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Beyond SAF Certification: Reconciling ISCC CORSIA and ISCC EU through Life-Cycle Carbon Accounting, Feedstock Eligibility and Double-Counting Prevention in International Aviation

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Abstract

The international expansion of sustainable aviation fuel (SAF) has exposed a critical distinction between sustainability certification, quantified life-cycle greenhouse gas reductions, and legal recognition of those reductions. This qualitative literature review examines the relationship between ISCC CORSIA and ISCC EU, emphasizing their different regulatory purposes, life-cycle assessment methods, feedstock criteria, and controls against duplicate environmental claims. Drawing on 64 journal articles published during 2020-2026 and authoritative ICAO and European Union documents, the review synthesizes six themes: certification non-equivalence, carbon-intensity methodology, feedstock eligibility, chain-of-custody integrity, market implications, and institutional interoperability. The analysis identifies a recurrent governance error: treating possession of a recognized certificate as sufficient proof that the same emissions benefit can be claimed under multiple compliance or voluntary frameworks. It proposes a three-gate model that separates qualified physical fuel, regime-specific life-cycle calculation, and exclusive claim entitlement. Particular attention is given to the differentiated legal treatment of palm-derived materials, including palm fatty acid distillate, palm oil mill effluent, and empty palm fruit bunches. A linked physical-batch and claims-ledger architecture, supplemented by minimum evidence datasets and transparent regulatory mapping, is advanced as a practical alternative to automatic certificate equivalence. The review concludes that cross-border SAF recognition depends on auditable data exchange, explicit jurisdiction-specific eligibility decisions, and prevention of double issuance, double use, and double claiming, rather than universal acceptance of any one sustainability certificate.

Keywords: Sustainable Aviation Fuel, ISCC Corsia, ISCC EU, Life-Cycle Assessment, CORSIA Eligible Fuels, ReFuelEU Aviation, Feedstock Sustainability, Double Counting, Chain of Custody, Regulatory Interoperability.

Introduction

International aviation confronts a structural decarbonization problem that differs from the challenge faced by many terrestrial transport sectors. Long-range aircraft require energy-dense fuels, existing fleets turn over slowly, and the production of credible low-carbon liquid substitutes is constrained by feedstock, conversion capacity, renewable electricity, hydrogen and capital. Sustainable aviation fuel (SAF) is therefore often treated as a near-term bridge between the current fleet and future technologies, but neither the description of a fuel as sustainable nor its physical compatibility with aircraft establishes the magnitude of its net climate benefit. The relevant climate assessment must consider upstream production, processing, transport, land-use effects and the rules for assigning environmental attributes to the entity making a compliance claim. These complications make SAF simultaneously an engineering product, a life-cycle accounting object and a regulated environmental claim [1-4]. The rise of multiple SAF certification systems intensifies that problem. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), administered through the International Civil Aviation Organization (ICAO), provides an internationally coordinated framework for eligible fuels and aviation emissions compliance. The European Union, by contrast, combines the Renewable Energy Directive (RED), ReFuelEU Aviation and the EU Emissions Trading System (EU ETS), each with distinct legal purposes and accounting consequences. ISCC CORSIA and ISCC EU provide certification within different regulatory settings: a supplier's ability to demonstrate conformity under one does not, by itself, establish that a fuel is eligible, receives the same carbon-intensity value, or creates the same compliance benefit under the other. Their relationship is one of partial technical overlap rather than interchangeable legal authority [5-8].

This distinction matters increasingly as SAF producers serve airlines whose operations span several regulatory jurisdictions. A single physical batch can acquire laboratory fuel-qualification documents, sustainability audit records, feedstock provenance data, life-cycle calculations, mass-balance records, and evidence

of delivery. Yet those documents answer different questions. Technical qualification addresses whether a fuel may be used safely; sustainability certification verifies conformance with a specified scheme; life-cycle analysis estimates emissions under defined assumptions; and compliance accounting determines whether, when and by whom an environmental benefit may be reported. The research problem arises when actors compress these separate steps into a single statement that a certified SAF shipment has necessarily generated a universally recognized reduction in aviation emissions [9-12]. The importance of carefully distinguishing emissions reduction from emissions-reduction recognition is not merely semantic. A life-cycle emissions estimate expressed in grams of carbon dioxide equivalent per megajoule is an analytical result, whereas a reduction counted toward an airline's CORSIA obligations or an EU supplier's aviation mandate is a rule-dependent compliance outcome. An airline that purchases environmental attributes through a voluntary book-and-claim arrangement may possess a contractual claim that is meaningful under that program without thereby obtaining the same evidentiary standing for every statutory reporting purpose. Conversely, the use of physical SAF at an airport does not authorize two independent parties to assert the same exclusive life-cycle benefit. Double issuance, double use and double claiming can therefore compromise environmental integrity even when the fuel itself is genuine [13-16].

Life-cycle divergence adds a second layer of complexity. CORSIA uses its prescribed life-cycle emissions methodologies and an aviation fossil reference; EU rules apply their own sustainability and emissions-saving methodologies, including relevant energy and feedstock restrictions. Results may differ when the same input is modeled with different assumptions about direct or indirect land-use change, co-product allocation, waste or residue treatment, electricity sources, hydrogen production and counterfactual land management. Such methodological differences do not necessarily indicate that one certification is fraudulent or technically unsound. They can reflect genuinely different statutory objectives and boundary choices, although they make simplistic comparison of headline percentage savings scientifically indefensible [5,17-19]. Feedstock eligibility is especially consequential for palm-oil-producing countries, including Indonesia. A formulation that treats all palm-derived SAF routes as equally eligible or uniformly excluded under European rules is inaccurate. Oil palm feedstock discussions must distinguish crop oils and certain processing derivatives from materials that may fall within the EU's specified waste and residue categories. Palm oil mill effluent (POME) and empty palm fruit bunches (EFB), for example, have different regulatory characteristics from palm fatty acid distillate (PFAD). Their possible acceptance depends on classification, origin, documentation, the applicable pathway and current regulatory instruments, not on a broad commodity label. These distinctions create a practical research agenda for feedstock recognition, traceability and export competitiveness [20-23].

The review consequently asks whether international SAF climate governance can recognize scientifically defensible life-cycle reductions across borders while preserving the distinct authority of each legal system and preventing multiple incompatible claims over the same environmental attribute. Its specific objectives are to compare ISCC CORSIA and ISCC EU, identify sensitive life-cycle and feedstock decisions, examine the mechanics of double counting, evaluate market and distributional consequences, and propose a governance architecture relevant to ICAO technical work and national aviation regulators. The paper advances the proposition that trustworthy interoperability is possible only if certification status, emissions valuation and claim entitlement are managed as three separate but linked decisions. The analysis is qualitative and interpretive rather than an empirical measurement of observed fraud or a quantitative estimate of SAF market outcomes [4,10,11,24].

Literature Review

SAF as a Technological and Institutional Object

The SAF literature describes several production pathways, including hydroprocessed esters and fatty acids (HEFA), Fischer-Tropsch synthesis, alcohol-to-jet, catalytic conversion and power-to-liquid fuels synthesized from renewable hydrogen and captured carbon. The technological diversity matters because feedstock requirements, energy intensity, readiness and process emissions differ materially between pathways. HEFA pathways can exploit established hydroprocessing practices, whereas many lignocellulosic and synthetic routes face more demanding scale-up or input-energy constraints. A single policy category called SAF thus encompasses heterogeneous industrial systems whose climate impacts depend on their entire supply chain. Research on commercialization and technology deployment repeatedly identifies feedstock availability, cost, conversion efficiency and infrastructure as interacting constraints rather than problems that can be solved by the issuance of a sustainability certificate alone [25-30]. Several techno-economic studies illustrate why a credible certification debate must be connected to production realities. Hydrothermal liquefaction, catalytic hydrothermolysis and refinery co-processing can yield alternative feedstock and processing configurations, but their environmental performance depends on integration, energy sourcing and the treatment of co-products. Forest residues, lignocellulosic materials and other potentially lower-conflict feedstocks differ in collection and transport intensity, while microalgal pathways confront questions of cultivation energy and industrial scaling. These studies are not direct assessments of certification equivalence; their contribution is to show why credible policy recognition requires pathway-specific underlying data instead of a blanket declaration that an approved technology necessarily has a fixed environmental benefit [31-35].

Alternative and synthetic fuel pathways further expose the need to distinguish a fuel's chemical identity from its climate identity. Power-to-liquid fuels can be produced using captured carbon dioxide and hydrogen, but their net emissions depend strongly on the electricity system, electrolysis efficiency, carbon source, plant operation and capital intensity. Hydrogen price trajectories are uncertain and affect the feasibility of compliant synthetic SAF supply. The mere presence of synthetic molecules or captured carbon in the process does not establish negligible life-cycle emissions. An environmental claim must therefore identify the actual or legally recognized emission factors applied to hydrogen, electricity, captured carbon and downstream operations [36-43]. Technological approval also occupies a different regulatory layer from carbon recognition. Aircraft fuel standards and qualification procedures determine whether alternative components may be blended and safely used in current aviation systems. Combustion and particle-emissions studies address relevant atmospheric and non-CO2 performance aspects, but they cannot be substituted for formal greenhouse gas life-cycle evaluation. Moreover, a technology's potential to reduce soot or contrail-related effects, although climatically important, should not be converted into a CORSIA life-cycle carbon-intensity credit unless the applicable

methodology expressly authorizes that treatment. Such distinctions preserve analytic consistency between physical climate impacts, the accounting scope of aviation policies, and legally recognized savings [9,44-48].

The Regulatory Foundations of Corsia and the EU Framework

ICAO's CORSIA framework addresses eligible aviation fuels through a defined system of sustainability criteria, recognized sustainability certification schemes and life-cycle emissions calculations [49,50]. The CORSIA fossil aviation-fuel reference value is 89 gCO2e/MJ, and the applicable framework specifies the minimum life-cycle reduction required for a CORSIA eligible sustainable aviation fuel. However, stating a threshold without checking the relevant edition of ICAO implementation material or the fuel category would risk freezing an evolving framework. For analytical purposes, the decisive issue is that ICAO prescribes the basis on which a CORSIA fuel-related reduction may be calculated and verified. The analysis of its policy effectiveness must also account for the way fuel use interacts with CORSIA offsetting requirements, rather than treating an eligible fuel certificate as a tradable offset credit [5,8,24]. The EU framework distributes obligations differently. The RED defines relevant sustainability and greenhouse gas rules and provides the basis for recognized voluntary sustainability certification [51,52]. ReFuelEU Aviation sets aviation-specific supply obligations and additional definitions or exclusions that must be considered when determining what qualifies toward aviation targets. The EU ETS is an emissions trading instrument governing covered operators and routes; its recognition provisions are not identical to a fuel-supply mandate [53]. Therefore, an ISCC EU certificate can provide important RED documentation while leaving a further question of ReFuelEU eligibility or EU ETS monitoring and reporting to be determined. Analyses of EU climate regulation and the interface with CORSIA indicate that policy interaction is shaped by coverage, market incentives and legal accounting boundaries rather than nomenclature alone [6,7,54-56].

Recent evidence strengthens the distinction between certification harmonization and legal convergence. Kadam and Dwivedi compare sustainability criteria among CORSIA-approved certification schemes and find important differences in the thematic emphasis placed on greenhouse gas accounting, feedstock management, and social safeguards [57]. Their comparison concerns certification standards operating within CORSIA rather than ISCC EU, but it demonstrates why a common scheme label cannot substitute for verification of specific rules. In parallel, Reisdorf, Kummer and Soklaridis show how European SAF regulation can reshape competition and procurement incentives [58]. Taken together, these studies suggest that a cross-regime recognition arrangement should harmonize reusable evidence while retaining explicit jurisdiction-specific legal tests [57,58]. These differences are usefully interpreted through regulatory pluralism. The same material object is assessed by multiple institutions that define their own eligibility tests, evidence requirements, reporting entities and consequences of noncompliance. Harmonization may reduce costs, but full identity of rules is neither realistic nor always desirable where authorities govern different emissions scopes or social risks. A nuanced approach distinguishes technical interoperability, such as sharing a feedstock audit record, from normative equivalence, such as declaring two carbon-intensity calculations legally interchangeable. The reviewed policy and market literature suggests that the most promising coordination strategies are those that permit verified exchange of source evidence without automatically transferring jurisdiction-specific compliance status [4,22,59,60].

Life-Cycle Accounting and Environmental Integrity

Life-cycle assessment connects upstream cultivation or waste collection to processing, distribution, fuel delivery and aircraft use under an explicitly defined functional unit. Its apparent simplicity conceals choices that can change reported savings: co-product allocation, supply-chain geography, fuel yields, energy recovery, treatment of residues, avoided emissions and system boundaries. A fuel may perform differently under an average national electricity mix than under contractually or physically verified renewable electricity. Likewise, the emissions associated with hydroprocessing, catalyst production or hydrogen supply can shift the ranking of candidate pathways. The value of LCA is not that it produces a single timeless truth but that it makes the assumptions and sensitivity of comparative emissions estimates inspectable [5,17,19,61,62]. Land-use change illustrates the distinction between scientifically contestable attribution and a prescribed accounting rule. Direct land-use change can be tied to conversion history and carbon-stock changes, while indirect land-use change is estimated using market and land-system responses that may extend beyond a particular farm or plantation. Spatially explicit methods can improve the representation of regional carbon stocks and payback periods, yet uncertainty persists over counterfactual trajectories and the allocation of induced changes. Jurisdictions may adopt different approaches to default land-use factors or the replacement of indirect estimates with directly assessed effects. Consequently, a report showing different CORSIA and EU values for the same feedstock requires a methodological bridge explaining why, rather than a claim that one system has discovered a universally more accurate percentage saving [5,18,63,64].

A further accounting issue is the relationship between global physical outcomes and the distribution of claims among companies. An additional unit of low-emissions fuel may displace fossil fuel in a particular supply chain, but the contractual allocation of that benefit is separate from the physical displacement itself. In mass-balance arrangements, eligible inputs and products may be tracked across a bounded system using defined balancing rules. In book-and-claim systems, environmental attributes can be transferred separately from physical delivery, subject to program conditions. These arrangements can help overcome logistical constraints, but their credibility depends on whether the claim is accurately described, whether a unique quantity of environmental benefit exists, and whether the same benefit is sold or counted a second time. The existence of a private registry does not by itself establish statutory recognition [13-16].

Feedstock Eligibility and Justice in Low-Carbon Fuel Transitions

Eligibility is a normative as well as a technical decision. Waste and residue labels may imply low opportunity cost and limited land pressure, but those implications do not always hold when a material has existing uses, high market value or an incentive-induced production response. In the palm-oil context, the material's point of generation, processing history, economic status and legal classification can determine whether it is treated as a crop derivative, a processing residue or a listed eligible material. Verification of a POME-derived route requires evidence that the relevant feedstock and pathway actually meet the operative conditions; a generic reference to palm-industry waste is not enough. The sustainability

literature therefore favors explicit feedstock taxonomy over an undifferentiated palm-versus-non-palm debate [20,21,23,26]. Market considerations create a second institutional challenge. Policy incentives and procurement decisions influence which technologies receive investment, which suppliers can enter markets, and who bears the expense of traceability and audit systems. SAF reviews report persistent cost gaps and investment uncertainty, while analyses of airline behavior show that policy treatment affects demand, supply and competitive responses. For producer countries outside Europe, the administrative cost of demonstrating compliance under several non-equivalent systems can be disproportionately high even when the same physical fuel is produced to acceptable technical quality. A credible governance response should therefore combine environmental stringency with accessible guidance, risk-proportionate assurance and transparent pathways to prove eligibility [4,12,54,60,65].

Method: An Interpretive Qualitative Literature Review

Research Design and Evidence Hierarchy

The study adopts a critical qualitative literature review rather than a systematic literature review. Its purpose is to interpret interrelated technical, regulatory and institutional claims, identify inconsistencies between them, and develop a coherent analytical framework for policy and practice. It does not attempt exhaustive publication retrieval, calculate pooled effects, assign meta-analytic weights, or infer the frequency of any regulatory violation from a literature sample. Instead, it applies purposive and iterative literature engagement to a multidisciplinary question that crosses energy systems, life-cycle analysis, aviation economics, climate governance and certification. The interpretive unit is not the article alone but the proposition made within it: what is certified, what emissions quantity is calculated, which authority recognizes that quantity, and which actor is permitted to report it. This design is appropriate where regulations evolve faster than some of the scholarship describing them [4,10,11,61]. The journal-article corpus comprises 64 articles published during 2020-2026, selected for conceptual relevance and coverage of six substantive themes. Literature on production routes was included when it clarified why carbon intensity and feedstock provenance are pathway-dependent; economic and policy studies were included where they illuminated the effects of different rules; and analyses of CORSIA, EU ETS, LCA and chain-of-custody systems were included to examine institutional mechanisms. The final synthesis places particularly strong weight on work that expressly analyzes the CORSIA method, land-use accounting, SAF production economics, aviation market incentives or claim allocation. The publication date window aligns the interpretation with the contemporary growth of SAF policy without implying that all articles speak directly to the latest rule amendments. No numerical count of screened or excluded documents is presented because the method is qualitative and purposive, not a formally exhaustive systematic search [5,13,18,24].

Official policy and certification documentation is analyzed as a separate authority tier. ICAO's CORSIA eligible-fuel documents, sustainability-criteria guidance and frequently asked questions are consulted to establish what the international aviation framework requires. The text of Regulation (EU) 2023/2405, relevant EU implementing and delegated provisions, European Commission guidance and ISCC scheme descriptions is consulted for their respective legal or administrative roles. Where there is a conflict between a scholarly simplification and a currently operative regulatory instrument, the latter governs the statement of the rule. This distinction prevents journal discussion from being mistaken for binding law and avoids interpreting a voluntary certification body's public-facing description as proof that regulators have accepted all claims associated with its scheme [6,7,8,56].

Thematic Coding and Synthesis Procedure

A six-theme coding framework was initially constructed from the research questions: scheme scope and legal purpose; methodological variability in life-cycle GHG accounting; feedstock eligibility and provenance; chain of custody and double counting; market and distributional effects; and governance interoperability. Documents were then interpreted comparatively, and cross-cutting concerns were captured as inductive subthemes, including the ambiguity of waste labels, confusion between voluntary attributes and statutory credits, possible information asymmetry, and the risk of presenting a technical certificate as a legal authorization. The analysis asks, for example, whether an apparently contradictory finding reflects a genuine empirical disagreement or simply a different regulatory boundary. This procedure emphasizes mechanism-based explanation and analytic transferability over raw frequency of coded terms [4,10,11,22]. Three tests guide the synthesis. First, every regulatory proposition must identify its legal or scheme authority, reporting subject and, when necessary, relevant time version. Second, every emissions comparison must identify the functional unit, reference fuel, pathway, feedstock assumptions, land-use treatment and allocation method before equivalence is considered. Third, every proposed carbon claim must identify the unique fuel quantity and the party entitled to use the environmental attribute in a defined reporting context. Where these tests cannot be met, the review describes a risk or unresolved condition rather than asserting noncompliance or an observed double count. This cautious approach separates the normative proposition that duplicate claiming should be prevented from the unsubstantiated empirical claim that a specified number of such cases has occurred [5,15-17].

Scope, Reflexivity and Limitations of Inference

The review does not perform a numerical re-estimation of either ICAO or EU life-cycle values, and it does not audit individual producers' sustainability certificates or access proprietary batch registries. It therefore cannot demonstrate that a particular company has double claimed an emissions reduction or that a particular palm-oil residue is eligible in every country and period. Studies reporting greenhouse gas savings under different feedstocks, geographic contexts and analytical boundaries are used as evidence of methodological sensitivity, not merged into a spurious cross-study average. The proposed interoperability architecture is a normative governance model requiring validation in operational pilots. These limitations are consistent with the interpretive aim and provide a transparent boundary between scholarly findings, regulatory facts and policy proposals [13,18,62,64].

Results: Thematic Findings from the Literature

Theme A: Certification Systems are not Interchangeable Compliance Instruments

The review identifies a recurrent category error in discussions of SAF sustainability: the conflation of certification scheme participation with entitlement to claim a particular emissions benefit. ISCC CORSIA certifies against criteria relevant to the CORSIA eligible-fuels framework; ISCC EU operates under the European Union's renewable-energy sustainability architecture [66,67]. The distinction concerns the governing rules and accepted proof, not necessarily the existence of different physical fuel

molecules. A fuel producer can invest in documentation capable of supporting several audits, but each compliance framework retains authority over eligibility and the emissions value it accepts. The resulting institutional structure may impose duplication on industry without implying that the same document has identical consequences across jurisdictions. Scholarly studies that compare CORSIA and EU measures reinforce the need to specify the applicable mechanism before inferring market effects [5-8].

Table 1 summarizes the principal points of divergence between the certification and emissions-accounting systems. It distinguishes the legal purpose of each scheme from the separate decision about whether a particular fuel batch can contribute to the relevant reporting obligation. The comparison is functional and necessarily simplified; current primary legal and scheme provisions must be consulted before making an operational eligibility determination.

Table 1: Functional Comparison of Scheme Coverage and Emissions-Claim Recognition. Source: ICAO CORSIA, ReFuelEU, EU RED and ISCC Guidance; Interpretive Synthesis.

Decision point	ISCC CORSIA / ICAO	ISCC EU / RED–ReFuelEU
Scheme purpose	CORSIA eligible-fuels certification and related airline fuel claims	RED sustainability proof; aviation-specific ReFuelEU conditions
LCA basis	ICAO-prescribed well-to-wake method with applicable land-use treatment	RED methods and rule-specific EU calculation/reporting
Feedstock status	ICAO eligibility and sustainability criteria	Relevant RED categories plus ReFuelEU restrictions/exclusions
Reporting beneficiary	Operator applying eligible SAF under CORSIA requirements	Supplier or operator as required by the relevant EU instrument
Recognition of claim	No unconditional recognition of separately acquired EU/voluntary certificates	No unconditional recognition of CORSIA-only claimed reductions
Avoidance of duplicates	Batch records and no-incompatible-double-claim conditions	Mass balance, reporting controls and other relevant EU requirements

The table shows that documentary overlap can coexist with materially different compliance outcomes. The practical question is therefore not whether ISCC CORSIA or ISCC EU is universally more stringent, but whether the specified pathway, feedstock classification, methodology and claim all satisfy the requirements of the intended jurisdiction. A producer seeking multiple markets can use the same underlying source evidence while maintaining distinct legal conclusions and emissions factors for each use. The outcome is better understood as conditional recognition. Meeting the technical requirements of an approved SAF pathway is only the first decision. A certification may then confirm sustainability and custody conditions, while a competent authority or regulatory process determines the eligible life-cycle benefit and its use within a reporting system. For a European aviation fuel supplier, the question of whether a batch contributes to a ReFuelEU obligation is not identical to the question of whether an international aircraft operator can count CORSIA eligible fuel against its CORSIA obligations. The rules can differ even when sustainability auditors examine overlapping feedstock documents. Therefore, claims that a certificate is globally accepted should be replaced with precise statements concerning recognized scope, reporting period, pathway and end use [4,12,24,56].

Figure 1 distinguishes these decision gates and locates legal recognition after the production of a technically supported life-cycle value. It is designed to prevent both overclaiming by operators and overpromising by certification intermediaries. The figure presents a general conceptual model, not a representation of the formal workflow of every regulator. It also makes visible the critical point at which a scheme-compliant batch can fail to generate a specific claimed compliance benefit: absence of an accepted reporting pathway, a disqualifying feedstock condition or a prior use of the same claim.

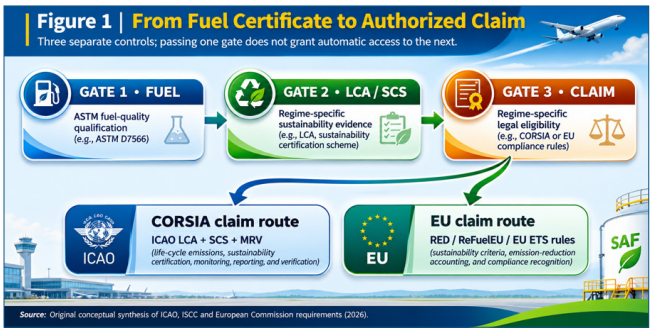

Figure 1: Three Decision Gates from Physical Fuel Qualification Through Sustainability Verification to Regime-Specific Claim Recognition. Source: Original Conceptual Synthesis; not a Reproduction of an Official Regulatory Figure.

The three-gate model clarifies why certification is necessary for certain statutory uses yet never conceptually sufficient for all emissions claims. Gate one establishes qualified physical inputs and a verifiable chain of custody; gate two evaluates the relevant carbon-intensity calculation; gate three determines the unique and authorized use of the attributed reduction. An interoperable system must preserve evidence and status at each gate rather than recording only a final binary field marked certified. This separation is consistent with the technical heterogeneity of SAF pathways and with the legal distinctions identified across aviation climate-policy studies [4,5,9,13].

Theme B: Life-Cycle Reductions are Method-Dependent, not Universal Fuel Properties

A second finding is that life-cycle reductions are conditional analytical quantities. For a given amount of delivered energy, carbon intensity can be represented as the sum of upstream feedstock emissions, processing emissions, transport and distribution, combustion-related accounting items and relevant land-use effects, subject to the boundaries and allocation specified by the applicable methodology. CORSIA uses a prescribed life-cycle approach whose land-use component can be significant for agricultural pathways; the EU applies its own greenhouse gas methodology and regulatory definitions. Even when both systems

report gCO2e/MJ, the numbers should not be compared without identifying which processes are included, what baseline is used and how feedstock-induced land changes are modeled. The literature demonstrates that such assumptions have practical significance across several conversion technologies [5,17,18,61]. More recent evidence supports the need for sensitivity analysis rather than a single transferable carbon-intensity figure. Zhang evaluate multiple SAF technology pathways with a life-cycle prediction framework and show that estimated environmental performance varies with route and scenario assumptions [66-68]. That result supports maintaining distinct calculation modules for CORSIA and EU applications, even if they draw on the same verified operational data. In such a framework, reporting differences are explained through boundary choices, energy inputs and regulatory rules instead of being hidden by an average percentage saving [5,68]. The most consequential methodological sensitivities fall into three groups. The first consists of feedstock and land-use assumptions, including direct conversion history, indirect land effects, prior uses of residues and the time horizon used to spread carbon-stock changes. The second concerns process configuration, especially hydrogen sourcing, heat integration, electricity intensity and allocation of co-products. The third covers reporting conventions, including the use of default rather than actual values, data-quality rules and accepted treatment of transport and distribution. A cross-regime comparison must report these assumptions explicitly instead of treating a difference of several percentage points as sufficient evidence of either an invalid certificate or a flawed model. The scientific literature offers strong grounds for sensitivity reporting but does not itself confer legal recognition on any particular figure [18,19,21,62,64,].

Figure 2 presents an analytic decomposition of carbon-intensity determinants. The diagram is deliberately schematic: it separates measured or modeled process contributions from land-use terms and optional credits subject to specific ICAO rules. The governing CORSIA formulation adds the applicable land-use-change term to core LCA and subtracts any eligible emissions credits, for which defined municipal-solid-waste cases are relevant. It should not be read as an instruction to add an indirect land-use factor and a direct land-use factor simultaneously regardless of the applicable CORSIA provisions. Instead, the diagram emphasizes the obligation to record which component was used and why, so that independent reviewers can reproduce the reported value under the chosen framework.

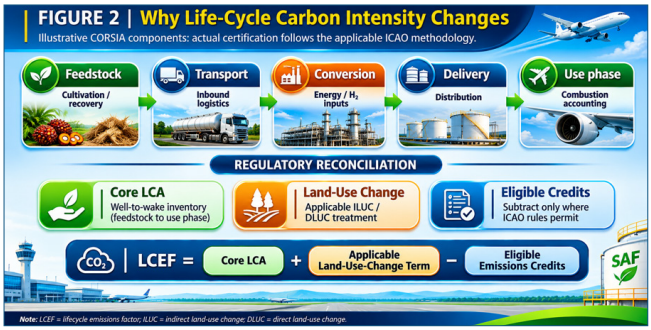

Figure 2: Core LCA, Land-Use-Change Treatment, and the Subtraction of Eligible Emissions Credits Under ICAO CORSIA. Source: Original Conceptual Synthesis; not a Reproduction of an Official Regulatory Figure.

The interpretation of Figure 2 also reveals a governance opportunity. A single high-quality underlying evidence package can contain feedstock origin, production energy, hydrogen carbon intensity, actual transport distances and documented land history, while parallel calculation sheets apply ICAO and EU conventions. This architecture reduces repeated data collection without making unwarranted claims about numerical equality. It is especially relevant for power-to-liquid and integrated biofuel plants, where electricity, carbon sources and system boundaries can dominate the carbon-intensity result. The policy goal should be transparent reconciliation, not the forced convergence of all calculated values [36,40,41,69,70].

Theme C: Feedstock Eligibility Varies by Material, Origin and Regulatory Purpose

Feedstock classification is the third decisive finding. The EU's aviation framework differentiates among food and feed crops, specified listed wastes and residues, synthetic fuels and particular disqualified material categories [51,52]. Under current ReFuelEU guidance, the treatment of palm fatty acid distillate cannot simply be generalized to POME or empty palm fruit bunches; some materials may be recognized by reference to Annex IX categories when the relevant conditions are fulfilled [51,52,71]. Nor can a positive label in one certification document override an exclusion under the specific aviation law. These decisions call for material-level identification, documented generation processes, a suitable supply-chain audit and a current eligibility crosswalk. They also call for careful language: materials should be described as potentially eligible under specified conditions rather than automatically accepted whenever they originate from a particular mill [20-23]. The fuel-producing context shapes the risk of reclassification. A residue with an existing commercial use may create substitution or leakage effects if incentives shift it into SAF production, and its collection may involve upstream environmental burdens. The treatment of used cooking oil and other waste lipids illustrates the importance of measured composition, chain of custody and the actual conversion pathway. Likewise, land-use modeling can materially change the apparent performance of agricultural feedstocks, particularly when plantation expansion, drainage or high-carbon land is relevant. Sustainability certification should test these conditions instead of assuming that the word waste automatically implies zero upstream emissions or no indirect consequences [17,18,20,64].

Figure 3 maps the sequence from feedstock identity and origin to jurisdiction-specific acceptance. It should be read as an eligibility-checking workflow rather than a categorical map of legal decisions in every country. The labels illustrate why a palm-associated feedstock must be analyzed by material class, processing history and the particular legal rule applicable at the time of reporting. A supplier should use this structure to compile a documented reason for acceptance, a documented reason for exclusion, or a record identifying an unresolved decision requiring confirmation from the competent authority.



Figure 3: Parallel ICAO and EU Feedstock Eligibility Pathways Based on a Common Feedstock Dossier. Source: Original Conceptual Synthesis; not a Reproduction of an Official Regulatory Figure.

As Figure 3 illustrates, the principal governance improvement is to record an evidence-backed classification before assigning any percentage saving. A producer may benefit from producing a feedstock-specific evidence dossier containing the official material designation, source facility, waste-versus-co-product reasoning, country of origin, collection and processing arrangements, and current scheme references. Such documentation is relevant to Indonesia's effort to commercialize palm-mill and other biomass-derived fuels while complying with international sustainability expectations. However, this paper neither treats a potential opportunity as a blanket regulatory approval nor advocates weakening restrictions designed to address land-use, biodiversity or displacement risks [4,21,63,65].

Theme D: Double Counting is an Accounting and Entitlement Failure

The fourth theme concerns the distinction among several forms of double counting that are often collapsed in public debate. Double issuance occurs where more than one environmental attribute is created for the same underlying eligible reduction contrary to the rules of the relevant programs. Double use occurs where one issued attribute is applied more than once to satisfy obligations or claims. Double claiming concerns separate actors asserting exclusive rights to the same emissions benefit, potentially including a producer, aircraft operator, customer and downstream certificate buyer. These problems cannot be prevented solely by confirming that a shipment was physically produced. The claim layer must also specify its owner, quantity, reporting purpose and current status. Research on carbon-claim integrity and on book-and-claim allocation shows why independent entitlement tracking is a necessary complement to supply-chain certification [13-16,].

The ICAO framework explicitly addresses the risk that eligible fuel benefits are claimed inconsistently through requirements and documentation associated with fuel batches and reporting [72]. Relevant fuel information includes production or purchasing evidence, carbon intensity and quantities, with declarations designed to guard against the same reduction being claimed under incompatible arrangements. Where another jurisdiction separately regulates a producer or operator, however, the conceptual question is not whether two authorities are allowed to observe the same physical batch. They may need to observe it for different legal purposes. The question is whether the same exclusive environmental benefit is being counted twice against obligations where the governing rules prohibit such duplication. A well-designed assurance system distinguishes information sharing from duplicate benefit creation and does not confuse identical observation with unlawful duplicate crediting [5,6,8,16].

Figure 4 outlines how a unique batch identifier and emissions-attribute record can travel through production, certification, allocation, disclosure and claim retirement. The diagram proposes a dual-ledger approach. The physical ledger records fuel quantity, conversion batches, custody changes and any applicable mass-balance adjustments; the claims ledger records a distinct authorized environmental attribute, its beneficiary and its use status. Where program rules permit voluntary attributes, the ledger must describe those claims separately and explicitly restrict statements that would imply unapproved CORSIA or EU compliance. The checkpoints in Figure 4 must not be interpreted as permitting the same exclusive reduction to be claimed under all listed mechanisms. The model is a governance proposal, not an assertion that a unified worldwide registry has already been adopted.

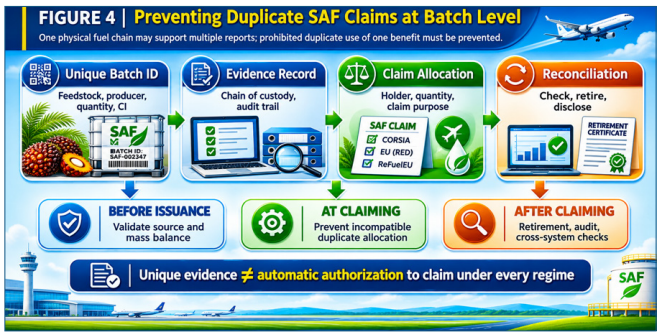

Figure 4: Proposed Batch-Level Controls Against Duplicate Issuance, Use, and Unauthorized Claiming. Source: Original Conceptual Synthesis; not a Reproduction of an Official Regulatory Figure.

The practical significance of Figure 4 is that duplicates become detectable at the event level rather than only during an annual audit. A verification workflow would compare the mass of eligible fuel, the quantity of allocable life-cycle savings, the program identifier and the declared beneficiary before accepting a new claim. It would also store the precise rule version, accepted carbon-intensity method, transaction date and supporting assurance statement. A cancellation or retirement event would prevent the relevant exclusive attribute from being reissued or reused in an incompatible context. Such safeguards can reduce ambiguity and improve the credibility of both physical mass-balance systems and separately governed book-and-claim markets, although technical standards and legal obligations must still determine which transfers are permitted [13-16].

Theme E: Divergent Rules Alter Investment Incentives and Distributional Outcomes

A fifth theme concerns the economic significance of non-equivalence. SAF supply faces well-documented cost and scale constraints, and regulators influence investment decisions through mandates, emissions pricing and rules that define a qualifying fuel. Producers may rationally pursue several certifications to reach several customer groups, but separate audits, data models, material lists and reporting calendars impose additional costs. Airlines likewise face uncertainty when evaluating long-term purchase agreements or the suitability of an environmental attribute for their emissions inventories. The costs of duplicate documentation should be distinguished from the legitimate costs of checking different environmental criteria. This distinction

prevents the discussion from treating all administrative friction as socially wasteful or, conversely, accepting every repeated audit as necessary for integrity [4,7,12,60,62]. Newer work has also emphasized that constraints on SAF deployment arise jointly from production systems and certification practices. Ding identify interacting technological and certification barriers, while Reisdorf connect European SAF rules to competition and the willingness of different customers to pay for lower-emissions flights [58,73]. These findings strengthen the review's argument for reducing avoidable documentation duplication without weakening feedstock restrictions or verification. Policy design should evaluate the costs of evidence collection separately from the environmental benefit of rigorous, independent compliance decisions [58,73].

Cost pressures are likely to differ across pathways. Synthetic fuels are sensitive to power costs and hydrogen availability, while biomass-based pathways depend on feedstock density, procurement logistics, land use and conversion technology. Facility-level integration can materially influence both emissions outcomes and production economics. Because policy incentives may change which pathways are commercially feasible, unequal recognition rules can determine where capital accumulates and which countries supply SAF to international markets. Literature on alternative pathways and global SAF strategies suggests that rules should be judged not only by their nominal stringency but also by whether they provide predictable, science-based access for demonstrably sustainable innovations [21,38-40,63].

Producer countries with significant agricultural and industrial residues face a further fairness problem. They must demonstrate that their materials are genuinely eligible and traceable, often through standards designed or administered outside their own jurisdictions. This burden is justified to the extent that it provides evidence of environmental protection; it becomes unnecessarily exclusionary when the same verified underlying facts must be repeatedly collected in incompatible formats or when regulatory decision rules are opaque. Coordinated templates, reliable local testing infrastructure and recognition of shared primary evidence could therefore improve access without compromising substantive sustainability screens. The focus should be equivalence of demonstrable facts where appropriate, not automatic acceptance of all feedstocks [10,22,59,65].

Theme F: Institutional Coordination is More Feasible than Universal Regulatory Identity

The sixth finding is that technical coordination can be substantial even while legal requirements remain different. ICAO technical discussions relating to LCA, feedstock recognition and sustainability criteria provide a legitimate setting for examining common terminology and reproducible evidence standards. EU authorities have their own mandates, and certification organizations act as auditors or scheme administrators rather than sovereign regulators. This institutional map implies that sustainable convergence should focus on common fuel-batch identifiers, quality-controlled datasets, auditable emissions inputs, comparable disclosures and standardized evidence exchange. The final determination of eligibility and claim rights must remain explicit for each regulatory use. This approach preserves both scientific comparability and jurisdictional autonomy [4,5,24,56].

The literature also reveals a tension between efficiency and integrity in fuel-attribute markets. Market tools can reduce the logistical barriers associated with matching SAF delivery to the buyer's preferred airport, but the environmental benefit of flexibility depends on credible additional supply and transparent allocation rules. A registry that records transfers without specifying whether the recipient can make a statutory or voluntary claim may improve commercial convenience while increasing the possibility of misleading communications. Regulatory coordination should therefore demand common definitions for fuel quantity, environmental attribute, certificate holder and retirement event, together with explicit disclosure of the framework under which a claim is permitted. Technically aligned documentation is a means to better accountability, not a substitute for it [13-16].

Discussion and Analysis

Explaining the Certification-Recognition Gap

The six thematic findings collectively indicate that an internationally reliable SAF system should be designed around the distinction between the creation of a lower-carbon product and the recognition of a specific reduction claim. The first step is physical and evidentiary: a particular fuel batch has a known feedstock, production route, sustainability history and chain of custody. The second is computational and rule-dependent: a competent methodology calculates its accepted emissions intensity relative to the relevant reference fuel. The third is institutional and transactional: a rule specifies the reporting party, the quantity and the conditions under which the reduction can be claimed. An error at any step can undermine the final statement even if the other two steps are technically sound. This three-part separation provides a direct answer to the central question of why ISCC CORSIA and ISCC EU certificates are not automatically equivalent for compliance [4,5,8,13].

This framing is also important for policy debates that use the term mutual recognition without defining its object. Mutual recognition of auditor competence would permit a regulator to rely on an audit process performed under common quality rules. Mutual recognition of evidence would allow a verified dataset, such as feedstock origin or laboratory analysis, to be reused in another system. Mutual recognition of calculations would accept a particular life-cycle value under another methodology, which could require a formal technical equivalence decision. Mutual recognition of compliance claims would go further still, potentially transferring benefits or liabilities across legal frameworks. These four objects have radically different implications. A sound international negotiation should state which is under consideration before declaring that a single global SAF certificate is desirable or achievable [6,7,22,56].

An illustrative case makes the distinction concrete. Suppose a batch of residue-derived SAF has physical quality documentation, an audit confirming feedstock provenance, and an ICAO-compliant life-cycle value. A European supplier may nevertheless need to demonstrate that the material is eligible under the relevant EU aviation rules and that the applicable EU accounting calculation and reporting duties have been satisfied. If the producer also sells an environmental attribute to a corporate customer, the customer must understand whether the transfer concerns a voluntary contribution claim, a physical fuel allocation or an authorized compliance benefit. The mere addition of three certificates in a marketing brochure cannot resolve this problem. The correct solution is a clear chain from source evidence to specific authorized beneficiary and reporting use [13-15,24].

Methodological Convergence Without Misleading Numerical Equivalence

The LCA evidence suggests that a minimum interoperability dataset would provide greater value than an undifferentiated international carbon-intensity number. The dataset should record the production pathway, site, batch quantity, fuel energy content, origin and category of feedstock, land history where relevant, processing energy, hydrogen sources, co-product assumptions, transport distances, default factors used, data vintage and independent assurance status. A jurisdiction-specific calculation module would then apply the CORSIA or EU method and preserve both the input and the calculated result. Any differences would be disclosed through a reconciliation sheet identifying the affected methodological elements. Such an approach supports reproducibility while recognizing that different regulatory methodologies may serve different purposes [5,17,18,61,64].

The proposed dataset must also contain rules for uncertainty disclosure. A low-carbon synthetic fuel made with renewable electricity may have a different life-cycle intensity from one produced using a fossil-intensive power system, even where downstream fuel quality is equivalent. Waste-derived pathways may be sensitive to the counterfactual destination of a residue, transport logistics, collection assumptions and the method for allocating upstream burdens. Land-use estimates can depend on spatial resolution and counterfactual land change, while hydrogen production introduces its own emissions and price sensitivities. These issues make it necessary to distinguish measured facility data, verified contractual information and model defaults. Reporting a false precision or a broad percentage saving without the boundary and rule version can undermine investor and public confidence [18,39,41,69,70].

It follows that apparent regulatory convergence should be assessed through practical testing. A pilot could select several representative production routes, compile one verified source dataset for each, and independently calculate CORSIA and EU outcomes. The outputs would identify which differences arise from feedstock eligibility, which from emission-factor methodology, and which from different reporting obligations. This exercise could be carried out with local auditors, recognized certification schemes and competent authorities without implying that the research team can pre-authorize the resulting claims. Its value would lie in producing traceable explanations and a bounded pathway toward administrative simplification. Published environmental and techno-economic assessments show the feasibility of detailed process modeling, but operational pilot evidence remains necessary to validate institutional interoperability [4,19,35,62,63].

Prevention of Double Counting as an Institutional Design Problem

Claims integrity requires more than independent certification of suppliers. A defensible system must identify a unique environmental attribute or quantity associated with an eligible batch, establish a single authoritative status for that attribute, and specify which claim types may coexist without creating a prohibited duplication. It must distinguish physical accounting of fuel from the exercise of a contractual or regulatory right to an emissions reduction. If reporting rules prohibit two parties from using the same benefit as an exclusive reduction, a custody ledger alone cannot demonstrate compliance. The system must establish whether an attribute was issued, transferred, split, canceled, retired or used in an airline's statutory declaration and reconcile those events against any parallel voluntary program where permitted. This is a principle of claim governance, not proof that each authority already operates an interoperable digital registry [13-16,].

This approach can clarify the role of book-and-claim models. They may support SAF market development by allocating environmental attributes in settings where physical delivery to a particular airline is difficult, but program rules differ and no general inference of eligibility under CORSIA or the EU is justified. A valid voluntary claim would need to state its accounting standard, attribute boundaries and relationship to other fuel-supply or compliance claims. The buyer should not imply physical use of a fuel at a specified airport unless the underlying evidence supports that statement. Conversely, a regulated operator should not assume that acquisition of a privately issued certificate substitutes for required eligible-fuel records or sustainability documentation. Separation of these statements can prevent overclaiming without prohibiting innovative and transparent procurement arrangements [13-16].

A Practical International Interoperability Architecture

Figure 5 integrates the preceding discussion into a multiactor governance architecture. The proposed framework assigns complementary responsibilities rather than concentrating authority in a single certificate issuer. Producers establish traceable fuel and feedstock data; accredited or recognized scheme auditors test conformity; calculation specialists apply the accepted LCA methods; regulators decide legal eligibility and reporting treatment; and operators or authorized beneficiaries make uniquely attributable claims. A linked evidence architecture can support these functions through standard identifiers, signed records, explicit method versions, access permissions and audit trails. The resulting system could allow evidence reuse across jurisdictions while visibly displaying distinct CORSIA and EU decisions.

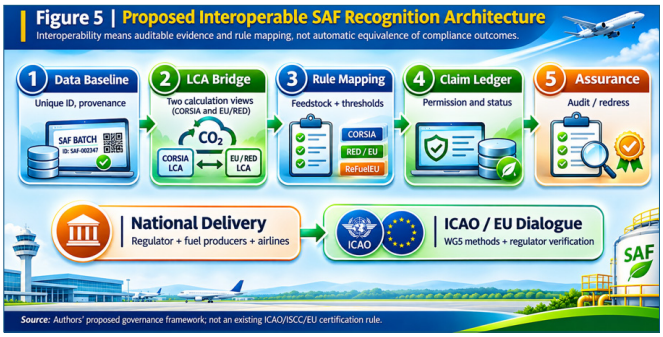

Figure 5: Proposed International Interoperability Architecture for SAF Evidence, Calculation, and Claims Assurance. Source: Original Conceptual Synthesis; not a Reproduction of an Official Regulatory Figure.

Figure 5 also illustrates a possible phased implementation roadmap. In the first phase, ICAO technical participants, EU stakeholders, national authorities and scheme operators would align a minimum vocabulary defining physical batch, eligible input, carbon-intensity result and exclusive claim. A second phase would create optional machine-readable evidence templates that preserve confidentiality while permitting verification. A third phase would pilot non-duplication checks between relevant ledgers and demonstrate how reporting entities can retrieve an auditable decision trail. In the final phase, regulators could consider narrowly defined recognition agreements concerning shared evidence or audit functions, without surrendering independent legal determinations

over qualifying feedstocks and valid reductions. This roadmap is a recommendation derived from the review, not a description of a formally adopted international program [5,6,11,24].

Policy Priorities for ICAO Technical Work, the EU and Indonesia

For ICAO and technical working discussions associated with life-cycle methods and feedstock criteria, the priority should be to clarify the interfaces among fuel-batch evidence, LCA attribution and recognized emissions claims. Technical documents would benefit from version-controlled reference values, explicit feedstock taxonomies, traceable exceptions and examples showing how the same production data can generate different legal outcomes. Where CORSIA fuel reporting requires information designed to avoid double claiming, this information should be specified in a form that auditors and national aviation administrations can check consistently. Cooperation with EU authorities should seek to resolve terminology and evidence-mapping problems without assuming that CORSIA and ReFuelEU have the same legal beneficiaries, fuels or obligations [5,7,8,10]. For EU regulators, administrative simplification should focus on transparent decisions and defensible reuse of verified underlying facts. A producer should be able to determine whether a feedstock is potentially eligible under RED and ReFuelEU, what documentation is needed, whether a particular carbon-intensity calculation must be reconstructed, and how EU ETS or fuel-supply reporting interacts with other declarations. This is not an argument for weakening material restrictions or including a palm-derived product solely because it has been certified elsewhere. Rather, transparent and stable eligibility distinctions can reduce speculation and enable companies to invest in genuinely qualifying pathways. The research literature suggests that policy predictability is especially important for production technologies exposed to substantial capital, feedstock and energy-price risks [4,54,55,60].

For Indonesia and comparable producer states, immediate priorities include mapping material-specific SAF opportunities against current CORSIA and EU rules, improving the quality of traceable feedstock data, strengthening life-cycle measurement capabilities and ensuring that producers understand the limits of each certification. POME-derived and empty-fruit-bunch-derived concepts warrant pathway-specific evaluation, but their mention in eligibility lists cannot substitute for verification of each operative requirement. A coordinated public-private technical platform could compile representative feedstock dossiers and evaluate their treatment under alternative rule sets. Such a platform could also prepare national experts to contribute evidence and methodological concerns to ICAO discussions, including the activities described as WG5 work in policy meetings. Its credibility would depend on an explicit commitment to transparent land-use records and the avoidance of duplicate environmental claims [18,20-22].

Implications for Theory, Assurance and Future Empirical Research

The proposed analysis adds to regulatory-pluralism scholarship by distinguishing interoperability of evidence from interoperability of rights. It explains how one physical good can be a compliant input in one system, an ineligible input in another, and a source of contractual voluntary attributes in a third without those classifications necessarily being logically inconsistent. The critical governance failure arises only when incompatible classifications or claims are concealed or when an environmental benefit is applied more than permitted. This distinction is particularly valuable for cross-border low-carbon commodity markets, in which technological standards, sustainability conditions and climate-accounting systems are often developed by different institutions. The three-gate model therefore provides a conceptual framework that can be tested outside aviation as well [6,13,16,56]. The review also identifies limits to its findings. It does not establish the prevalence of double claims or the average transaction cost of dual certification, and it cannot determine whether a particular shipment meets rules that are subject to case-specific interpretation or later amendment. Future research should compare paired LCA results from the same SAF facility and feedstock, audit actual duplicate-claim safeguards under agreed confidentiality protocols, and evaluate the effects of different registry models on verification burden and market access. Researchers should also assess whether administrative harmonization reduces costs without weakening feedstock integrity and whether benefit allocation is equitable among producers, airlines and customers. These studies would provide empirical tests for the governance propositions advanced here [4,11,15,24,].

Conclusions and Recommendations

The central conclusion is that SAF sustainability certification, life-cycle emissions measurement and recognition of an emissions-reduction claim are distinct stages of environmental governance. ISCC CORSIA and ISCC EU answer partly overlapping but legally non-identical questions; certification under either scheme does not create an automatic right to the same emissions benefit in every aviation market. The diversity of relevant rules does not make cross-border cooperation impossible. It means that genuine interoperability must be constructed through transparent evidence, regime-specific decisions and controls governing the exclusive use of environmental attributes. A second conclusion concerns analytical quality. Emissions savings cannot be compared credibly across schemes without making their baseline, feedstock, system boundary, land-use assumptions, energy inputs and calculation versions explicit. Equally, a broad commodity label is not enough to determine feedstock eligibility. Materials associated with the palm sector must be differentiated by their actual regulatory category and documented origin. These distinctions are especially important for SAF suppliers in emerging markets, where opportunities from residues and industrial by-products coexist with legitimate concerns about land conversion, displaced uses and the integrity of reported carbon reductions.

The review recommends a harmonized minimum evidence dataset, paired but separate CORSIA and EU calculation records, feedstock-specific eligibility matrices, and two connected but distinct records for physical batches and environmental attributes. It further recommends unambiguous declarations of claim ownership, purpose and status, including cancellation or retirement where required, and explicit differentiation between authorized compliance reporting and private voluntary claims. International technical cooperation should prioritize common terminology, version-controlled data, interoperable audit records and operational pilots, while preserving each regulator's authority to determine which fuels and reductions count under its own rules. Finally, the study calls for practical collaboration among ICAO technical experts, EU institutions, national aviation authorities, certification schemes, SAF producers and airlines. Indonesia can contribute by developing verifiable feedstock-level dossiers and testing parallel LCA calculations on representative domestic pathways. No single certificate can eliminate every institutional discrepancy, but a transparent governance architecture can make discrepancies

understandable, reduce avoidable compliance friction and defend the environmental credibility of aviation decarbonization. Future empirical work should test the proposed architecture against real transactions, changing feedstock classifications and the cost of preventing duplicate claims.

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