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PERSPECTIVE

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Sustainable Aviation Fuel 2.0: Carbon- and Contrail-Intensity Managed Refineries for Climate-Smart Aviation

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Abstract

Sustainable aviation fuel (SAF) is entering the mandate era while still representing a sub-percent share of global aviation fuel. This Perspective argues that the next bottleneck is not only production capacity, but climate allocation: which carbon sources, hydrogen, renewable electrons and molecular structures should become jet fuel, and where that fuel should be deployed to deliver the greatest avoided climate impact. SAF 2.0 is proposed as a carbon- and contrail-intensity managed refinery–airport architecture that links certified HEFA, Fischer–Tropsch, alcohol-to-jet, power-to-liquid/e-SAF and co-processing modules with molecular finishing, digital monitoring, reporting and verification, and targeted fuel dispatch. In this framework, hydrogen content, sulfur, naphthalene, aromatics and cycloparaffins are treated as design variables affecting soot, non-volatile particulate emissions and contrail-forming potential, rather than as secondary specification details. A Climate Yield Factor is introduced as a screening metric to compare pathways and deployment options by avoided climate impact per unit of scarce carbon, hydrogen, electricity, feedstock and cost. The Perspective closes with an R&D agenda for refinery–airport demonstration hubs able to accelerate SAF scale-up while avoiding first-generation feedstock bottlenecks and volume-only compliance logic.

Keywords: sustainable aviation fuel (SAF), carbon intensity, refinery integration, e-SAF, molecular design, hydrogen management, aviation decarbonization.

1 Snapshot: The SAF Scale Paradox

Sustainable aviation fuel is no longer waiting for legitimacy; it is waiting for a new operating logic. Aviation has few near-term options as practical as SAF for cutting emissions from long-haul flights. Batteries and hydrogen may serve selected segments in the future, but today's wide-body fleets, airport fueling systems, and international routes still depend on energy-dense liquid hydrocarbons. That is why most net-zero aviation scenarios place SAF near the center of the transition, together with efficiency gains, operational measures, and demand-side actions. The difficulty is that deep decarbonization requires not

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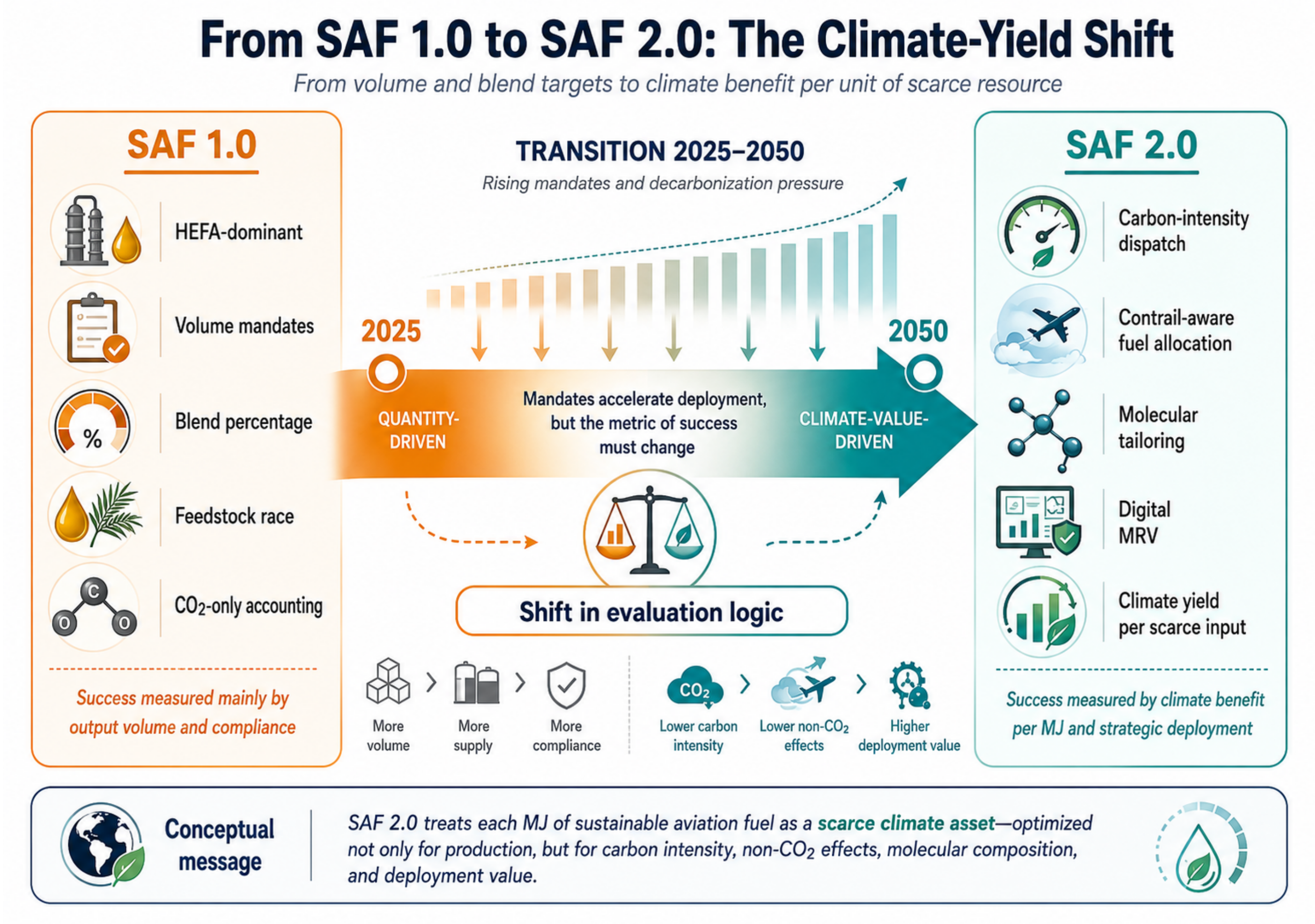

Figure 1. From SAF 1.0 to SAF 2.0: The Climate-Yield Shift.

only lower-carbon kerosene substitutes, but also a strategy that recognizes aviation's non-CO_2 climate effects [1, 2].

The scale gap remains a significant challenge. IATA estimates that SAF could deliver about 65% of the emissions reductions needed for aviation to reach net-zero CO_2 emissions by 2050 [3]; however, reported production was only 1.0 Mt in 2024, about 0.3% of global jet fuel use, and about 1.9 Mt in 2025, roughly 0.6% of demand [3]. Announced projects suggest growth, but not all announced capacity becomes operating capacity. Martulli et al. [4] found that only 24% of announced SAF capacity had been realized on time by 2024, while more than 40% of announced 2030 capacity faced delay or cancellation risk. The key engineering question is therefore shifting: the sector must scale SAF quickly, but it must also avoid using scarce feedstocks, hydrogen, electricity, and capital in low-value ways.

Figure 1 captures this change in evaluation logic. The first SAF deployment wave has been driven mainly by certified pathways, blend targets, and compliance volumes. Those metrics remain necessary, but they are no longer sufficient. In the SAF 2.0 view, each megajoule has to be judged by the climate value it can deliver once carbon intensity, molecular composition, non-CO_2 effects, and deployment context are considered.

Regulation is now moving faster than supply. ReFuelEU Aviation requires SAF shares at EU airports to start at 2% in 2025 and rise to 70% by 2050, with synthetic aviation fuel sub-mandates averaging 1.2% in 2030–2031, rising to 2% in 2032, 5% in 2035, and 35% in 2050 [5]. The United Kingdom follows a similar trajectory, beginning at 2% of total UK jet fuel demand in 2025, increasing to 10% in 2030 and 22% in 2040 [6]. These mandates create demand and reduce investment uncertainty, but they do not decide which carbon source, hydrogen input, conversion route, airport, or flight corridor yields the largest benefit per scarce input. That is the scale paradox: aviation needs more SAF, but the success metric must shift from volume alone to avoided climate impact per MJ [7].

Table 1. Pathway-to-Function Matrix for SAF 2.0

Route / module	Role in SAF 1.0	Main limitation	Proposed role in SAF 2.0
HEFA / CHJ	Near-term commercial paraffinic SAF route [9, 10, 12].	Limited lipid feedstocks; H_2 demand	Low-soot paraffinic fraction for high-climate-value deployment [7, 20].
FT-SPK / FT-SKA	Thermochemical route from biomass, wastes, or CO/CO_2 + H_2 [11, 32].	High CAPEX; syngas complexity	Molecular architecture platform for tailored SAF blending
ATJ / MTJ	Alcohol upgrading route [13, 33, 34].	Alcohol cost; jet-range selectivity	Regional bridge where ethanol/methanol supply is strong
PtL / e-SAF	Long-term synthetic SAF route [16].	Renewable electricity, green H_2, certified CO_2, and cost	Scarce-electron pathway for deep decarbonization
Co-processing	Fast transition route in existing refineries [15, 23].	Carbon attribution; catalyst and contaminant management	MRV-enabled refinery transition platform
SAK / bio-aromatics / cycloparaffins	Emerging functional blending components [14, 26, 35].	Certification and selective synthesis	Compatibility and density adjustment with controlled soot impact

ATJ = alcohol-to-jet; CHJ = catalytic hydrothermolysis jet; FT = Fischer-Tropsch; HEFA = hydroprocessed esters and fatty acids; MRV = monitoring, reporting, and verification; MTJ = methanol-to-jet; PtL = power-to-liquid; SAK = synthetic aromatic kerosene; SKA = synthetic kerosene with aromatics; SPK = synthetic paraffinic kerosene.

2 From Certified Pathways to Climate Function

Certified SAF pathways are no longer the main uncertainty; the harder question is what each pathway is useful for once feedstock, refinery, hydrogen, electricity, certification, and airport constraints are considered together. ASTM qualification and ICAO documentation already cover a broad family of options, including FT-SPK/FT-SKA, HEFA-SPK, CHJ, HC-HEFA-SPK (hydroprocessed hydrocarbons, esters and fatty acids–synthetic paraffinic kerosene), SIP (synthesized iso-paraffins), ATJ-SPK/ATJ-SKA, and co-processing routes certified under ASTM D7566, with finished fuel qualifying under ASTM D1655 [8]. However, approval is only an entry condition. For a fuel to support credible climate claims, sustainability criteria, carbon intensity, feedstock origin, and traceability still have to be demonstrated under CORSIA or related accounting frameworks [8]. This distinction is important in refinery planning. HEFA remains a practical near-term route because lipid hydroprocessing fits existing hydrotreating practice, but lipid supply, renewable diesel competition, feedstock price, and H_2 demand limit its ability to carry the transition alone [9, 10]. FT routes bring a different value: they can convert syngas into jet-range hydrocarbons and, with downstream upgrading, support more tailored synthetic kerosene formulations; yet CAPEX, syngas cleanup, scale, and carbon-efficiency losses remain difficult barriers [11, 12]. Table 1 therefore treats certified and emerging routes not as competing labels, but as functional modules within SAF 2.0.

Taken together, Table 1 shows that SAF 2.0 is not a winner-take-all pathway race. HEFA provides a near-term paraffinic bridge but should be allocated as a low-soot fraction; FT offers molecular architecture; ATJ/MTJ provides regional carbon flexibility; PtL/e-SAF becomes climate-rational only where abundant low-carbon electricity and verified CO_2 are available; and co-processing turns existing refineries into MRV-enabled transition hubs. This functional framing moves SAF selection from pathway labels to marginal climate value under feedstock, hydrogen, electricity, refinery, and airport constraints [13–16].

3 The Hidden Lever: Fuel Composition and Contrails

SAF is usually introduced as a lifecycle-carbon solution, but its most underused lever is molecular. Beyond reducing fossil carbon, SAF can change combustion chemistry, soot formation, volatile particle formation, and therefore the microphysics of contrails. This is crucial because contrails do not form from CO_2; they form when water vapor in the exhaust and ambient atmosphere condenses and freezes on emitted particles under cold, ice-supersaturated conditions. Lower sulfur, lower naphthalene, lower aromatic content, and higher hydrogen content generally reduce the sooting tendency of jet fuel, although the magnitude of the effect depends on the engine, thrust setting, fuel blend, and atmospheric state. Measurements with aircraft engines have shown that aromatic and naphthalene content strongly influence non-volatile particulate matter emissions, while SAF blends with higher hydrogen content and lower complex aromatics can substantially reduce particle mass and number emissions [17–19].

The ECLIF3 campaign provides the clearest experimental basis for this shift. In a controlled in-flight comparison behind an Airbus A350-941 equipped with Rolls-Royce Trent XWB-84 engines, contrails from 100% HEFA-SPK were compared with those from conventional Jet A-1 under similar cruise and ice-supersaturated conditions. The study reported a 56% reduction in contrail ice particle number per mass of fuel burned and a 35% reduction in soot particle number for HEFA-SPK relative to Jet A-1; global modeling conservatively estimated a 26% decrease in contrail radiative forcing when the observed particle reductions were applied to the fleet [20]. The same study linked these reductions to near-zero aromatic and naphthalene content, higher hydrogen content, and much lower sulfur in HEFA-SPK. More recent in-flight evidence further suggests that sulfur can modulate ice crystal formation by affecting volatile aerosols and soot activation, meaning that sulfur control may become increasingly important as engines become cleaner and soot emissions decline [21].

The composition data discussed above still need a practical decision rule. For that reason, Box 1 proposes the Climate Yield Factor (CYF) as a screening metric, not as a compliance method. Its purpose is simple: before a SAF route, batch, or deployment option is promoted, the avoided climate impact should be weighed against the scarce inputs required to obtain it.

Box 1. Climate Yield Factor: A screening metric for SAF 2.0

$$CYF_i = \frac{N(\Delta CO_{2e,WTW,i}) + \alpha N(\Delta EF_{\text{contrail},i}) + \beta N(\Delta EI_{\text{nvPM},i})}{N(H_{2,i}) + \gamma N(E_{\text{ren},i}) + \delta N(F_{\text{scarcity},i}) + \epsilon N(C_{\text{premium},i})} \quad (1)$$

where CYF_i compares pathway, batch, or deployment option i on a normalized basis. The numerator groups the expected benefits: well-to-wake CO_2e reduction, potential reduction in contrail forcing, and lower non-volatile particulate emissions. The denominator groups the penalty side: renewable H_2, renewable electricity, feedstock scarcity, and cost premium. The weighting factors should be transparent and scenario-specific, because contrail forcing depends on aircraft, engine operation, route, weather, altitude, latitude, and time of day.

The metric is deliberately modest. It does not claim that SAF eliminates contrails, nor does it replace CORSIA, ASTM, RED, or airline accounting rules. Its value is to prevent two very different SAF options from being treated as equivalent simply because they have a similar lifecycle CO_2 score. A batch that requires less scarce hydrogen, carries a lower soot-forming fingerprint, and can be used on a route with high contrail-warming potential may deliver more climate value than a larger but less targeted volume. This is consistent with targeted-use modeling by Teoh et al. [7], who showed that allocating limited SAF to flights with the strongest warming contrails could multiply climate benefits, and with Quante et al. [22], who evaluated segregated low-contrail kerosene supply in demonstration flights between Stockholm and Copenhagen. The operational lesson is not to spread scarce SAF thinly everywhere, but to document each batch well enough to place it where its marginal climate benefit is highest.

4 A Carbon- and Contrail-Intensity Managed Refinery

Refineries already have part of the SAF 2.0 hardware: hydrotreaters, hydrogen networks, blending systems, analytical laboratories, storage, logistics routines, and product-release protocols. What they do not yet have is an operating logic that ranks carbon, hydrogen, molecules, certification data, and airport deployment in the same decision space. Figure 2 should therefore be read less as a new process route and more as a refinery–airport control architecture. The refinery selects and verifies carbon inputs, routes them through certified or transitional SAF modules, finishes the product against a defined molecular envelope, and releases the batch with the information needed for climate-aware use. Co-processing and refinery-integration studies support this approach, but also show that catalyst stability, feed variability, hydrogen demand, and carbon attribution must be solved early rather than treated as bookkeeping issues after production [15, 23].

The operating logic can be reduced to four refinery-facing pillars.

Pillar 1. Carbon-quality ledger.
A refinery cannot manage carbon quality if every non-fossil stream arrives under a broad label such as bio, waste, recycled, or captured. Waste oils, residues, off-gases, alcohols, or captured CO_2 can

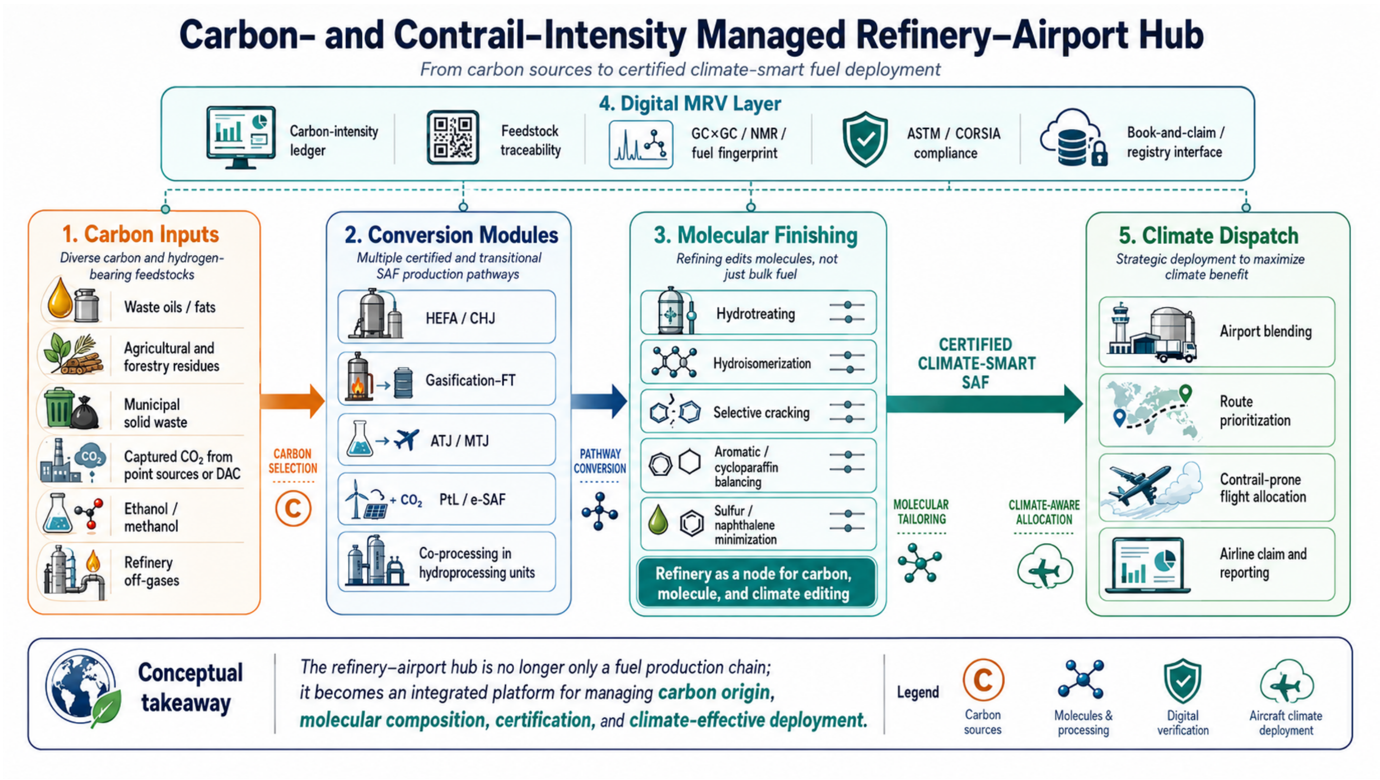

Figure 2. Carbon- and Contrail-Intensity Managed Refinery–Airport Hub.

carry very different land-use histories, logistics burdens, contaminant profiles, alternative uses, conversion losses, and certifiable carbon intensities. A carbon-quality ledger should record feedstock origin, direct and indirect land-use change risks, permanence of recycling or capture claims, sectoral competition, and batch-level carbon intensity (CI), consistent with CORSIA-style life-cycle accounting and with LCA uncertainty studies showing how land-use and allocation choices can reshape the apparent benefit of HEFA-type fuels [24, 25]. Its practical role is simple: rank incoming carbon by climate credibility, traceability, conversion fit, and scarcity before the reactor schedule is fixed, not after the product certificate is written.

Pillar 2. Molecular tailoring.

Once a SAF intermediate reaches the finishing section, the question becomes less about pathway identity and more about release criteria. A SAF 2.0 batch envelope should include GC×GC/NMR or equivalent molecular fingerprints, H/C ratio, total and mono-/polycyclic aromatics, naphthalene, sulfur, density, freezing point, smoke point, viscosity, thermal-stability indicators, and material-compatibility limits. Hydrotreating, hydroisomerization, selective cracking, and controlled blending with cycloalkane-rich or synthetic aromatic components then become operating levers to meet that envelope. Rather than treating molecular composition as a passive outcome of the certified route, the refinery can classify batches by functional use (low-soot paraffinic SAF, density-restored SAF, compatibility-adjusted SAF, or contrail-priority SAF) provided that each claim is backed by analytical fingerprinting, prescreening, and ASTM/CORSIA-compliant documentation [14, 26–28].

Pillar 3. Hydrogen and electron stewardship.

The third pillar is to treat renewable hydrogen and low-carbon electricity as scarce strategic inputs rather than invisible utilities. SAF pathways are often compared by liquid yield or production cost, but deep decarbonization may be constrained by the availability of clean H_2 and renewable electrons: HEFA and co-processing require hydrogen for deoxygenation and saturation; FT and ATJ intermediates require hydrogen for upgrading; and PtL/e-SAF requires large amounts of renewable electricity for electrolysis, with additional energy demands for CO_2 capture, reverse water–gas shift, methanol synthesis, or Fischer–Tropsch synthesis depending on the configuration. Techno-economic and LCA work shows that the climate performance and cost of e-SAF are highly sensitive to renewable electricity, electrolyzer performance, CO_2 source, and system integration [16], while broader analyses of hydrogen-based e-fuels warn that their climate effectiveness is fragile if renewable electricity is scarce, carbon-intensive, or diverted from more efficient uses [29]. A managed refinery should therefore allocate H_2 and low-carbon electrons through a merit-order logic that prioritizes routes and units with the highest marginal climate value. This allocation should incorporate hydrogen pinch analysis, renewable power profiles, marginal electricity CI, and pathway-specific hydrogen efficiency into SAF production scheduling, not merely into the plant utility balance.

Pillar 4. Digital MRV and climate dispatch.
The fourth pillar is to connect production, environmental claims, and deployment through a digital monitoring, reporting, and verification layer. SAF 1.0 MRV mainly verifies whether a certified quantity of SAF was produced, purchased, blended, and claimed without double counting; this remains essential, and recent IATA initiatives (the SAF accounting and reporting methodology and the SAF Registry) provide a foundation for consistent accounting of emissions reductions, SAF transactions, environmental attributes, and claims [30, 31]. For SAF 2.0, that MRV layer should carry more than a volume claim. A useful batch record would combine dynamic LCA, feedstock traceability, GC×GC/NMR or equivalent fuel fingerprinting, ASTM/CORSIA/RED status, book-and-claim information, airport dispatch data, and claim-management rules. In practice, the release document should answer four audit questions: where did the carbon come from, how was the batch converted and finished, what molecular/performance envelope was verified, and where was the fuel ultimately used? That level of documentation would make climate dispatch less of a conceptual promise and more of a controlled logistics decision. Targeted-use modeling and segregated supply demonstrations already indicate that limited SAF can be allocated more effectively when the fuel batch, airport, route, and claim are linked in the same record [7, 22]. The refinery–airport hub proposed here is therefore a practical control point: it does not simply certify a finished SAF volume, but records the carbon, hydrogen, molecular and deployment choices that determine whether that volume delivers high climate value.

5 R&D Agenda and Call to Action

SAF 2.0 will only be useful if it can be tested at the interface between laboratory analysis, refinery operation, airport logistics, and environmental accounting. The near-term agenda should therefore be practical: build common datasets, compare pathways under the same assumptions, and demonstrate that a SAF batch can be traced from carbon source to final deployment. Over the next 18–36 months, five tasks would provide a realistic starting point.

First, the analytical work should start with fuel fingerprinting. Each SAF batch should be described with the measurements that matter for both certification and deployment: GC×GC-resolved hydrocarbon families, NMR-based structural information, H/C ratio, mono- and polycyclic aromatics, naphthalene, sulfur, density, freezing point, smoke point, and selected stability or compatibility indicators. This dataset would allow refinery teams to compare batches before full ASTM testing and to link molecular composition with expected fuel behavior, building on prescreening and GC×GC-based property-prediction work [27, 28].

Second, catalyst and process screening should be benchmarked against climate yield, not only liquid yield. HEFA, ATJ, co-processing, FT liquids, and PtL intermediates should be compared under a common Climate Yield Factor framework that includes jet-range selectivity, hydrogen demand, renewable electricity burden, feedstock scarcity, carbon intensity, soot-relevant composition, and cost premium. This would move catalytic R&D away from isolated maximum-conversion targets and toward pathway-specific climate functionality. Existing TEA and refinery-integration studies provide the foundation, but the next step is to test these routes under identical analytical and MRV assumptions [13, 15, 16, 23, 32].

Third, dynamic LCA and TEA must be coupled from the beginning. Static carbon-intensity values are useful for certification, but insufficient for investment and deployment decisions. SAF 2.0 requires models that integrate CI, cost, hydrogen, electricity, feedstock scarcity, logistics, coproduct allocation, direct and indirect land-use change, and airport proximity. The CORSIA LCA framework already provides an internationally adopted basis for aviation fuel GHG accounting, while uncertainty studies show that methodological choices and land-use assumptions can materially change the apparent climate benefit of SAF pathways [24, 25]. A credible R&D program should therefore report ranges, sensitivities, and marginal climate value, not only single-point emissions numbers.

Fourth, contrail-aware deployment should be treated as a refinery–airport simulation exercise. The task is to combine batch-level fuel fingerprints, SAF inventory, storage and blending limits, aircraft assignments, route structure, forecast meteorology, and claim-management rules in one dispatch model. The output should not be another proof that targeted use can help; that case has already been made in modeling and segregated-supply studies. The useful deliverables include route-prioritization maps, airport blending scenarios, uncertainty ranges for avoided climate impact, and auditable records linking each SAF batch to its final use [7, 22].

Finally, a refinery–airport pilot should be selected as the proof point. The ideal hub would combine an existing refinery or hydroprocessing complex, an international airport, available lipid, residue, alcohol, or captured-carbon feedstocks, analytical laboratories, renewable hydrogen potential, and a digital MRV platform. Latin America is a particularly relevant region for such pilots because it combines feedstock potential, refinery infrastructure, and growing air demand. An MIT CS3 technical assessment of Brazil, Chile, Colombia, Ecuador, Mexico, and Peru found that SAF could offer a significant decarbonization pathway in the region; under an ambitious 1.5 °C scenario with 65% SAF use by 2050, aviation emissions could be reduced by about 60% relative to current-trend projections, but projected SAF costs remain above fossil jet fuel and stable policy frameworks are needed to make investment viable [36].

The next generation of SAF will not be defined only by what it is made from, but by how intelligently its carbon, hydrogen and molecular structure are deployed. In a climate-constrained aviation system, every megajoule of SAF should be treated as a scarce climate asset.

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Conflicts of Interest

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AI Use Statement

The author declares that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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