The Sustainability Dimension for Sustainable Aviation Fuels (SAF): Comparing Regional and International Approaches

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Article

The Sustainability Dimension for Sustainable Aviation Fuels (SAF): Comparing Regional and International Approaches

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Abstract

The deployment of Sustainable Aviation Fuels (SAFs) is central to decarbonizing aviation. However, diverse regulatory frameworks create complexity for SAF market deployment. Differing greenhouse gas (GHG)-reduction thresholds, feedstock eligibility rules and certification systems increase the compliance burden, especially for those operating across regional and international markets. This paper compares an example of regional approach (European) with the international ICAO sustainability certification. The comparison focuses on chain-of-custody models, substantiality principles, GHG accounting methodologies and approaches to ILUC. It highlights the need for harmonized GHG calculation rules, mutual recognition of certification schemes and interoperable traceability systems. Aligning these elements is critical for reducing administrative barriers, supporting market integration and enabling scalable SAF deployment. The analysis aims to assist policymakers, certifiers and producers in developing coordinated and transparent regulatory strategies.

Keywords: sustainable aviation fuels; RED III; CORSIA; life cycle assessment; sustainability certification; RFNBO; ILUC

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1. Introduction

The decarbonization of the aviation sector is becoming a central priority for the industry [1] and many regions, such the European Union, the UK [2], India and Brasil [3], among others [4], are setting specific sector strategies to meet climate neutrality targets by 2050 [5]. At the European level, the EU Green Deal, together with sector-specific legislation such as the ReFuelEU Aviation Regulation [6] and the Renewable Energy Directive (RED III), aims to operationalize the deployment of SAFs within the broader context of energy and transport decarbonization.

Sustainable Aviation Fuels (SAFs) are considered one of the key enablers of this transition, as they offer a significant reduction in greenhouse gas (GHG) emissions compared to conventional jet fuels (Jet A1) [7]. Sustainable Aviation Fuels (SAFs) are non-conventional aviation fuels derived from non-fossil sources. While the term SAF is widely used, other designations such as sustainable alternative fuel, renewable jet fuel or bio jet fuel are often used interchangeably.

SAFs are produced from a variety of renewable resources [8], including waste oils, agricultural residues, municipal solid waste and even renewable electricity combined with captured CO_2, depending on the production pathway (Figure 1). SAFs are considered ”drop-in” fuels, meaning they can be blended with fossil Jet A or Jet A-1 and used without modifications to existing aircraft engines or fuelling infrastructure. The environmental benefit of SAF arises primarily from its potential to reduce net CO_2 emissions, depending on the feedstock and production process, as well as its ability to displace fossil fuels [9].

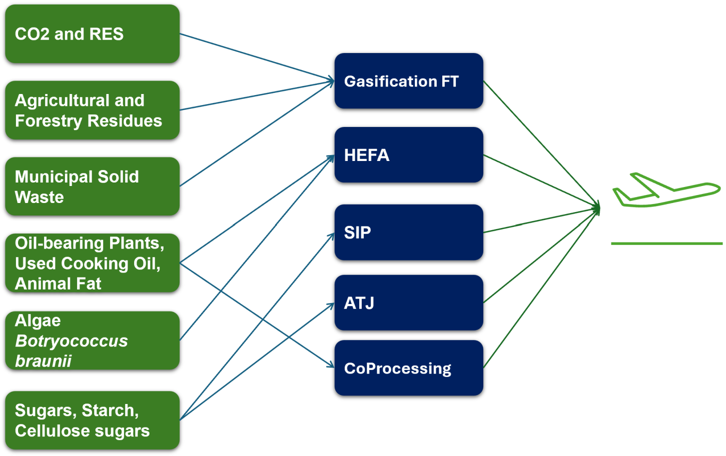

Figure 1. SAF feedstock to process options.

To be used in commercial aviation, an SAF must pass rigorous technical, safety and performance evaluations. This process is governed by ASTM International [10], particularly through the ASTM D4054 and ASTM D7566 standards. ASTM D4054 outlines the protocol for evaluating and certifying new jet fuel formulations, including laboratory tests, rig tests, engine tests and fleet evaluation. If a candidate fuel meets all necessary performance criteria, it is then considered for inclusion under ASTM D7566, the specification for aviation turbine fuels containing synthesized hydrocarbons. Once listed in ASTM D7566, the SAF is recognized as safe for use when blended with fossil jet fuel up to a certified limit—typically 50%, although this may vary depending on the specific pathway. Certified fuels under ASTM D7566 are deemed equivalent to Jet A or Jet A-1 and are thus fully fungible with existing fuel supply chains. This harmonized certification framework is critical not only for ensuring the safety and reliability of aviation operations but also for enabling the commercialization of SAF technologies by allowing them to integrate seamlessly into global fuel-distribution systems.

Currently approved conversion pathways for SAF are defined by three key elements:

- the specific conversion process;
- the applicable ASTM annex or equivalent standard;
- a technical description of the pathway and its associated feedstocks or synthesis routes.

The first category includes Fischer–Tropsch (FT) pathways, such as Gasification FT and CO_2 FT. These thermochemical processes convert carbon-rich materials—like biomass, coal or captured CO_2—into syngas, which is subsequently processed into synthetic paraffinic kerosene (FT-SPK). Certified under Annex A1 of ASTM D7566, these fuels are approved for blending up to 50% with conventional Jet-A due to their excellent performance characteristics.

The Hydroprocessed Esters and Fatty Acids (HEFA) pathway, covered by Annex A2, is the most commercially established SAF technology. It uses renewable lipids (e.g., vegetable oils, used cooking oil, and animal fats), converting them to SPK via hydrogenation and deoxygenation [11]. HEFA-SPK currently represents the dominant share of SAF production globally.

The Synthesized Iso-Paraffins (SIP) pathway, certified under Annex A3, involves hydroprocessing of fermented sugars. Although technically viable, SIP-SPK is limited to a 10% blend ratio due to its lack of aromatic hydrocarbons, which are essential for compatibility with older aircraft fuel systems.

FT-SKA, listed in Annex A4, is a variant of the FT process that includes the production of synthetic aromatics via alkylation. This enables the fuel to meet aromatic content currently required by Jet A1 specifications [12].

Annex A5 includes multiple Alcohol-to-Jet (ATJ-SPK) fuels, produced from alcohols such as ethanol, isobutanol or isobutene through dehydration, oligomerization and hydroprocessing. The ATJ platform offers feedstock flexibility but faces limitations due to the complexity of upgrading and the cost of bio-alcohol production.

Catalytic Hydrothermolysis Jet (CHJ), certified under Annex A6, employs hydrothermal liquefaction to convert wet biomass or oils into an intermediate oil, which is then upgraded catalytically to jet fuel. This method enables the use of high-moisture feedstocks with minimal preprocessing.

The HC-HEFA-SPK route (Annex A7) expands the traditional HEFA platform by using hydrocarbon-based esters and fatty acids, while ATJ-SKA (Annex A8) integrates alcohol synthesis with aromatic production to meet full-specification jet fuel requirements, addressing the aromatic deficiency of standard ATJ-SPK.

In addition to these standalone pathways, ASTM D1655 permits the co-processing of renewable feedstocks—such as esters, FT intermediates or HEFA precursors—within conventional petroleum refineries [13]. These co-processing options offer a cost-effective and scalable interim solution by leveraging existing refinery assets [14]. However, they require rigorous traceability to ensure that the biogenic portion is properly quantified and recognized in sustainability programs such as CORSIA.

Apart from the quality aspects, to be classified as sustainable, aviation fuels must meet a set of established criteria, including significant life cycle greenhouse gas (GHG) emission reductions and the exclusion of feedstocks sourced from land with high carbon stock or biodiversity value. The sustainability of SAFs is strongly influenced by the feedstock utilized for their production, as reported by [15] in a recent review, the large-scale biomass cultivation may lead to indirect land-use change, increased water demand and potential negative impacts on biodiversity. Crucial is the proper design of the whole SAF supply chain; Mohammadi et al. [16] highlighted that integrating decentralized processing with optimized logistics creates a resilient, low-emission biomass supply chain that balances economic efficiency with environmental sustainability. The need to carefully consider the SAF supply chain has also been stressed by Liang et al. [17]: the review highlights that SAF production depends on coordinated management of feedstock sourcing, conversion technology, transportation logistics and airport demand to balance cost, emissions and reliability. The study of Liang et al. concluded that integrating advanced modeling, decentralized processing and supportive policies are essential elements for SAF to become a sustainably scalable alternative to fossil jet fuel.

To address this complexity, sustainability frameworks for alternative fuels have been developed over recent decades for road applications and subsequently extended to other transport modes. In the USA, the biofuel certification framework relies on voluntary, third-party verification systems to ensure that biofuels meet high standards of quality, environmental protection and social responsibility. Programs like BQ-9000, which accredits biodiesel producers and marketers based on ASTM D6751 standards, emphasize rigorous quality control across storage, blending and distribution. Meanwhile, international schemes such as the International Sustainability and Carbon Certification (ISCC) can be used to verify sustainability, traceability and greenhouse gas (GHG) reductions across complex supply chains. Independent audits and adherence to detailed benchmarks provide transparency, signal responsible production to consumers and foster a market that rewards sustainable biofuels, thereby strengthening the growth of a low-carbon energy sector.

In Brazil, the RenovaBio policy serves as the primary framework for biofuel certification, aimed at promoting renewable energy and reducing greenhouse gas (GHG) emissions [18]. Managed by the National Agency of Petroleum, Natural Gas and Biofuels (ANP), the program certifies production units through an efficiency assessment conducted by accredited firms using the RenovaCalc tool. Certified producers receive a Certificate of Efficient Production of Biofuels, which enables them to issue decarbonization credits (CBIOs). These credits are traded on Brazil's B3 stock exchange, creating a market mechanism that compels fossil fuel distributors to meet national emission-reduction targets. By assigning energy-environmental efficiency ratings and facilitating a financial market for low-carbon fuels, RenovaBio supports the decarbonization of Brazil's energy matrix while aligning domestic production with international sustainability standards, such as Bonsucro.

Another relevant example of regional setup is Japan. The country mandates sustainability certification for biomass fuels within its Feed-in Tariff (FIT) system to guarantee that renewable electricity generation is based on environmentally and socially responsible practices. The Ministry of Economy, Trade and Industry (METI) recognizes certification schemes such as the International Sustainability and Carbon Certification (ISCC) Japan FIT and the Roundtable on Sustainable Biomaterials (RSB) Japan FIT, which verify compliance with criteria including reduced greenhouse gas emissions, biodiversity protection and prevention of deforestation. These schemes require producers and traders to meet sustainability standards, maintain a chain of custody that ensures traceability from origin to power generation and undergo independent verification. Once certified, biomass fuels become eligible for FIT incentives, such as subsidies, thereby enabling producers to access Japan's renewable energy support system while promoting responsible production and sustainable market practices.

As a relevant example of the regional level allowing to investigate the details of these complex processes, the European Union approach, as described in the Renewable Energy Directive and its recasts [19], has paved the way. As of today, sustainability frameworks are implemented through Sustainability Certification Schemes (SCSs), both at the European as well as at the international scale.

A robust sustainability certification system is essential to ensure that SAFs deliver genuine climate benefits, avoid unintended environmental and social impacts and are accounted for consistently across regulatory frameworks [20]. In the European context, sustainability certification is governed by the RED and its associated delegated acts [21,22], which establish strict criteria for GHG savings, feedstock eligibility and traceability. Parallel to this, the International Civil Aviation Organization (ICAO) has developed the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which includes a global sustainability framework for SAF eligibility and offsetting purposes [23].

Although both frameworks share a commitment to sustainability, they differ in scope, criteria and implementation. These divergences have practical implications for SAF producers operating in both EU and international markets, especially in terms of compliance pathways, certification strategies and investment decisions.

This paper provides a comparative analysis of a regional approach (i.e., European) and ICAO sustainability certification systems applicable to SAFs, with a particular focus on certification schemes, chain of custody models and greenhouse gas accounting methodologies. The goal of this work is to support SAF producers and policymakers in navigating this complex regulatory landscape and to identify areas for potential harmonization or alignment.

2. Chain of Custody and Traceability

A critical component of sustainability certification systems is the ability to trace the origin and characteristics of sustainable fuels throughout the supply chain. This is accomplished through Chain of Custody (CoC) models, which define how sustainability information is transmitted along the production and distribution process (Figure 2).

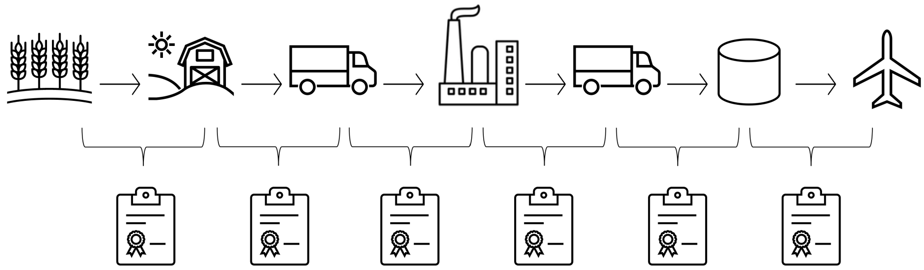

Figure 2. Overview of chain of custody and related documental traceability.

Three main CoC models are used across schemes: Identity Preservation (IP), Segregation (SG) and Mass Balance (MB).

2.1. Identity Preservation (IP)

Identity Preservation is the most stringent CoC model. It ensures that certified products remain entirely segregated from non-certified materials throughout the entire supply chain. Each batch is uniquely traceable back to a specific production site and feedstock lot. While this model guarantees the highest level of traceability and consumer confidence, it is operationally complex and rarely used in fuel supply chains due to cost and logistical constraints.

2.2. Segregation (SG)

Segregation allows certified materials to be pooled with other certified materials, but only if they are certified to the same standard. No mixing with non-certified materials is permitted. This approach ensures that certified output can be confidently attributed to sustainable input, while offering greater flexibility. Documentation under SG must ensure traceability of batches and compliance with certification thresholds.

2.3. Mass Balance (MB)

The Mass Balance approach is the most widely used CoC model in SAF certification. It allows certified and non-certified materials to be physically mixed at any stage in the supply chain, provided that:

- the quantities of certified inputs and outputs are reconciled over a defined time period (e.g., monthly or quarterly);
- the sustainability characteristics (e.g., GHG emissions savings, feedstock type) are tracked and recorded administratively;
- certified output does not exceed the volume or energy content of certified input.

Mass Balance offers a pragmatic solution that supports scalability while maintaining environmental integrity. It is explicitly recognized under Article 30 of RED III [19] and is accepted in the CORSIA framework. Some certification schemes allow for additional constraints (e.g., geographic scope or processing step-level tracking) to enhance assurance.

2.4. Book and Claim

The “Book and Claim” system is a chain of custody model designed to enable the decoupling of physical product delivery from sustainability claims, offering flexibility in how sustainable products, such as SAF, are marketed and consumed. In this system, SAF producers generate certificates (or "claims") for the sustainability attributes of a given volume of SAF, which are then sold separately from the physical fuel. The actual SAF is blended with conventional aviation fuel and enters the general supply chain without being directly allocated to any specific buyer. Instead, airlines or other end users purchase these certificates to claim the environmental benefits of SAF usage, even if the physical fuel is not used in their own operations.

According to various sources (e.g., [24]), this approach enables greater scalability and market access for SAF, especially in cases where logistical or infrastructure constraints prevent physical delivery to certain locations. It also supports early investment and demand signals for SAF production, by allowing buyers in hard-to-reach regions or with lower volumes to contribute to the decarbonization of aviation. Importantly, the environmental integrity of the Book and Claim system relies on robust traceability mechanisms, independent third-party verification and registries that prevent double-counting and ensure transparency in the transaction of sustainability attributes.

When a "Book and Claim" model aligns with international principles for credible chain of custody systems, it can be considered as a complementary mechanism to physical chain of custody models (such as Mass Balance or segregation). As a relevant example, Brazil embraces the Book and Claim accounting system, enabling fuel decarbonization through verified emissions credits even if the physical SAF is not consumed at the point of sale [25].

While CORSIA does not specifically touch on the Book and Claim issue, ICAO considers the adoption of such approaches, noting that chain-of-custody tools like Book and Claim or Mass Balance systems can unlock efficiency and broader uptake by enabling sustainability claims to travel independently of fuel flows [26]. Likewise, the Roundtable on Sustainable Biomaterials (RSB) has already registered its first Book and Claim Unit (BCU) for co-processed SAFs [27].

At the EU level, Article 15(2) of Regulation (EU) 2023/2405 (ReFuelEU Aviation) obliges the European Commission to evaluate whether additional measures should complement the weighted average approach used by aviation fuel suppliers when providing Sustainable Aviation Fuel (SAF) at EU airports. Among the options under consideration is a tradability system, such as a "Book and Claim" mechanism, for aircraft operators and/or fuel suppliers, designed to facilitate SAF supply and uptake. As of today, a final decision about the implementation of such measures has not yet been made public

2.5. Relevance for SAF Certification

Under ReFuelEU Aviation, all SAF volumes counted toward compliance targets must be certified using traceable CoC systems. Most SAFs in the EU market today are certified using Mass Balance, reflecting the need to integrate SAFs into existing infrastructure and blend them with fossil jet fuel (Jet A-1) before distribution [6].

While ICAO allows SAF producers to use any CoC model approved by the certification scheme, it places significant emphasis on documentation, volume reconciliation and the integrity of sustainability claims. Potential needs for dual compliance with both EU and CORSIA systems often requires producers to ensure that their CoC model can satisfy the more stringent of the two frameworks.

As the SAF market matures, there is increasing interest in harmonizing CoC requirements to facilitate trade, reduce audit burden and ensure interoperability between voluntary schemes. Until then, careful design of CoC systems remains a strategic priority for producers and auditors alike.

3. Sustainability-Certification Frameworks

3.1. The EU Sustainability Framework

The European Union's regulatory approach to sustainability certification of alternative fuels is governed by the Renewable Energy Directive (RED), currently in its third revision (RED III) [19]. RED III establishes mandatory sustainability and greenhouse gas (GHG) criteria for biofuels, bioliquids, biomass fuels, renewable fuels of non-biological origin (RFNBOs) and recycled carbon fuels (RCFs). Fulfilment of these criteria is essential for eligibility toward renewable energy targets and access to market incentives.

To operationalize certification, the EU recognizes a series of voluntary Sustainability Certification Schemes (SCSs), such as ISCC EU and RSB EU RED, under Article 30 of the Directive [28]. These schemes must demonstrate conformity with specific EU-recognized principles and verification protocols and they serve as third-party mechanisms to ensure compliance across the fuel-production chain. The schemes check that the fuel producer respects the sustainability criteria set under the EU context, in particular that:

- the production of feedstock for these fuels does not take place on land with high biodiversity;
- the land with a high amount of carbon has not been converted for such feedstock production;
- the biofuel, bioliquid and biomass fuel production leads to sufficient greenhouse gas emissions savings.

To qualify as sustainable, an SAF must demonstrate at least a 70% GHG reduction compared to the fossil comparator baseline of 94 gCO_2eq/MJ [21]. Compliance is assessed through harmonized life cycle assessment (LCA) methodologies, as set out in Commission Delegated Regulation (EU) 2023/1185. Certification bodies verify this reduction through detailed data reporting, including input quantities, energy use, emissions factors and transport distances.

In the RED III, there is a clear differentiation of feedstock categories. Only advanced biofuels—derived from feedstocks listed in Annex IX Part A—along with RCFs and RFNBOs, qualify toward the aviation blending mandates specified in the ReFuelEU Aviation Regulation [6]. Biofuels originating from food or feed crops are explicitly excluded from eligibility as part of the EU's strategy to avoid indirect land-use change (ILUC) impacts.

The background of the ILUC concept is related to the possibility that biofuel production may trigger the need for additional land to cover the feed and food demand, indirectly pushing for a change in the current use of land with potential related CO_2 emissions. To address the issue of ILUC in the Clean Energy for All Europeans package, the revised renewable energy directive introduces a risk-based approach: it sets limits on high ILUC-risk biofuels, bioliquids and biomass fuels with a significant expansion in land with high carbon stock. These limits will affect the amount of the fuels that Member States can count towards their national targets when calculating the overall national share of renewables and the share of renewables in transport. The directive also introduces an exemption from these limits for biofuels, bioliquids and biomass fuels certified as low ILUC risk. For the implementation of this approach, as required by the directive, the Commission adopted the Delegated Regulation (EU) 2019/807. It has to be highlighted that, conversely from other approaches (i.e., CORSIA), ILUC is not calculated under REDII.

Differently from biogenic feedstock-derived SAFs, Renewable Fuels of Non-Biological Origin (RFNBO) have different sustainability criteria to meet. RFNBOs (also referred to as Power-to-Liquid (PtL) fuels, e-fuels or synthetic fuels) are central to the ReFuelEU Aviation Regulation [6], which mandates a progressive incorporation of SAFs, starting at 2% in 2025 and increasing to 70% by 2050. A specific sub-target for synthetic fuels (i.e., RFNBOs) sets minimum blend shares of 0.7% in 2030 and 1.2% in 2032. This underlines the EU's commitment to promoting synthetic fuels that can reduce dependency on crop-based biofuels and scale SAF supply through electrification pathways.

The current EU framework, complemented by Commission Delegated Regulation (EU) 2023/1184, sets strict conditions for the electricity used in RFNBO production. This includes the core principles of:

- **Additionality** —electricity must originate from newly built renewable energy installations, to avoid harmful renewable energy displacement effects;
- **Temporal correlation**—electricity consumption and generation must align within the same month (until 2029) and on an hourly basis thereafter;
- **Geographical correlation**—electricity must be produced within the same bidding zone as the RFNBO facility.

Multiple sourcing scenarios are recognized to determine when electricity qualifies as "fully renewable":

1. Direct connection to a renewable installation with no grid draw;
2. Grid-based sourcing in zones exceeding 90% renewable electricity share;
3. Use of grid electricity with emission intensity < 18 gCO_2eq/MJ, combined with Power Purchase Agreements (PPAs), cancelled Guarantees of Origin (GoOs) and correlation requirements;
4. Electricity-mitigating redispatch of renewable capacity (with operator verification).

Importantly, storage installations cannot be counted as renewable generators. Although renewable electricity sources do not require certification themselves, the RFNBO producer must provide robust documentation demonstrating full compliance with these conditions during certification audits.

RFNBOs are also subject to a minimum 70% GHG savings threshold, calculated using harmonized life cycle assessment (LCA) methodologies [21]. To meet this, producers must not only track the energy source, but also account for transport emissions, and process energy use and carbon inputs.

Regarding carbon sources, the CO_2 used for RFNBO synthesis can originate from:

- **Industrial waste streams**, if subject to carbon pricing (e.g., EU ETS);
- **Biogenic sources**, such as emissions from biofuel fermentation;
- **Atmospheric capture or geological sources**, including geothermal CO_2.

Fossil-based CO_2 may be used only until 2035 and must not be intentionally generated for the sole purpose of fuel production. Fuels derived from intentionally generated fossil CO_2 are not classified as RFNBOs.

Closely related to RFNBOs are Recycled Carbon Fuels (RCFs), also regulated under the same Delegated Acts. While RCFs originate from non-renewable waste streams and do not contribute to the EU-wide renewable energy share, they may count toward national transport targets if they achieve >70% GHG savings and are derived from unavoidable industrial by-products. To qualify, these waste gases must not be intentionally diverted for fuel production.

Together, RFNBOs and RCFs constitute the synthetic fuel categories positioned to complement bio-based SAFs in achieving the EU's aviation decarbonization and climate neutrality goals.

Beyond environmental performance, RED III also enforces social and traceability criteria (e.g., [29]). Economic operators must demonstrate:

- Legal land use and no conversion of high-carbon or high-biodiversity areas.
- Respect for human rights and labor standards.
- Compliance with applicable laws in feedstock origin regions.

- Transparent documentation from point of origin to final fuel production.

Traceability is implemented through mandatory chain of custody systems, among these, Mass Balance is the predominant model used in fuel certification due to its practicality. RED III mandates that the Mass Balance system be robust, documented and subject to third-party audits, which include on-site inspections, record verification and risk-based sampling [29].

Certification bodies approved under voluntary schemes must follow detailed auditing protocols, ensure auditor competence and apply sanctions for non-compliance. Audits cover not only conversion facilities but also upstream operators including farms, collection points, warehouses and transport operators.

The EU's multi-level certification architecture is designed to ensure credibility, transparency and environmental integrity and is continuously updated to reflect evolving sustainability science and geopolitical priorities. For SAF producers, understanding and implementing RED III-compliant systems is a prerequisite for participation in the EU renewable fuels market.

To facilitate harmonized implementation, the European Commission maintains a registry of recognized certification schemes, which must be renewed every five years [30]. These schemes must demonstrate transparency, reliability, auditor competence and full traceability of certified volumes.

3.2. The ICAO CORSIA Framework

At the international level, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), developed by the International Civil Aviation Organization (ICAO), is the primary instrument guiding sustainability criteria for aviation fuels [23].

The framework defines three main categories of fuels:

- **CORSIA Sustainable Aviation Fuels (SAFs)**—renewable or waste-derived fuels meeting the full set of sustainability criteria.
- **CORSIA Lower Carbon Aviation Fuels (LCAFs)**—fossil-derived fuels that meet GHG criteria and some sustainability safeguards.
- **CORSIA Eligible Fuels (CEFs)**—the umbrella term encompassing both SAFs and LCAFs.

CORSIA establishes sustainability criteria that alternative fuels must meet to be recognized as CORSIA Eligible Fuels (CEFs). These criteria include both environmental and social safeguards. In particular, for a fuel to qualify as a CORSIA Sustainable Aviation Fuel (SAF), it must achieve at least 10% GHG emissions savings compared to the baseline fossil jet fuel and must not be produced from biomass sourced from land with high carbon stock or high biodiversity [23].

While GHG thresholds under CORSIA are initially lower than those in the EU RED III, the framework is designed to be progressively strengthened. From 2027 onward, participation in CORSIA becomes mandatory for most ICAO Member States and the sustainability criteria include additional social and environmental dimensions, such as labor rights, water use and biodiversity [23].

A distinguishing feature of the CORSIA sustainability framework is its explicit inclusion of indirect land-use change (ILUC) emissions in life cycle assessment (LCA) calculations. ILUC refers to the displacement of existing land use—typically food or feed production—caused by the expansion of land dedicated to biofuel feedstock cultivation. ICAO provides predetermined ILUC emission factors for eligible fuel-production pathways, based on global economic modelling tools such as GTAP-BIO [31] and GLOBIOM [32].

In addition, CORSIA permits a zero ILUC factor for SAFs produced using low-ILUC-risk feedstocks or practices. These include:

- Use of agricultural, industrial or municipal waste and residues.
- Cultivation of energy crops on degraded, marginal or unused land.
- Implementation of yield-increasing practices that avoid land expansion.

By integrating ILUC considerations into its fuel accounting, CORSIA aims to avoid unintended negative consequences of SAF expansion and ensure that life cycle GHG savings are robust and verifiable. However, growing concerns are expressed by stakeholders, with respect to this quantitavie approach to ILUC [33].

Beyond greenhouse gas (GHG) emission reductions, the CORSIA sustainability-certification framework mandates compliance with a broader set of sustainability criteria. These criteria are verified during the certification of fuel producers and their supply chain operators, to ensure that Sustainable Aviation Fuels (SAFs) are eligible.

CORSIA requires that SAF producers demonstrate adherence to social, environmental and economic safeguards, including but not limited to protection of biodiversity, soil and water resources, food security, land-use rights and respect for human and labor rights. These aspects align with the definitions and structure set forth by ISO 13065 "Sustainability criteria for bioenergy" [34], which CORSIA references to structure its sustainability framework.

Accordingly, sustainability is organized into three hierarchical components (Table 1):

- **Sustainability themes**, which refer to broad areas of concern, such as water quality and availability.
- **Sustainability objectives**, which specify the desired outcome within each theme, e.g., fuel production should maintain or enhance water quality and availability.
- **Sustainability indicators**, which define measurable or observable criteria, such as the implementation of practices that ensure efficient water use and prevent the depletion of surface or groundwater resources beyond natural replenishment rates.

Table 1. Theme, principle and criteria in CORSIA.

Theme	Principle	Criteria
Greenhouse Gases (GHG)	CORSIA SAF should generate lower carbon emissions on a life cycle basis	CORSIA SAF will achieve net greenhouse gas emissions reductions of at least 10% compared to the baseline life cycle emissions values for aviation fuel on a life cycle basis.

The ICAO's CORSIA framework defines 14 sustainability themes that must be addressed for a fuel to be considered a CORSIA Eligible Fuel (CEF) (Figure 3). These themes are grouped into three main categories: carbon reduction, environmental and socio-economic. Each theme is supported by a specific principle ensuring that fuel production contributes to climate mitigation, environmental protection and social responsibility. These themes provide a comprehensive framework that ensures that CORSIA Eligible Fuels are not only effective in reducing aviation-related emissions but also contribute to broader goals of environmental protection and social equity.

Compliance with these sustainability elements is assessed through third-party audits carried out by CORSIA-approved Sustainability Certification Schemes (SCSs).

Certification under CORSIA is performed by schemes approved by ICAO, which assess fuel batches for compliance with sustainability, traceability and GHG performance criteria. These schemes must adhere to ICAO's guidance on life cycle assessment (LCA), which specifies the use of a well-to-wake boundary for emissions accounting [35]. As of today, three schemes are approved: ISCC CORSIA [36], RSB [37] and ClassNK [38].

This structured and standards-based approach enables CORSIA to promote not only climate mitigation but also holistic sustainability in the global deployment of alternative aviation fuels.

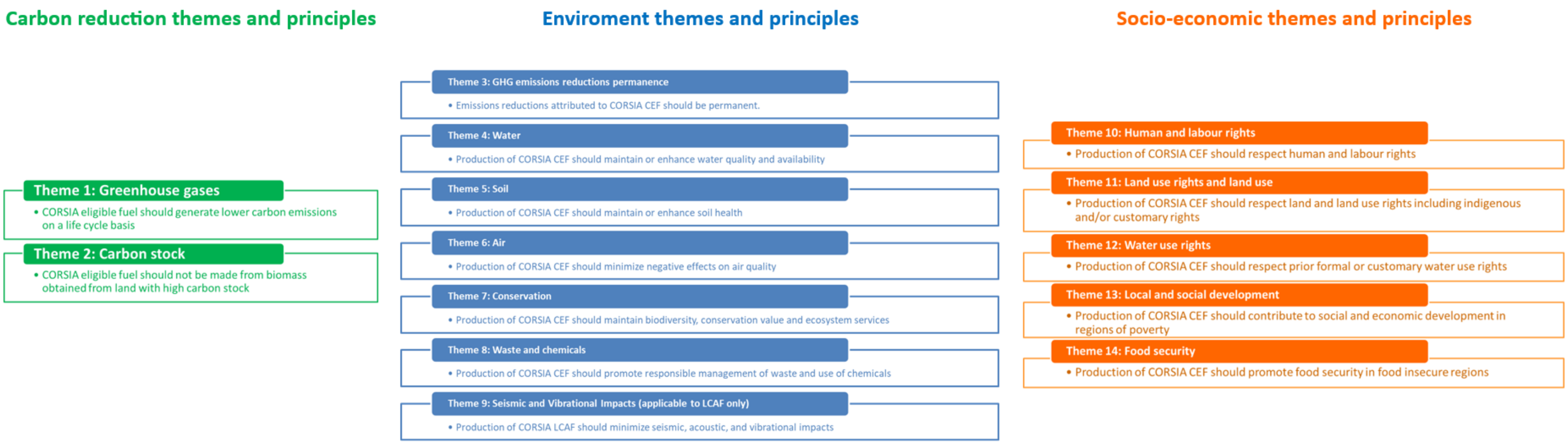

Figure 3. CORSIA sustainability elements.

3.3. Comparison of EU and ICAO Requirements

The European Union (EU) and the International Civil Aviation Organization (ICAO) through its CORSIA framework have both established systems to certify the sustainability of alternative aviation fuels. While they share the overarching goal of reducing greenhouse gas (GHG) emissions from aviation by promoting sustainable fuels, their approaches differ in structure, scope, criteria and implementation mechanisms (Table 2). These differences have significant implications for fuel producers seeking recognition under both regimes.

Table 2. Comparison of sustainability certification requirements: EU vs. CORSIA.

Aspect	EU (RED III/ReFuelEU)	CORSIA (ICAO)
Environmental Criteria	Strict no-go land rules, ILUC risk feedstock caps, mandatory LCA	Principle-based, ILUC defaults, broader feedstock flexibility
Social Criteria	Defined via voluntary schemes	Mandatory themes (e.g., labor rights, food security)
Certification Body	EU-recognized Voluntary Schemes	ICAO-approved SCS (i.e, ISCC, RSB and ClassNK)
Verification Model	Annual audits, traceability, EU registry (UDB)	Traceability templates, CORSIA registry, MRV
Chain of Custody	Mass Balance, segregation, supply chain documentation	Mass Balance or segregation, supply chain documentation
Scope of Certification	Fuel type + feedstock + land origin	Fuel + process + compliance with sustainability themes

3.3.1. Regulatory Scope and Legal Structure

The EU sustainability framework for fuels is anchored in binding legislation through the Renewable Energy Directive (RED III), supported by delegated and implementing acts that specify methodological details and compliance requirements. This legislative architecture applies to all EU Member States and is deeply embedded within the broader EU climate and energy policy (e.g., ReFuelEU Aviation).

In contrast, CORSIA operates as an international market-based mechanism under the auspices of ICAO, agreed upon by its Member States. Its legal character is less binding and relies on voluntary commitments transitioning to mandatory participation over time (phased implementation through 2027–2035). CORSIA defines eligibility rules for fuels used to offset international aviation emissions but does not directly regulate blending obligations or national targets.

3.3.2. GHG Accounting and Emissions Thresholds

Greenhouse Gas (GHG) accounting is a crucial step in assessing the sustainability of SAF production. A recently published global bibliometric analysis by Li et al. [39] on Life Cycle Assessment (LCA) highlighted how the field has become a key framework for greenhouse gas (GHG) accounting and climate policy. The authors show that LCA research has grown almost exponentially since 2000, with strong focus on quantifying carbon footprints, global warming potential and other GHG metrics as core indicators of environmental performance. Keyword trend analysis reveals an increasing emphasis on carbon footprint, greenhouse gas emissions and climate change as central themes, reflecting a shift from purely methodological debates to application-driven studies that inform low-carbon strategies across sectors. Specifically about SAF, the study by Zhang et al. [40] expands the discussion of life cycle assessment (LCA) and GHG accounting by applying these methods specifically to bioenergy and aviation fuel pathways. It emphasizes that accurate greenhouse gas inventories require cradle-to-grave system boundaries, inclusion of upstream land-use change emissions and careful allocation of co-products to avoid underestimating climate impacts. The study shows how feedstock variability, transport distances and conversion efficiencies drive most of the carbon footprint and compares alternative supply chain configurations to reveal opportunities for lowering emissions through optimized logistics and renewable energy inputs. It also highlights that harmonized datasets and transparent uncertainty treatment are critical for ensuring comparability of SAF GHG results across regions and technologies, reinforcing earlier bibliometric findings that data quality and methodological consistency remain key barriers to reliable, policy-relevant LCA.

This studies highlight the need for a harmonized accounting methodology and clear thresholds for defining sustainability elements. As anticipated, both EU and ICAO frameworks defined specific GHG accounting methodologies; RED III mandates a minimum of 70% GHG savings compared to a fossil fuel comparator of 94 gCO_2eq/MJ for all fuels eligible under the aviation blending mandate. The GHG performance is calculated using harmonized life cycle assessment (LCA) rules laid out in Delegated Regulation (EU) 2023/1185. These rules specify inputs, emissions factors, transport stages and co-processing methods in a consistent format applicable across Member States.

CORSIA, by contrast, requires a lower threshold: a minimum of 10% GHG savings compared to conventional jet fuel (89 gCO_2eq/MJ) but it includes ILUC. The GHG calculations under CORSIA follow a "well-to-wake" boundary and rely on default or actual values, based on ICAO-approved methodologies [35].

3.3.3. Feedstock Eligibility and Fuel Classification

Under RED III, only fuels produced from specific feedstock categories are eligible for compliance, particularly advanced biofuels (Annex IX Part A). Conventional biofuels from food or feed crops are excluded from aviation targets. RFNBOs must meet strict conditions related to electricity sourcing (e.g., additionality, temporal/geographical correlation), while RCFs must be derived from unavoidable industrial waste streams.

CORSIA adopts a broader definition of eligible fuels. It allows the use of a wider range of feedstocks, provided they meet sustainability criteria related to land use, carbon stock and social safeguards. The following are CORSIA Eligible Fuels (CEFs): SAFs and Lower Carbon Aviation Fuels (LCAFs), each with specific sustainability elements.

A practical example of illustrating the implication of the differences among the international and regional approaches is the use of food crops. Produced on extensive areas and with high agricultural mechanization,in many regions, these feedstocks fully aligned with the HEFA (Hydroprocessed Esters and Fatty Acids) conversion pathway and they are compatible with coprocessing in existing refineries. Certified under ASTM D7566 and supported by traceability frameworks, vegetable oils offer a robust, scalable short-term feedstock for Sustainable Aviation Fuel (SAF). However, while these are fully compatible with the ICAO scheme, they cannot be used to produce SAF for the EU market.

3.3.4. Treatment of Indirect Land-Use Change (ILUC)

One of the most notable differences lies in how the two systems address indirect land-use change (ILUC). CORSIA explicitly incorporates ILUC into its LCA framework using model-based default values from GTAP-BIO and GLOBIOM. It also recognizes "low-ILUC-risk" practices that qualify for a zero ILUC factor, such as use of waste/residues or production on degraded land.

By contrast, ILUC is not quantified in RED III's GHG calculations. Instead, the EU uses a risk-based regulatory approach. High-ILUC-risk fuels (e.g., derived from palm) are not allowed against aviation targets, while low-ILUC-risk biofuels, demonstrated through improved agricultural practices, are exempt from these restrictions.

In the EU context, there are specific provisions to exclude high-risk feedstock, such as palm oil. While this is not the case in CORSIA, it is worth noticing that the default ILCU value implies the potential risk of this feedstock, resulting in a fairly high value: 39.1 gCO2e/MJfuel

This distinction underscores a philosophical divergence: CORSIA quantifies ILUC, whereas the EU controls it via supply-side restrictions and delegated regulation (e.g., EU 2019/807). It is worth noticing that the International Maritime Organization (IMO) decided to adopt, for its marine fuels LCA guidelines [41], a risk-based approach.

3.3.5. Sustainability Criteria and Social Safeguards

Both systems go beyond GHG performance to include social and environmental sustainability. RED III requires compliance with a wide range of sustainability principles, including protection of high-carbon-stock lands, legal land use, respect for human rights and traceability throughout the supply chain.

CORSIA similarly mandates sustainability safeguards, grouping them into broad themes such as water, land, labor and social development. These themes are operationalized through objectives and measurable indicators. These requirements must be verified through approved Sustainability Certification Schemes (SCSs), which independently assess compliance. For example, in relation to human and labor rights, CORSIA requires that all production respects workers' rights and ensures fair treatment. Under the theme of land-use rights, producers must respect both formal and informal land tenure, including indigenous and customary rights. Similarly, water-use rights must be safeguarded, with certification confirming that local and indigenous communities' prior or customary access to water is upheld. Beyond resource rights, CORSIA integrates broader social objectives: production activities should support local and social development by improving socio-economic conditions in regions affected by poverty, while also safeguarding food security by ensuring that biofuel production in food-insecure areas does not undermine, and ideally enhances, local food availability. Together, these safeguards covering human, environmental and social dimensions establish a comprehensive sustainability framework, ensuring that aviation fuels under CORSIA contribute to emissions reductions without causing unintended negative impacts.

3.4. Data-Reporting Systems

The European Union has established the Union Database (UDB) [42], a centralized digital platform designed to monitor the life cycle and sustainability of biofuels and Renewable Fuels of Non-Biological Origin (RFNBOs). The UDB records transactions across the supply chain to prevent double counting, supports the implementation of Mass Balance chain of custody systems and enables verification of compliance with the sustainability and greenhouse gas (GHG) reduction requirements under the Renewable Energy Directive (RED). All certified parties, including economic operators, voluntary schemes and certification bodies, are mandated to submit data, thereby ensuring traceability across national borders and throughout the supply chain.

In parallel, the International Civil Aviation Organization (ICAO) has developed the CORSIA Central Registry [43], which is used to track emissions, offsetting obligations and Sustainable Aviation Fuel (SAF) usage by aircraft operators. The registry collects data through the Monitoring, Reporting and Verification (MRV) process, as submitted by national authorities. This includes details on the volume and characteristics of CORSIA-eligible fuels used by airlines. However, unlike the EU UDB, the CORSIA Registry does not record transaction-level data across the supply chain. Its primary function is emissions accounting and monitoring SAF uptake, rather than ensuring supply chain traceability.

While the EU UDB offers granular, transaction-level data for both fuels and feedstocks to support robust traceability and sustainability verification, the CORSIA Registry focuses more on aggregated emissions data and SAF deployment by operators, with limited emphasis on supply chain-level reporting.

4. Policy Implications

The evolving landscape of sustainability certification for Sustainable Aviation Fuels (SAFs) presents both regulatory challenges and market opportunities for producers operating regionally (e.g., European Union) and internationally [44].

One of the key challenges faced by SAF producers is navigating divergent sustainability criteria and certification requirements. The EU imposes stringent greenhouse gas (GHG)-reduction thresholds (≥70% for RFNBOs and RCFs) and feedstock restrictions (excluding food and feed crops) [19], whereas CORSIA has lower entry thresholds, ILUC calculation and a broader feedstock eligibility [23]. This dual system may require producers to pursue separate certification pathways, duplicating administrative efforts and increasing compliance costs. The interplay between regional and international initiatives creates a complex environment for operators.

Additionally, the differences in audit cycles, recognition procedures and accepted methodologies for GHG calculations increase the uncertainty and resource burden for SAF producers, particularly for small and emerging players who may lack the institutional capacity to manage multi-scheme compliance.

A move toward harmonization—such as mutual recognition of schemes, alignment of GHG calculation principles or interoperability of digital traceability systems—would reduce duplication and foster greater scalability of SAF deployment. Without convergence, regulatory fragmentation risks undermining the climate credibility, economic efficiency and global trade of sustainable aviation fuels.

4.1. Opportunities and Strategic Levers

Despite the regulatory fragmentation, SAF producers can capitalize on early compliance and dual certification as a market differentiator. Producers who align proactively with both RED III and CORSIA standards are better positioned to access public support mechanisms (e.g., mandates, subsidies, blending quotas, etc.) and to participate in carbon credit schemes and international fuel trade.

The progressive incorporation targets under ReFuelEU Aviation, starting from 2% in 2025 and reaching 70% in 2050, offer a long-term market signal that encourages investment in certified SAF-production capacity [6]. Meanwhile, the evolving stringency of CORSIA post-2027 may close the gap with RED III, enabling certification schemes to converge over time.

The deployment of harmonized digital traceability systems, also presents an opportunity to streamline compliance across jurisdictions, reduce audit costs and enhance transparency for end users and regulators alike.

4.2. Recommendations for Harmonization

To reduce regulatory friction and promote global SAF deployment, several harmonization measures should be considered:

- **Establish common baseline sustainability criteria** for SAFs across regional and CORSIA frameworks, particularly for GHG reduction thresholds, land-use safeguards and social principles.

- **Promote mutual recognition of certification schemes** that demonstrate equivalence in verification, auditing and traceability standards.
- **Align standardised methodologies** for life cycle GHG emissions accounting, including default values and treatment of co-products, etc.
- **Support digital integration** of chain-of-custody systems via interoperable registries and secure, auditable data infrastructure.
- **Facilitate capacity building for small producers** to ensure inclusive access to certification and market participation.

By pursuing regulatory alignment and fostering technical interoperability, both the EU and ICAO can accelerate the deployment of SAFs in line with climate targets, while safeguarding environmental integrity and market transparency.

5. Conclusions

Sustainable Aviation Fuels (SAFs) play a vital role in achieving decarbonization targets in the aviation sector, both within the European Union and at the global level. Ensuring that SAFs deliver verifiable environmental benefits requires robust and transparent sustainability-certification frameworks. This paper has reviewed and compared two relevant systems currently in place: the EU's Renewable Energy Directive (RED III), as an example of a regional scheme, and ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

As the SAF market is rapidly evolving, the sustainability certification is a foundational pillar for participating in and benefiting from this transformation. While both frameworks share the common objective and several important methodological approaches, from an SAF producer perspective there are significant operative differences, for instance in their stringency and implementation mechanisms. RED III imposes more rigorous greenhouse gas (GHG) thresholds and restricts feedstock eligibility, while CORSIA allows for broader inclusion with lower initial GHG requirements. These divergences pose challenges for SAF producers, especially those seeking access to both regulatory markets.

A central focus of this analysis has been the role of certification schemes and chain-of-custody models in ensuring compliance. Most SAF producers currently adopt Mass Balance due to its practicality and compatibility with blended fuel infrastructure, though future developments may drive increased use of more granular tracking systems. Book and Claim is currently under discussion, as it potentially facilitates logistics, allowing for a wider adoption of SAF.

Looking forward, greater harmonization between regional and ICAO frameworks is essential to streamline certification efforts, lower administrative barriers and foster cross-border SAF trade. Aligning GHG accounting methods, sustainability safeguards and digital traceability systems would not only benefit producers but also strengthen consumer confidence and policy coherence.

The policy and market momentum behind SAFs is accelerating. Aligning certification requirements and providing consistent regulatory signals will be instrumental in ensuring that SAF deployment meets both climate goals and sustainability standards, while enabling producers to operate competitively at a global scale.

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Abbreviations

The following abbreviations are used in this manuscript:

SAF	Sustainable Aviation Fuel
RED III	Renewable Energy Directive (Recast, version III)
ICAO	International Civil Aviation Organization
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
RFNBO	Renewable Fuel of Non-Biological Origin
RCF	Recycled Carbon Fuel
ILUC	Indirect Land-Use Change
SCS	Sustainability Certification Scheme
CoC	Chain of Custody
IP	Identity Preservation
SG	Segregation
MB	Mass Balance
CHJ	Catalytic Hydrothermolysis Jet
FT	Fischer–Tropsch
ATJ	Alcohol-to-Jet
SIP	Synthesized Iso-Paraffins
HEFA	Hydroprocessed Esters and Fatty Acids
SPK	Synthetic Paraffinic Kerosene
UDB	Union Database
MRV	Monitoring, Reporting and Verification
ISCC	International Sustainability and Carbon Certification
RSB	Roundtable on Sustainable Biomaterials
PtL	Power-to-Liquid
GoO	Guarantee of Origin
ETS	Emissions Trading System

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