, co-product handling, blending, distribution, and final fuel use. Therefore, SAF assessment is commonly performed using well-to-wake or cradle-to-grave system boundaries, with GHG emissions expressed as g CO₂-eq/MJ of fuel [143]. To facilitate comparison among different SAF production pathways, lifecycle greenhouse gas emissions are commonly reported as carbon intensity (CI) in g CO₂-eq/MJ. Conventional Jet A-1 has a lifecycle carbon intensity of approximately 89 g CO₂-eq/MJ, whereas representative values for major SAF pathways generally range from 15–45 g CO₂-eq/MJ (HEFA), 10–35 g CO₂-eq/MJ (FT), 20–55 g CO₂-eq/MJ (AtJ), and <10–30 g CO₂-eq/MJ (PtL), depending on feedstock, hydrogen source, electricity mix, and lifecycle boundary assumptions. A central issue in SAF LCA is the treatment of biogenic carbon. Bio-based SAF releases CO₂ during combustion, but this carbon was previously absorbed from the atmosphere during biomass growth. However, this does not automatically make all bio-based SAF carbon neutral. Carbon neutrality depends on the feedstock baseline, land-use change, biomass regrowth period, soil organic carbon dynamics, fertilizer inputs, avoided decomposition, avoided burning, and alternative uses of the biomass [144]. For example, SAF derived from genuine waste oils or unavoidable

residues may provide strong climate benefits, whereas SAF derived from feedstocks linked to deforestation, peatland drainage, food-crop displacement, or high fertilizer demand may have weaker or even adverse sustainability outcomes [145].

The selection of system boundaries, functional units, allocation approach, and background databases can strongly influence LCA conclusions. Most SAF studies use 1 MJ of fuel lower heating value as the functional unit, which allows comparison among fuel-production pathways. However, future aircraft-level assessments may also consider performance-based functional units, such as useful energy delivered or distance travelled, because fuel density, combustion properties, and non-CO₂ effects may influence actual aviation performance. Similarly, the choice of cradle-to-gate, well-to-wake, or cradle-to-grave boundaries should be explicitly justified because excluding fuel combustion, co-product displacement, or upstream land-use effects may underestimate the real sustainability burden. Several methodological parameters require particular attention in SAF LCA. ILUC can substantially alter the carbon intensity of crop-based pathways, especially when energy crops or oil crops displace food production or trigger land conversion elsewhere [143]. Fertilizer-derived nitrous oxide emissions can also be important because N₂O has high global warming potential and varies with soil type, climate, fertilizer practice, and nitrogen-use efficiency. Hydrogen source is critical for Hydroprocessed Esters and Fatty Acids (HEFA), Alcohol-to-Jet (AtJ), and other hydroprocessing-intensive routes; grey hydrogen can increase life-cycle emissions, whereas renewable hydrogen can reduce the conversion-stage footprint [145]. Carbon electricity intensity is decisive for Power-to-Liquid (PtL), electrochemical, algae, and other energy-intensive routes [87]. Co-product allocation can also significantly affect reported SAF carbon intensity because many routes produce renewable diesel, naphtha, propane, biochar, lignin-rich residues, process heat, or captured CO₂. Therefore, SAF LCA studies should transparently report allocation methods and include sensitivity analysis for ILUC, fertilizer emissions, feedstock transport distance, hydrogen source, electricity mix, conversion yield, and co-product displacement [146]. Direct comparison of reported GHG reduction and carbon intensity values among SAF pathways should be made with caution, as LCA outcomes are highly dependent on methodological choices. Variations in system boundaries (e.g., cradle-to-gate, well-to-wake, or cradle-to-grave), functional units, co-product allocation methods, feedstock assumptions, hydrogen and electricity sources, and land-use change treatment can substantially influence reported results. Therefore, representative values presented in this review should be interpreted within the context of methodological assumptions of each study rather than as directly comparable performance metrics.

6.2. Pathway-Specific Sustainability Hotspots

The sustainability performance of SAF differs significantly across HEFA, Fischer-Tropsch (FT), Alcohol-to-Jet (AtJ), Sugar-to-Jet, algae-derived SAF, and Power-to-Liquid (PtL) pathways. Therefore, pathway-specific LCA hotspots must be clearly identified rather than assuming that all SAF routes provide similar benefits [147]. HEFA is among the most commercially mature routes, converting lipid feedstocks such as used cooking oil, animal fats, and vegetable oils into paraffinic hydrocarbons via hydrogenation, deoxygenation, and isomerization [148]. HEFA sustainability strongly depends on lipid origin. Waste lipids offer high circular-bioeconomy value by avoiding cultivation and reducing waste burdens. In contrast, virgin vegetable oils raise concerns over ILUC, food-versus-fuel competition, fertilizer-derived N₂O emissions, biodiversity loss, and water demand. Accordingly, HEFA should be evaluated based on lipid origin, waste-oil traceability, hydrogen source, and co-product allocation.

FT-SAF relies on gasification of carbon-rich feedstocks, including agricultural residues, forest residues, and municipal solid waste (MSW), followed by syngas cleaning and catalytic synthesis. Sustainability potential is high when genuine residues are used, but biomass logistics, gasification efficiency, and carbon conversion efficiency are major LCA hotspots [87]. Excessive crop-residue removal may reduce soil organic carbon and increase erosion risk, while excessive forest-residue extraction can affect nutrient cycling. For MSW-based FT-SAF, careful sorting is required because fossil-derived plastics can increase the fossil-carbon fraction of the final fuel. Thus, residue-based FT-SAF must integrate soil-carbon protection, sustainable harvesting limits, and fossil-carbon screening [149]. AtJ-SAF converts alcohol intermediates, mainly ethanol or isobutanol, into jet-range hydrocarbons via dehydration, oligomerization, and hydrogenation. Sustainability depends heavily on the alcohol production route. Alcohols from sugar or starch feedstocks carry land-use, fertilizer, and water burdens, whereas those from lignocellulosic residues or waste gases align better with circular-bioeconomy objectives. Carbon losses during upgrading, hydrogen use, and process heat demand must also be considered.

Sugar-to-Jet pathways can be attractive when using cellulosic or industrial sugar-rich residues, but sugar-crop feedstocks raise land occupation, irrigation, and food-system concerns. Algae-derived SAF offers high productivity and CO₂ utilization but faces challenges in energy-intensive harvesting, dewatering, and extraction; sustainability requires wet biomass conversion, wastewater integration, and nutrient recycling. PtL-SAF uses renewable hydrogen and captured CO₂ to produce synthetic hydrocarbons, offering deep decarbonization potential without direct biomass dependence [87]. However, PtL-SAF is highly sensitive to electricity carbon intensity, electrolyzer efficiency, CO₂ source, and synthesis efficiency [150]. It also requires large renewable electricity volumes, creating potential competition with other decarbonization priorities. Therefore, PtL-SAF should be assessed using prospective LCA scenarios that reflect regional grid decarbonization, electrolyzer performance, and sustainable CO₂ sourcing.

6.3. Circular Bioeconomy Perspective

The circular bioeconomy concept is highly relevant to SAF because it emphasizes renewable carbon management, waste valorization, resource recovery, and reduced fossil-carbon dependence [151]. In a circular SAF system, preferred feedstocks should avoid direct competition with food production, land conversion, and ecological degradation. Suitable carbon sources include used cooking oil, animal fats, agricultural and forest residues, municipal organic waste, wastewater-grown algae, industrial off-gases, fermentation CO₂, biogas-derived CO₂, and renewable-energy-derived captured CO₂. A waste and resource hierarchy should guide feedstock prioritization. The most preferred sources are unavoidable organic wastes, waste lipids, residues, industrial off-gases, and biogenic CO₂ streams. Secondary options include cover crops or biomass grown on degraded or marginal land, provided they avoid land-use change, water stress, and food competition. Dedicated energy crops are acceptable only when regionally justified and demonstrably low-risk. First-generation food crops warrant caution due to their links to ILUC, fertilizer demand, water use, and food-versus-fuel competition [151].

However, waste or residue feedstocks do not automatically guarantee sustainability. Many residues already serve important functions: agricultural residues as soil cover or livestock bedding, forest residues in nutrient cycling, used cooking oil in biodiesel or oleochemical markets, and municipal waste as a possible source of fossil-derived plastics. Therefore, circularity must be evaluated using feedstock availability, competing uses, collection logistics, displacement effects, regional supply curves, and residue-removal limits. Cascading biomass use is another key principle. Rather than converting biomass directly

to fuel in a single-use model, cascading systems extract higher-value materials first and then route the remaining residues to fuel or energy production. For example, lignocellulosic biomass may first be used for materials or biochemicals, while lignin-rich residues, black liquor, or fermentation residues can be directed to thermochemical conversion, anaerobic digestion, or energy recovery. Such integrated biorefineries can improve total resource efficiency and reduce environmental burdens assigned to SAF. Circular-bioeconomy claims should be supported by measurable indicators, including waste diversion, fossil-carbon displacement, nutrient recovery, material circularity, co-product substitution, avoided emissions, and reduced linear resource losses.

6.4. Beyond-Carbon Sustainability Indicators

Although GHG reduction drives SAF deployment, carbon intensity alone is insufficient to define sustainability. A low-carbon pathway may still create burdens related to water use, eutrophication, acidification, biodiversity loss, land occupation, toxicity, social risk, or soil degradation. Therefore, SAF assessment should include both climate and non-climate indicators [152]. For biomass-derived SAF, land-use change and soil-carbon effects are particularly important. Feedstock cultivation may require fertilizer, irrigation, and pesticides, contributing to eutrophication, ecotoxicity, water stress, and biodiversity loss. Residue-based SAF avoids direct cultivation, but excessive residue removal can reduce soil organic matter and nutrient recycling. Thus, assessment should include land-use risk, soil-carbon balance, sustainable residue-removal rates, nutrient balance, and biodiversity safeguards [143].

Water footprint is another critical indicator. Irrigated oil or sugar crops may have high water requirements, whereas waste oils, residues, wastewater-grown algae, and PtL routes may reduce agricultural water demand but introduce other burdens. Pathway-specific water use should therefore be evaluated against regional water scarcity rather than total water volume alone. A low-GHG pathway may still be unsuitable in arid regions if it increases freshwater depletion [153]. Biodiversity and ecosystem-quality indicators should also be included. Feedstocks from converted grasslands, forests, wetlands, or high-conservation-value land may generate biodiversity impacts not captured by carbon-only metrics. Residue extraction can also affect habitat quality and soil fauna if removal exceeds sustainable thresholds. Biodiversity characterization, ecosystem-service assessment, and conservation safeguards should be incorporated into future SAF LCA and LCSA studies where data permit.

Social sustainability should be considered, particularly for large-scale biomass systems and global waste supply chains. Potential risks include land-tenure conflicts, informal labor in waste collection, occupational exposure in thermochemical systems, local air-quality impacts, and unequal benefit distribution. Certification systems address some issues, but social LCA remains underused. Future studies should include labor conditions, land rights, food security, local employment, community acceptance, and occupational safety [154]. Air-quality and non-CO₂ climate impacts also merit attention. Many SAFs have lower sulfur and aromatic contents than fossil jet fuel, which may reduce particulate matter and soot formation. However, non-CO₂ aviation effects, including contrail and cirrus-cloud formation, depend on fuel composition, engine technology, flight altitude, and atmospheric conditions [155]. Future SAF assessments should therefore consider both CO₂ and non-CO₂ climate effects.

6.5. Policy, Certification, and Traceability

Policy and certification systems are essential for SAF deployment because they define eligible feedstocks, GHG accounting rules, technical certification, traceability requirements,

and market access. CORSIA provides an international framework for eligible aviation fuels [143], while regional policies such as RED III and ReFuelEU Aviation impose stricter requirements for specific markets [136]. Technical certification also ensures that SAF meets aviation fuel safety, blending, and performance requirements before commercial use [142]. However, certification should be viewed as a minimum compliance mechanism rather than a complete sustainability assessment. This distinction is important because certification frameworks differ in GHG thresholds, ILUC treatment, feedstock eligibility, and traceability requirements. Recent comparative work shows that European and ICAO-CORSIA systems diverge in certification scope, chain-of-custody models, GHG accounting, and ILUC approaches [141]. Therefore, pathway-level sustainability assessment should complement certification by identifying the actual environmental hotspots and resource constraints of each SAF route. Traceability is especially critical for waste- and residue-derived SAF. As demand increases, risks of feedstock misclassification, double counting, and substitution of virgin materials for waste streams also rise. Digital traceability systems, third-party verification, mass-balance accounting, and transparent chain-of-custody documentation are therefore important for maintaining environmental integrity. Despite significant policy progress, several regulatory challenges continue to hinder large-scale SAF deployment, including differences in sustainability criteria, GHG accounting methodologies, feedstock eligibility, certification requirements, and incentive mechanisms across regions. Greater international harmonization of certification systems, transparent carbon accounting, and stable long-term policy support will be essential to accelerate global SAF commercialization and investment.

6.6. Multi-Criteria Sustainability Evaluation of SAF Pathways

Because SAF pathways involve trade-offs among climate mitigation, water use, land occupation, biodiversity, cost, scalability, technology readiness, and social safeguards, a single indicator cannot define the most sustainable option. Life-cycle sustainability assessment (LCSA) provides a broader framework by combining environmental LCA, life-cycle costing, and social LCA. This is particularly relevant for SAF because the pathway with the lowest GHG intensity may not necessarily have the lowest water footprint, biodiversity impact, cost, or social risk. Multi-criteria decision analysis (MCDA) can support SAF pathway ranking by integrating diverse indicators into a structured decision framework. Methods such as technique for order of preference by similarity to ideal solution (TOPSIS), Preference ranking organization method for enrichment evaluation (PROMETHEE), or weighted scoring can compare pathways using criteria including GHG reduction, water scarcity footprint, land-use risk, soil-carbon protection, feedstock circularity, social compliance, technology readiness level, production cost, scalability, and certification readiness [152]. Criterion weighting should be region-specific; for example, water scarcity may receive higher weighting in arid regions, while land-use protection may be more critical in biodiversity-sensitive or agriculturally intensive regions.

A multi-criteria approach also explains why no SAF pathway is universally sustainable. Waste-lipid HEFA may perform well where traceable waste-oil supply chains exist, but its scalability is limited by feedstock availability. Lignocellulosic FT-SAF may provide strong circularity benefits in biomass-rich regions but requires advanced conversion infrastructure and careful residue management. AtJ-SAF may be attractive where low-carbon ethanol or isobutanol is available, but its performance depends on carbon alcohol intensity and upgrading efficiency. PtL-SAF may suit regions with abundant renewable electricity and sustainable CO₂ sources, although high cost and electricity demand remain key limitations. Algae-derived SAF may be promising when wastewater treatment, nutrient recovery, and CO₂ utilization are integrated, but energy balance and scale-up readiness remain critical

challenges [57]. Future SAF deployment should therefore be treated as a portfolio of pathways rather than a single solution. Sustainability assessment should follow a multi-layer framework covering: feedstock sourcing and circularity; conversion-stage impacts such as process energy, hydrogen source, electricity intensity, carbon efficiency, water demand, and co-product handling; broader environmental indicators including land-use change, soil carbon, eutrophication, acidification, air quality, biodiversity, and non-CO₂ aviation effects; and socio-economic feasibility, including technology readiness, production cost, infrastructure compatibility, local employment, social safeguards, certification readiness, and scalability [152].

Future assessments should move beyond static carbon-intensity reporting toward dynamic, regionalized, and decision-oriented methods. Dynamic LCA can address the timing of biogenic carbon uptake and release, while regionalized LCA can improve assessment of water scarcity, land-use change, biodiversity, and soil-carbon effects [156]. Planetary-boundary-based assessment may also become important because relative GHG reduction does not guarantee absolute sustainability [157]. Overall, a credible SAF pathway should demonstrate measurable GHG reduction, responsible feedstock sourcing, low land-use and water risks, soil and biodiversity protection, transparent co-product accounting, economic feasibility, social acceptability, and compliance with recognized sustainability criteria.

Table 3 summarizes the comparative performance of the principal SAF pathways across environmental, economic, and commercialization metrics. HEFA remains the most commercially mature pathway, whereas FT and AtJ offer strong long-term scalability with continued technology development. Although PtL has the potential to achieve the lowest lifecycle carbon intensity, its deployment is currently constrained by renewable electricity and green hydrogen availability, while VFA- and algae-based pathways require further advances in product recovery, process integration, and pilot-scale validation. Despite significant advances, the commercial deployment of SAF remains constrained by high production costs, feedstock availability, renewable hydrogen demand, and capital-intensive conversion technologies. Market expansion also depends on robust supply chains, compatible infrastructure, fuel certification, and supportive policy incentives. While HEFA is commercially mature, emerging pathways such as FT, AtJ, PtL, and VFA-derived SAF require further improvements in process efficiency, cost reduction, and industrial scale-up. Therefore, integrated techno-economic assessment (TEA), life-cycle assessment (LCA), and supportive policy frameworks are essential to accelerate large-scale SAF commercialization.

Table 3. Comparative techno-economic, environmental, and commercialization assessment of major SAF pathways.

SAF Pathway	Typical Feedstock	Carbon Intensity (g CO ₂ -eq/MJ)	Production Cost/MFSP (US\$/L)	Commercial Status	TRL	Scalability	Major Challenges	References
HEFA	Used cooking oil, animal fats, vegetable oils	15–45	0.8–1.3	Commercial	9	High	Limited waste-lipid availability, hydrogen demand, ILUC for virgin oils	[141,145, 148]
Fischer–Tropsch (FT)	Agricultural residues, forest residues, MSW	10–35	1.2–2.5	Demonstration–Commercial	6–8	High	High capital cost, gasification complexity, biomass logistics	[87,147, 158]
Alcohol-to-Jet (AtJ)	Ethanol, isobutanol	20–55	1.1–2.0	Demonstration	6–8	Medium–High	Alcohol production cost, upgrading efficiency, hydrogen demand	[145,147]
Sugar-to-Jet (SIP/DSHC)	Sugars, lignocellulosic hydrolysates	20–50	1.5–2.5	Pilot–Demonstration	5–7	Medium	Feedstock cost, fermentation efficiency, catalyst performance	[147]

Table 3. Cont.

SAF Pathway	Typical Feedstock	Carbon Intensity (g CO ₂ -eq/MJ)	Production Cost/MFSP (US\$/L)	Commercial Status	TRL	Scalability	Major Challenges	References
VFA-to-Jet	Organic waste, volatile fatty acids	15–40 *	1.8–3.5	Laboratory–Pilot	3–5	Low–Medium	Dilute VFA streams, costly product recovery, catalytic upgrading, limited pilot-scale validation	[147]
Algae-to-Jet	Microalgae	20–80	3.0–7.0	Pilot	4–6	Low	High cultivation, harvesting and dewatering costs	[57,147]
Power-to-Liquid (PtL)	Captured CO ₂ + renewable H ₂	<10–30	2.5–6.0	Demonstration	5–7	Medium	Renewable electricity demand, electrolyzer cost, CO ₂ capture cost	[57,150]

Note: Representative values compiled from the cited literature. Carbon intensity and production cost ranges vary depending on feedstock type, process configuration, plant capacity, hydrogen source, electricity mix, geographical location, and life-cycle assessment assumptions. * Values for VFA-to-Jet are indicative because techno-economic and pilot-scale studies remain limited.

7. Research Gaps and Future Perspectives

Despite significant advancements in SAF technologies, critical scientific and engineering gaps hinder large-scale commercialization. A primary challenge is the absence of feedstock-flexible production platforms capable of efficiently processing a variety of renewable carbon sources such as lignocellulosic biomass, organic wastes, algae, waste plastics, and captured CO₂ within a cohesive biorefinery framework. Future research should prioritize maximizing carbon utilization efficiency over optimizing individual conversion pathways. Catalyst development is another essential area of focus. Next-generation catalysts must achieve high activity, long-term stability, resistance to coking and feedstock impurities, reduced hydrogen demand, and efficient regeneration under industrial conditions [159,160]. Additionally, process intensification through membrane-assisted separations, continuous-flow reactors, renewable hydrogen integration, AI-driven optimization, and digital twins presents opportunities to enhance energy efficiency and economic viability. Establishing standardized lifecycle assessment (LCA) and techno-economic assessment (TEA) frameworks is equally crucial for consistent comparison of SAF pathways, considering factors such as feedstock origin, hydrogen source, electricity mix, carbon efficiency, and coproduct allocation [161]. Ultimately, the future of SAF lies in integrated circular-carbon biorefineries that synergistically combine various processes, thereby maximizing renewable carbon recovery and contributing to sustainable aviation.

8. Conclusions

The future of SAF will be determined not by the availability of renewable carbon alone, but by the ability to efficiently convert diverse carbon resources into aviation-grade hydrocarbons through integrated, carbon-efficient production systems. This review demonstrates that no single pathway currently satisfies the combined requirements of feedstock availability, carbon efficiency, economic competitiveness, and industrial scalability. Instead, SAF deployment will rely on complementary technologies, each addressing different aspects of the aviation decarbonization challenge. HEFA remains the most commercially mature pathway but is constrained by sustainable lipid availability. Fischer–Tropsch (FT) synthesis provides exceptional feedstock flexibility yet requires energy-intensive gasification and high capital investment. Alcohol-to-Jet (ATJ) benefits from established fermentation platforms but suffers from carbon losses during upgrading. Lignocellulosic biorefineries maximize biomass utilization through integrated valorization of cellulose, hemicellulose, and lignin, whereas algae and Power-to-Liquid (PtL) technologies offer long-term carbon-neutral po-

tential but remain limited by cultivation costs, renewable electricity demand, and hydrogen availability. Emerging volatile fatty acid (VFA)-based pathways uniquely integrate biological waste valorization with catalytic upgrading, establishing a circular-carbon route that simultaneously mitigates waste emissions and produces aviation-grade hydrocarbons.

Across all production routes, catalyst engineering has emerged as the principal determinant of carbon utilization efficiency, oxygen removal, hydrocarbon selectivity, and fuel quality. Advances in multifunctional catalysts, oxygen-vacancy engineering, and integrated biological catalytic systems have substantially improved molecular upgrading, yet common bottlenecks including feedstock heterogeneity, catalyst durability, renewable hydrogen supply, product separation, process integration, and inconsistent lifecycle assessment methodologies continue to limit commercial deployment. Future SAF development should therefore move beyond optimizing individual conversion pathways toward integrated circular-carbon biorefineries that couple biological, thermochemical, electrochemical, and catalytic technologies within a unified platform. Priorities should include feedstock-flexible processing, durable multifunctional catalysts, renewable hydrogen integration, AI-assisted process optimization, intensified product recovery, and harmonized techno-economic and lifecycle sustainability frameworks. The transition from feedstock-driven to carbon-driven integrated biorefineries represents the next paradigm in SAF development and provides the most promising pathway toward scalable, economically viable, ASTM-compliant fuels capable of supporting a resilient and net-zero aviation sector.

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Abbreviations

AI	Artificial Intelligence
ALD	Atomic Layer Deposition
ASTM	American Society for Testing and Materials
ATJ	Alcohol-to-Jet
BECCS	Bioenergy with Carbon Capture and Storage
BES (BESA)	2-Bromoethanesulfonate (2-Bromoethanesulfonic Acid)
BICCAPS	Bicarbonate-Based Integrated Carbon Capture and Algae Production System
CCU	Carbon Capture and Utilization
CELF	Co-solvent Enhanced Lignocellulosic Fractionation
CH	Catalytic Hydrothermolysis
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
DBTL	Design–Build–Test–Learn
FOGs	Fats, Oils, and Greases
FT	Fischer–Tropsch

GHG	Greenhouse Gas
HDO	Hydrodeoxygenation
HEFA	Hydroprocessed Esters and Fatty Acids
HEFA-SPK	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene
HRT	Hydraulic Retention Time
HTL	Hydrothermal Liquefaction
ILUC	Indirect Land-Use Change
LCA	Life Cycle Assessment
LCB	Lignocellulosic Biomass
LCSA	Life Cycle Sustainability Assessment
MFSP	Minimum Fuel Selling Price
ML	Machine Learning
MCDA	Multi-Criteria Decision Analysis
MSW	Municipal Solid Waste
OLR	Organic Loading Rate
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PtL	Power-to-Liquid
PTJ	Pyrolysis-to-Jet
RCF	Reductive Catalytic Fractionation
RED III	Renewable Energy Directive III
ReFuelEU Aviation	ReFuelEU Aviation Initiative
RLO	Refined Lignin Oil
RW-EDI	Resin-Wafer Electrodeionization
SAF	Sustainable Aviation Fuel
SPK	Synthetic Paraffinic Kerosene
SubMBR	Submerged Membrane Bioreactor
SVM	Support Vector Machine
TAGs	Triacylglycerols
TEA	Techno-Economic Assessment
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRL	Technology Readiness Level
UCO	Used Cooking Oil
VFAs	Volatile Fatty Acids

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