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From Agricultural Residue to Aviation Fuel: Classifying Oil Palm Trunk (OPT) and Reassessing Its Carbon, Sustainability and Policy Consequences

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ABSTRACT

This qualitative literature review critically examines the proposed classification of oil palm trunk (OPT) as an agricultural residue and its implications for sustainable aviation fuel (SAF) development. Anchored in Indonesia's October 2026 CAEP/14 policy agenda, it differentiates regulatory feedstock designation from lifecycle carbon intensity, physical sustainability and certification eligibility. A critical thematic synthesis of 55 peer-reviewed articles published during 2020–2026, complemented by ICAO policy documents, identifies five interacting issues: the economic definition of residue; the boundary between assigned indirect land-use change treatment and actual core lifecycle assessment; the effects of trunk extraction on soil organic carbon, nutrients and counterfactual biomass management; uncertainties in feedstock logistics and conversion technologies; and traceability, social inclusion and avoidance of double counting. The review argues that an assigned zero ILUC value is neither a measured zero-emission result nor a substitute for actual LCA. It proposes a five-gate assessment architecture—regulatory recognition, ecological extraction, engineering validation, carbon accounting and independent assurance—and a phased Indonesian evidence roadmap. Findings support carefully conditioned residue utilisation, accompanied by representative plantation trials, technology-specific assessments, auditable supply chains and safeguards for smallholders. Neither OPT classification approval nor a default OPT lifecycle emissions value is presumed as of 15 October 2026.

Keywords: Oil Palm Trunk, Agricultural Residue, Sustainable Aviation Fuel, Corsia, Indirect Land-Use Change, Actual Lifecycle Assessment, Soil Organic Carbon, Sustainable Biomass Removal, Traceability, Circular Bioeconomy

JEL Classification: Q42, Q53, Q54, Q56, L93.

Introduction

Decarbonising Aviation without Confusing Feedstock Labels and Climate Results

International aviation faces a difficult decarbonisation problem because long-haul energy requirements, aircraft fleets and supporting infrastructure cannot be transformed as rapidly as many surface-transport technologies. Sustainable aviation fuel (SAF) is therefore a critical near- and medium-term option, yet its climatic performance differs among feedstocks, conversion routes, energy inputs and lifecycle accounting boundaries. Describing a feedstock as a waste or residue cannot, by itself, establish a low-emission fuel: collection, drying, processing and conversion may still have substantial environmental burdens. Conversely, a carefully sourced lignocellulosic material may support genuine mitigation when these operations are managed appropriately. This heterogeneity requires a systems-level appraisal that integrates technical performance, land management, market responses and certification rather than assigning sustainability on the basis of feedstock names alone [1-5].

Oil palm trunk (OPT) is generated when older palms are felled and replaced in the replanting cycle. Unlike fresh fruit bunches or crude palm oil, trunk biomass is not the principal output that motivates palm cultivation. It is nevertheless a physical and economic resource with possible roles in timber substitutes, fibre products, sap fermentation, bio-based chemicals and energy. Its wetness, fibrous structure, spatial distribution and exposure to decay create both opportunities and obstacles for high-value utilisation. Research on palm biomass pretreatment, integrated

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biorefineries and OPT management provides a credible technical basis for examining these options, but does not establish that OPT-to-SAF has a certified commercial configuration at a particular carbon intensity. The distinction between scientific possibility and pathway eligibility must remain explicit [6-9].

The IPOSS briefing prepared for Indonesia's October 2026 ICAO CAEP/14 Steering Group engagement identifies the proposed designation of OPT as an agricultural residue as an immediate policy question. Slide 7 reports that Working Group 5 (WG5) has proposed this classification and requests Steering Group consideration; it also identifies the absence of a published OPT-specific default core lifecycle value and therefore the need for an actual LCA route. Slide 8 identifies environmental integrity, traceability, certification and possible double counting as further technical tasks. This article treats the proposal as pending at the evidence cut-off of 15 October 2026 rather than as an adopted ICAO decision. Importantly, the ICAO feedstock webpage inspected for this review lists several palm-related processing residues but does not explicitly identify oil palm trunk [10-12].

The stakes go beyond Indonesia. The growth of SAF markets could change the economic meaning of materials historically left in plantations, creating new markets, incentives, rental values and contractual relationships. A feedstock may be a residue because its quantity responds weakly to demand, but the emergence of material prices can create new extraction margins or changes in management. These responses are essential when judging additionality and the legitimacy of credits. Studies of residue bioenergy and SAF production show that sustainability is conditional on regional land management, the reference scenario and the distribution of costs across supply chains. Consequently, a regulatory label should be considered the beginning of an evidentiary process rather than the culmination of a mitigation assessment [13-16].

Research problem, questions and contribution

The central research problem is a category error: public discussions sometimes translate zero assigned indirect land-use change (ILUC) emissions for a recognised residue into the claim that the resulting fuel has no land-related climate risk or a negligible total footprint. These claims are not equivalent. ILUC accounting concerns a specified methodological component, whereas core lifecycle assessment addresses direct supply-chain processes under prescribed boundaries. Additional consequential questions concern what trunk material would otherwise have done, whether nutrients or carbon are lost from the plantation and which alternative products are displaced. The distinction matters because analyses of alternative aviation fuel pathways show that both land-use assumptions and life-cycle system design can materially alter outcomes, especially when assessing feedstocks with complex supply chains [17-20].

This article asks six linked questions. First, under what institutional and economic conditions can OPT be treated as an agricultural residue? Second, which emissions are affected by that treatment and which require new measurement? Third, what does sustainable removal mean for soil carbon, nutrient management and local ecosystem services? Fourth, which preprocessing and conversion systems could meet certified SAF demands? Fifth, how should traceability, smallholder participation and competing uses influence regulatory implementation? Finally, which evidence should Indonesia generate before claiming a competitive and credible OPT-based SAF pathway? This framing places carbon-accounting coherence alongside environmental protection and commercial development rather than treating any one as a subordinate technicality.

The review makes three contributions. Conceptually, it links the regulatory ontology of residues to the physical ecology of perennial plantations and the economic behaviour of emergent feedstock markets. Methodologically, it proposes a structured but explicitly qualitative synthesis that separates normative rules, empirically reported findings and hypotheses requiring field validation. Practically, it outlines a staged decision architecture extending from documentation of trunk origins to sustainable extraction tests, actual LCA, conversion validation and independent certification. Such an architecture is useful because contemporary SAF scholarship increasingly favours multi-criteria screening that combines emissions, economics, implementation readiness and sustainability rather than any single performance indicator [21-24].

Literature Review

What Constitutes an Agricultural Residue?

The concepts of product, co-product, by-product, processing residue, agricultural residue and waste are neither perfectly interchangeable nor governed by the same economic assumptions. The policy purpose of distinguishing them is to prevent emissions and land demand from being hidden behind an apparently low-value material stream. Agricultural residues commonly arise incidentally from biological production, while processing residues emerge downstream in mills or factories. For OPT, the primary productive purpose of an oil-palm plantation is fruit production; trunks arise predominantly because old planting stock must be removed during renewal. This supports a prima facie residue argument. However, the stronger case also requires evidence that trunk supply is primarily determined by the replanting schedule rather than by a profitable new market for trunks. ICAO's published definitions and feedstock guidance provide the operative institutional framework; their current status must be checked before implementation [11].

Economic value is not a binary physical property. A wet trunk may have almost no immediate value at a remote farm but command a higher netback near a fibre plant or biorefinery. If competing buyers emerge, some farms might recover greater proportions of trunk material, change felling practices or harvest additional associated biomass. These consequences need not disqualify an agricultural-residue classification, but they complicate a blanket claim that supply is invariant to demand. The relevant question is whether induced material recovery merely makes use of an unavoidable replanting stream or materially changes production, land management and displaced product systems. Studies of biomass cascades, local feedstock constraints and SAF supply-chain optimisation reinforce the need to analyse elasticity and substitution in geographical context [9,13,6,25].

A residue label also conveys a normative judgment about what society considers unused. OPT left to decompose in the field is

not necessarily worthless: it contributes carbon, nutrients, surface protection and habitat functions, depending on local practices and hydrological circumstances. Similarly, an OPT component used as a panel material already performs an economic function and its diversion to fuel may induce production of an alternative panel elsewhere. Thus, physical generation, market status and ecological service are three analytically distinct dimensions. The emerging circular-bioeconomy literature cautions against assuming that energy conversion invariably outranks material recovery; value preservation and soil stewardship may deserve priority in particular settings [7,26,27,14].

Attributional LCA, ILUC and the Regulatory Decision Chain

Attributional lifecycle assessment (LCA) inventories emissions and resource flows allocated to an observed or modelled product system, whereas consequential LCA examines changes induced by a decision relative to a counterfactual system. The two approaches answer different questions, and neither should be substituted for the other without explaining its purpose. CORSIA specifies how eligible fuel emissions are calculated, including the core lifecycle component, the applicable induced land-use change (ILUC) component and any permitted credits. Under ICAO's published framework, recognised wastes, residues and by-products are assigned an ILUC value of zero for the prescribed calculation; this is a methodological rule, not an empirical finding that soil-carbon losses, displacement or market responses cannot occur. An actual core LCA must still follow the applicable methodology and account for the required supply-chain processes [11,12,28,29].

Empirical studies demonstrate that aviation fuel lifecycle results are sensitive to system boundaries, co-product allocation, electricity and hydrogen inputs, the treatment of displaced energy supplies and assumptions about land demand. Such distinctions matter when stakeholders compare a palm-oil HEFA pathway with a hypothetical OPT pathway. The IPOSS presentation reports model-dependent ILUC figures for palm-oil HEFA and, separately, a core lifecycle value for POME HEFA; neither result is an OPT measurement and neither may be transferred automatically to trunk-based fuel. Recent engineering-led LCA research also shows why transparent mass and energy balances are essential for estimating fuel-production emissions rather than relying on generic conversion efficiencies. Comparisons should consequently disclose the functional unit, inventories, geographical context, baseline assumptions and sensitivity ranges [17,18,19,29,21].

A further distinction exists between eligibility and a favourable score. Under a certification regime, a fuel pathway must satisfy current feedstock requirements, sustainability criteria, approved production routes and documentary assurance. The fact that a class of feedstocks receives a particular ILUC treatment does not grant unrestricted permission to claim eligible fuel. Regulators may request an actual LCA when default intensities are not established and will consider chain-of-custody and sustainability claims separately. For an OPT project, these become multiple evidence gates: confirmed category status, traceable material origins, verified production data, lifecycle calculation, compliance with fuel specifications and independent assurance. Recent reviews of SAF certification and implementation obstacles indicate that weak documentary infrastructure can be as limiting as conversion chemistry [30,31,23].

A methodological clarification is necessary when a feedstock lacks an approved default core lifecycle value. The actual-value route does not authorise investigators to redefine the prescribed system boundary or independently select the most favourable emission factors. Instead, the approved calculation must be populated with auditable process and transportation information and checked under an approved sustainability certification scheme. This distinction is especially important for OPT because alternative conversion routes, electricity sources and feedstock moisture levels may produce very different fuel-production inventories. Consistency in functional units and physical input–output balances is a condition for credible comparison, not a minor documentation detail [12,32,29,21].

Plantation Soil Dynamics and the Residue-Removal Counterfactual

Oil palm is a perennial biological system in which biomass removal, decomposition, soil cover and fertilisation jointly determine carbon and nutrient dynamics. The counterfactual fate of OPT differs between mineral soils and peat, between managed and abandoned replanting sites, and among systems that chip, stack, burn where permitted or otherwise treat trunks. A valid environmental comparison must represent actual management rather than a stylised assumption that every trunk would otherwise be emitted instantaneously as carbon dioxide. Soil organic carbon reflects inputs and losses over time; management changes can therefore have delayed and nonlinear consequences. Studies from Sumatran plantations and experiments with organic residues provide relevant warnings about the consequences of altering organic-matter returns [26,33,27,34].

The nutrient issue is particularly important in areas where fertilizer application is insufficient or unbalanced. Potassium, nitrogen, phosphorus, magnesium and other nutrients embodied in biomass may require compensation if substantial trunk fractions are exported from fields. The quantity needing replacement depends on palm age, tissue fraction, nutrient concentration, soil condition and other residues left behind. Extrapolation from nutrient-deficient smallholder settings shows why a uniform extraction recommendation would be scientifically weak and potentially distributionally unfair. Such evidence does not prove that all OPT removal is harmful; rather, it requires a locally calibrated permissible removal fraction and an explicit nutrient-replacement accounting rule [35-37,34].

The scientific literature on annual crop residues highlights a related principle: theoretical residue generation generally exceeds ecologically sustainable biomass availability. Removing too much material can lower soil organic matter, worsen erosion or increase irrigation and fertilization requirements; maintaining cover crops and alternative organic inputs may offset some costs under specified conditions. Replanting trunks differ physically from cereal straw, so annual-crop estimates cannot be applied mechanically. Their methodological lesson remains valuable: researchers must define sustainable yield as an ecological constraint rather than a residual quantity after logistics have been optimised. Long-run measurements and dynamic soil-

carbon models are required before robust climate-benefit claims can be made [13-15].

Direct OPT-specific literature provides a stronger reason for nutrient caution than analogy alone. Pulingam identify nutrient removal associated with taking felled trunks out of plantations, while Indonesian smallholder research documents widespread nutrient deficiencies that could compound the problem [7]. The appropriate scientific response is not to prohibit all OPT extraction but to measure trunk nutrient stocks by tissue fraction and estimate the cost, emissions and agronomic effectiveness of replenishment. Paired removal-and-retention trials should track soil nutrients, crop yields and organic carbon across multiple years so that permitted recovery can be adjusted to plantation conditions [7,36,37].

Conversion Technologies and the Feedstock-to-Jet Distinction
Oil palm trunks contain lignocellulosic structures and potentially fermentable carbohydrate fractions, which makes biochemical processing plausible after suitable size reduction, pretreatment and hydrolysis. Nonetheless, OPT is not a ready-to-use triglyceride feedstock for the established hydroprocessed esters and fatty acids (HEFA) route. Hydroprocessing of lipids applies to oil-rich inputs, whereas lignocellulosic OPT requires a different conversion chain, potentially involving fermentable sugars, alcohol-to-jet synthesis, gasification and Fischer–Tropsch conversion, or other approved intermediates. Confusing these technologies would distort chemical yields, hydrogen demand, capital expenditure and emissions. Cellulosic conversion studies underscore the significance of fermentation, catalysis and integration efficiency in overall viability [6,38-41].

Oil palm trunks contain lignocellulosic structures and potentially fermentable carbohydrate fractions, making biochemical processing plausible after size reduction, pretreatment and hydrolysis. Crucially, OPT is not a triglyceride feedstock for the conventional hydroprocessed esters and fatty acids (HEFA) route. Lipid hydroprocessing applies to oil-rich inputs, whereas lignocellulosic OPT requires an alternative chain that might include sugar fermentation and alcohol-to-jet conversion, gasification and Fischer–Tropsch synthesis, or other qualified intermediate-production processes. Lignin-rich streams may offer additional fuel and chemical options, although effective depolymerisation and catalytic upgrading remain research challenges. Conflating these processes would misrepresent hydrogen needs, carbon yields, capital costs and emissions [6,38,39,41,42].

Literature on non-OPT SAF routes helps frame comparisons, but transferability must be qualified. Hydrothermal liquefaction of wet organic biomass may reduce the need for extensive drying; pyrolysis-based systems offer different preprocessing demands; alcohol-to-jet facilities can use existing alcohol infrastructure in some circumstances [43]. None of these descriptions verifies certification or positive economics for a specific Indonesian OPT route. A responsible comparison distinguishes laboratory results, integrated pilot evidence, commercial reference plants and formally eligible fuel processes. The relevant decision metric is not maximum theoretical ethanol or syngas yield but independently validated drop-in SAF yield and whole-pathway emissions under representative operating conditions [40,44-47].

Methodology: Qualitative Literature Review
Design, Material Selection and Source Hierarchy
This study applies a critical qualitative literature review (QLR) rather than a systematic literature review (SLR). Its purpose is to interpret converging and contradictory arguments across policy, plantation ecology, fuel engineering, lifecycle accounting, supply-chain economics and certification governance. Evidence was identified iteratively through targeted searches for oil palm trunk, agricultural residue classification, CORSIA feedstocks, indirect land-use change, soil carbon, biochemical conversion and sustainable aviation fuel, emphasising reputable peer-reviewed journal literature published from 2020 to 15 October 2026. Citation tracing and thematic relevance guided the selection. The synthesis does not claim exhaustiveness, a registered protocol, PRISMA screening counts or statistical meta-analysis.

Source materials were differentiated by epistemic function. Official ICAO publications provide the authoritative policy definitions and rules applicable at the access date. The October 2026 IPOSS presentation supplies a stakeholder account of the proposed Steering Group agenda and Indonesia's technical concerns, but is not treated as an enacted policy instrument. Journal articles contribute empirical findings, engineering reviews, scenario evaluations and analytical methods. When an article analyses agricultural residues outside oil-palm systems, its contribution is limited to transferable mechanisms rather than represented as experimental proof about OPT. This distinction prevents a general result concerning logging or cereal residues from becoming an unsupported local value for Indonesia [13,15,48,24].

Technology eligibility should be checked against the relevant aviation-fuel production and product-qualification standards rather than inferred from successful laboratory conversion. Research on lignin-to-SAF chemistry identifies pathways for hydrocarbon synthesis, but it also documents the need for catalytic carbon-chain extension, deoxygenation and careful product-property control. Similarly, analyses of biomass-derived aviation fuels distinguish intermediate generation from the production of fuel that satisfies aviation specifications. This places integrated pilot testing, independent product characterisation and documented fuel finishing ahead of claims concerning commercial SAF yields from OPT [42,49,5].

Scientific sources were appraised qualitatively on proximity to OPT, relevance to the CORSIA question, transparency of methods, geography, lifecycle boundary, measurement time horizon and reported uncertainty. Evidence about Indonesian oil-palm agronomy was weighted more heavily for local extraction implications than abstract national biomass projections. Actual LCA data would receive more weight than headline climate claims based solely on generic default values. Where primary articles disagree, the review identifies differences in assumptions rather than manufacturing a single central estimate. This evidence hierarchy recognises that both aviation lifecycle analysis and plantation carbon accounting are sensitive to choices that may be reasonable yet non-equivalent [33,17,21,18].

Thematic Coding and Analytic Safeguards
The reading process was organised into eight thematic domains: regulatory ontology, carbon-accounting boundaries, ecological

counterfactuals, recoverable supply, conversion pathways, chain-of-custody assurance, distributive political economy and policy implementation. Initial coding captured reported mechanisms and assumptions; a second interpretive pass sought tensions among themes, especially between feedstock valuation and residue definitions, removal logistics and soil protection, and nominally zero ILUC and uncertain actual core emissions. Findings are presented as a narrative synthesis with explicit qualification, not as numerical pooled results or a forecast of OPT feedstock output.

Three safeguards were applied to avoid interpretive overclaiming. First, all dates and institutional descriptions are tied to the available status on 15 October 2026; no anticipated decision is reported as accomplished. Second, values highlighted by IPOSS for palm-oil HEFA and palm oil mill effluent (POME) are used only as illustrations of methodological boundaries, never as default OPT metrics. Third, plausible causal channels—such as nutrient depletion, induced removal, substitution effects and certification exclusion—are discussed as risks to be tested unless direct OPT-specific evidence exists. Multi-criteria decision research motivates this transparent combination of technical, environmental, economic and social criteria [3,22,19,23].

The review's methodological limitation is deliberate rather than concealed. Purposive selection cannot provide a prevalence estimate of all published findings, and inaccessible project-specific industrial data preclude empirical verification of conversion yields or commercial emissions. Some bibliographic entries concern adjacent feedstocks because OPT-specific SAF evidence remains emerging; they are marked as analogical wherever used. Findings are thus strongest as an evidence-informed decision framework and weakest as a basis for numerical ranking of plants, investments or national emissions reductions. The recommendations explicitly identify field measurements and independently audited actual-LCA work needed to move beyond this evidence stage.

Results: Thematic Findings

Table 1 consolidates the main thematic findings into distinct evidence tests. It clarifies why favourable feedstock classification, a large physical biomass inventory or promising laboratory conversion cannot substitute for validated carbon accounting, eligible fuel production and traceable governance. Each row represents a separate burden of evidence addressed in the sections that follow.

Table 1: Analytical Findings and the Independent Evidence Needed to Assess an OPT-Derived SAF Pathway

Analytical finding	Separate evidence test
Feedstock classification	Official designation and current status
Supply volumes	Realistic replanting recovery versus ecological removal
Carbon results	Assigned ILUC versus independently calculated actual core LCA
Fuel feasibility	Qualified finished SAF rather than laboratory precursor yields
Governance	Chain of custody, allocation, audit and farmer participation

As Table 1 shows, qualification is necessarily cumulative rather than inferential: verifying one condition does not establish the others. The comparison consequently provides an organising device for the narrative synthesis, not an empirical scorecard or a claim that any particular OPT project has already passed the tests.

Finding I: Residue Designation Changes Accounting Treatment, not the Physical World

The strongest institutional finding is that classification and environmental performance are related but non-identical decisions. OPT's association with plantation replanting gives a defensible basis for describing it as an agricultural residue, subject to the definitions and procedures actually adopted by ICAO. That designation matters because it may influence assigned ILUC treatment and the process by which actual lifecycle values are determined. However, an accounting convention cannot erase emissions from felling equipment, chipping, truck fuel, pretreatment, external heat, process hydrogen or waste management. Nor does it establish the amount of soil carbon that would remain in the absence of trunk recovery. The IPOSS presentation appropriately separates inclusion of OPT from the unfinished actual LCA and verification work [10,11,12,32].

Figure 1 represents these decisions as linked but non-substitutable gates. The first concerns source material and its physical provenance; the second tests the applicable residue definition; the third applies the corresponding regulated ILUC accounting treatment; and the fourth concerns full certification eligibility. Two parallel checks are essential: core lifecycle modelling measures operational burdens, whereas environmental-integrity safeguards examine extraction, carbon persistence and displacement. The figure therefore discourages the mistaken shortcut from 'residue' directly to 'zero-carbon certified SAF'. This gate logic is consistent with broader findings that SAF production and market recognition depend on coupled technology, policy and certification processes, not merely favourable feedstock labels [30,50,23].

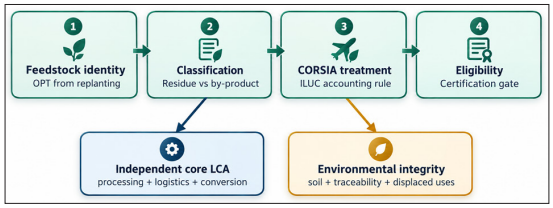


Figure 1: Separating feedstock identity, classification, regulated ILUC treatment and independent certification conditions. Conceptual synthesis developed by the author

A second institutional finding concerns temporal status. The October 2026 slides describe work proposed for the CAEP/14 Steering Group and subsequent engagement with WG5. They should not be cited as evidence that OPT already appears in ICAO's published positive list. This matters operationally: developers relying on a future policy outcome before it is formally documented could misstate eligibility or overvalue planned investments. Regulatory monitoring, decision-document retrieval and documented interpretation by the competent certification bodies are therefore preconditions for projects that

advertise CORSIA alignment. The broader literature on SAF regulatory and market risks supports deliberate sequencing rather than speculative claims based on expected decisions [2,51,31,23].

Finding II: Gross Trunk Biomass is not Sustainably Available Biomass

OPT arises periodically, not as a continuous mill output. Replanting age, location, ownership, machinery access, trunk dimension, transport distance and timing therefore define a dispersed resource landscape. A country may have a large physical stock of ageing palms without possessing a correspondingly large annual quantity of economically recoverable and ecologically removable trunks. The latter requires downward adjustments for water, inaccessible locations, field losses, competing demand and sustainability constraints. Research into Indonesian replanting and yields indicates that farm renewal itself involves complex timing and productivity considerations; SAF planning should not assume perfect alignment of these cycles across regions [35,16,25,24].

Figure 2 shows three successive supply estimates. Gross potential represents biomass physically generated by replanting. Technically recoverable volume deducts collection losses and logistical constraints. Sustainably available volume deducts the fraction needed for ecological functions or already committed to economically justified uses. Only then can process quality, actual LCA and verified certification be applied to estimate bankable supply. The visual distinction matters because a model that converts total standing trunk volume directly into litres of aviation fuel embeds unrealistically optimistic assumptions before conversion even begins. Regional residue studies and SAF supply-chain assessments repeatedly emphasise spatial and sustainability constraints in effective feedstock availability [13,24,48].

The supply funnel should also be treated as spatially and temporally dynamic. Wet trunks have short practical handling windows under some storage conditions, while replanting produces intermittent biomass flows that rarely match a refinery's continuous operating profile. Decisions about storage, decentralised preprocessing, aggregation and multi-feedstock blending should therefore be assessed jointly with land-management safeguards and verified finished-fuel yield. Multi-objective supply-chain analyses indicate that lower nominal procurement cost may be offset by higher emissions, losses or infrastructure requirements elsewhere in the chain; optimisation must reflect local evidence rather than a single national biomass total [16,52,25].

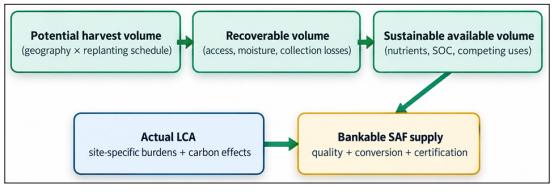


Figure 2: The narrowing funnel from gross replanting biomass to environmentally sustainable and commercially usable OPT feedstock. Conceptual synthesis developed by the author

Industrial estates and independent smallholders can face radically different recovery costs. Large holdings may coordinate contractors across planted blocks, while smallholders confront dispersed plots, limited equipment, constrained working capital and imperfect access to transport or certification services. In such conditions, aggregators could reduce collection costs, but they might also capture most of the new market value. The potential for OPT value creation should consequently be assessed against the opportunity costs of smallholder replanting, the support needed to preserve fertility and the administrative requirements of provenance documentation. Studies on certification obstacles and oil-palm livelihoods confirm that aggregate plantation performance is a poor substitute for explicit analysis of smaller operators [36,53-55].

Finding III: Counterfactual Carbon and Nutrient Pathways Can Reverse Simple Conclusions

When trunks remain on site, their physical carbon does not necessarily enter the atmosphere at the same moment or through one chemical pathway. Decomposition dynamics depend on tissue composition, particle size, climate, site hydrology and microbial activity. Some carbon may enter relatively persistent soil pools, and trunk placement may change microclimate or erosion exposure. Removing trunks therefore alters a time-dependent baseline; its impacts cannot be captured solely by crediting avoided open decomposition. Studies of palm-oil plantation carbon stocks, organic-residue application and soil decomposition demonstrate that management arrangements materially affect the direction and magnitude of soil processes, although they do not deliver a universal OPT removal factor [26,33,27].

Nutrient effects are similarly sensitive to context. A trunk's biomass exports mineral nutrients alongside carbon, and replacement may require mineral fertilisers whose manufacture and use cause their own lifecycle burdens. Under-fertilisation can undermine yields, potentially creating an indirect requirement for expansion or intensification elsewhere. This is particularly consequential in Indonesia's heterogeneous smallholder systems, where field research identifies nutrient deficiencies and imbalances. Conversely, partial retention, targeted fertilisation, returning appropriately treated process residues and site-specific soil management could mitigate damage. The sustainability test should therefore examine mineral balances, yield stability and long-term carbon effects jointly, rather than assess a one-time trunk removal without downstream plantation management [36,37,34,15].

Figure 3 formalises the counterfactual problem. Its baseline column asks what happens if the trunk remains within prevailing management; the intervention column covers collection and conversion; and the system-response column captures displaced material production, soil management and possible market feedbacks. The diagram then differentiates a regulated attributional LCA from a supplementary consequential sensitivity analysis. Such supplementary work should not be disguised as a change to ICAO's official prescribed method; rather, it supplies environmental due diligence about mechanisms that a narrow accounting boundary may fail to represent. General LCA research supports this explicit distinction between compliance calculations and broader policy assessment [14,21,18,19].

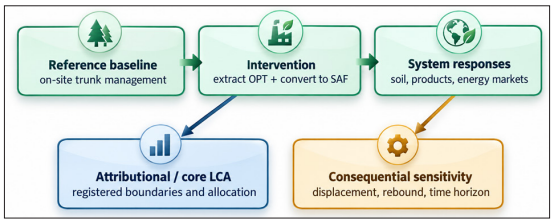


Figure 3: The physical counterfactual and the complementary roles of regulated core LCA and wider consequential sensitivity assessment. Conceptual synthesis developed by the author

Finding IV: Technological Plausibility does not Equal a Certifiable OPT-to-Jet Route

The available engineering literature supports multiple plausible biomass-conversion intermediates, but offers limited published evidence for a wholly integrated, economically proven and CORSIA-certified OPT-specific jet pathway. Biochemical strategies may extract fermentable sugars after pretreatment and hydrolysis, followed by fermentation and an alcohol-to-jet production sequence. Alternatives include thermal conversion to synthesis gas or upgraded liquids. Each configuration imposes different requirements for feedstock uniformity, drying, heat integration, catalyst performance and product upgrading. Studies directly involving palm biomass or OPT establish important chemical opportunities, whereas broader research on cellulose conversion explains why pretreatment cost and enzyme or catalyst efficiency remain central uncertainties [6,38,8,39,40].

Process selection should follow tissue-specific characterisation. High moisture may favour some processing approaches and penalise others, depending on energy integration and transportation distance. Sap-rich fractions may justify differentiated collection or fermentative use, while fibrous solids might be better reserved for another product stream. These distinctions alter product yields and burden allocation. Researchers have reported progress in OPT sap fermentation, hydroprocessing of lipids and hydrothermal liquefaction of wet feedstocks, yet those are distinct evidence classes. Directly equating their product yields, or equating crude alcohol production with aviation fuel delivery, would undermine technical credibility [56,41,46,47].

Comparative technology screening therefore requires a uniform functional unit: one megajoule of qualified aviation fuel at a specified delivery point, produced at credible industrial scale, alongside co-product treatment and uncertainty ranges. Early economic models should encompass field extraction, preprocessing, moisture removal, upgrading, utilities, hydrogen or electricity supplies, fuel finishing, distribution, certification and the cost of maintaining plantation fertility. Sensitivity scenarios should vary utilisation rates, capital expenditure and recovery efficiency. Studies of alternative SAF pathways and logistics consistently find that production cost and lifecycle performance depend strongly on process configuration and local infrastructure, making generic estimates insufficient for a bankable OPT project [2,57,25,44,45].

An additional engineering risk arises from treating the trunk as a uniform lignocellulosic material. Its sap-rich and fibrous portions may call for different pretreatment and conversion strategies, and the energy needed to reduce moisture content may be large relative to the value recovered from a marginal fraction. Lignin upgrading literature highlights both the promise and the remaining catalytic barriers of producing jet-range hydrocarbons from aromatic intermediates. The proper comparison is between fully specified routes that deliver certified-quality fuel, including energy and hydrogen requirements, rather than between isolated yields reported under incompatible laboratory conditions [38,42,49].

Finding V: Certification and Accounting Integrity are Major Design Variables

Traceability to point of origin should be treated as a technical architecture, not as an aspirational label. A certifiable OPT chain needs records for parcel identity, plantation replanting date, material ownership, volume harvested, intermediate storage, transport, conversion batch and any sustainability constraints imposed on removal. Evidence must be consistently transferred between landowners, aggregators, processors and fuel producers, with safeguards against duplicate registration of the same biomass. Digital platforms may aid these activities, but they cannot replace independent field verification and defensible measurement protocols. Work on digital systems in palm supply chains points to opportunities for more transparent emissions and transaction records alongside implementation challenges [58,55].

The potential for duplicated benefits is conceptually distinct from literal duplication of a physical batch. One problem arises if more than one actor claims the same carbon reduction; another occurs if incompatible product-system boundaries assign an identical avoided emission to several fuels. Interactions among crude palm oil, fresh fruit bunches, POME, trunk removal and by-product markets increase the importance of coherent allocation and explicitly stated counterfactuals. For example, a POME-based accounting credit should not automatically be attributed again to trunk-derived fuel merely because both arise within an oil-palm system. Book-and-claim arrangements, physical chain-of-custody systems and broader market-based instruments must each use clear rules about attribute ownership and cancellation [59,18,20].

The potential for duplicated benefits is conceptually distinct from double registration of a physical biomass batch. One issue occurs when two actors claim the same mitigation attribute, while another occurs when inconsistent system boundaries allocate the same avoided emission to more than one fuel or product. Accounting interactions among crude palm oil, fresh fruit bunches, palm oil mill effluent (POME), trunk removal and other by-product markets reinforce the need for coherent allocation rules and explicit baseline assumptions. In particular, a credit associated with a POME-based pathway must not be allocated again to trunk-derived fuel simply because both originate within an oil-palm landscape. Physical traceability, mass-balance systems and book-and-claim instruments involve different custody and attribute arrangements, and each requires robust rules for ownership, transfer and cancellation [20,18,59].

Discussion and Analysis

A Five-Gate Model of Credible OPT-Derived SAF

Synthesising the findings yields a five-gate decision model. Gate one is regulatory: confirm the adopted classification and the exact effect it has within the applicable CORSIA methodology.

Gate two is ecological: demonstrate that the proposed extraction fraction preserves soil functions, nutrient balances and legitimate land-management uses. Gate three is engineering: establish consistent feedstock quality and an approved conversion chain with verified operational performance. Gate four is carbon accounting: calculate actual core lifecycle emissions and appropriately distinguish the regulated ILUC rule from supplementary consequential sensitivity. Gate five is assurance and distribution: verify provenance, avoid conflicting environmental claims, and protect suppliers against the externalisation of new costs. Passing one gate does not presume passing the others; the model is therefore deliberately resistant to premature deployment claims.

The model offers an important correction to an overly linear vision of circular production. In practice, new demand for OPT can feed back into collection behaviour, local material prices, choices about biomass retention and the timing of supplier contracts. Technical design can similarly change sustainability outcomes, for example by making it economical to collect only certain trunk fractions or by returning treated process residues to plantations. Consequently, project appraisal should iterate between gates rather than progress once through a fixed approval checklist. The literature on decision screening, biorefineries and supply-chain planning supports such adaptive appraisal, particularly when uncertain costs, co-product values and environmental outcomes interact [8,22,16,25].

Several failure cases clarify why the model is useful. A project might possess favourable ILUC treatment but use fossil-intensive drying, leading to weak actual LCA results. Another might have good process yields but remove excessive biomass from low-fertility soils. A third could technically meet fuel specifications while failing traceability or double-claim safeguards. A fourth could deliver strong average emissions savings but exclude smallholders or rely on an economically unsustainable feedstock price. These are not hypothetical objections to OPT as such; they are structurally plausible scenarios that should be tested explicitly before making claims of superior climate performance. Recent analyses of SAF emissions, costs and certification likewise recommend joint risk assessment [3,30,21,23].

Interpreting Zero ILUC Without Undermining Environmental Integrity

The apparent tension between zero ILUC treatment and possible indirect effects can be resolved by separating a regulated accounting rule from a comprehensive scientific proposition. The rule is designed to specify how particular feedstock classes are treated consistently within an international framework. It is not intended to claim that biophysical, economic or managerial consequences never exist. A residue may receive zero assigned ILUC while the project still has direct operations, soil nutrient consequences and displaced uses. Maintaining this conceptual boundary protects both the legitimacy of the official methodology and the credibility of broader sustainability analysis. It also avoids treating discrepancies between ILUC models for crop-oil pathways as direct evidence about a physically distinct trunk pathway [17,14,21].

The original IPOSS briefing illustrates the risk of cross-pathway confusion. It presents POME HEFA as having an approved default core LCA of 18.1 g CO_2e/MJ, while separate slides compare GTAP-BIO and GLOBIOM estimates for palm-oil HEFA ILUC and discuss a model reconciliation result. These figures concern different input streams and modelling exercises. Their relevance to OPT is therefore methodological: they demonstrate how accounting boundaries, models and policy decisions may differ, not the numerical magnitude of the trunk pathway's own emissions. A new OPT actual-LCA study should specify conversion route, electricity and heat systems, transport radii, baseline treatment and co-product allocation before computing any result for comparison [10,12].

A robust research programme should quantify uncertainty at two levels. Within the regulated actual LCA, analysts should report the required methodological assumptions and empirical variability in major inventory inputs. Alongside it, scenario studies should examine uncertain decomposition baselines, substitution effects, replanting timing, nutrient replenishment and new demand responses, making clear that these analyses supplement rather than amend the official result. Reporting both layers reduces the risk of communicating a single deceptively precise number. Comparative fuel assessments demonstrate that assumptions about energy systems, scale, policy setting and alternative production routes can substantially change relative pathway rankings [21,48,44,19].

Sustainable Extraction, Additionality and the Time Dimension

A robust research programme should quantify uncertainty at two levels. Within the prescribed actual LCA, analysts should report the required boundaries, independently supported process inventories and variability in high-impact inputs. In a distinct supplementary analysis, scenarios should examine decomposition baselines, product substitution, replanting timing, nutrient replenishment and demand-driven recovery responses. Engineering-based mass and energy balances can reveal how hydrogen and electricity requirements affect operational emissions, while meta-analyses demonstrate that different conversion pathways remain sensitive to their technical and economic assumptions. Reporting the two analytical layers side by side avoids presenting a single point estimate as an exhaustive account of climate performance [29,21,44,19].

Time adds another dimension. Rapid collection and conversion may create emissions now while avoiding uncertain decay or fossil fuel emissions over later periods. Conversely, removal of a slow-decaying trunk may forego carbon storage and require fertiliser inputs that would not occur in the baseline. Studies should therefore present the time horizon, temporal distribution of fluxes and counterfactual assumptions rather than collapsing all carbon into an instantaneous event. Dynamic or scenario-based analysis is particularly valuable for perennial systems because a single replanting event affects management across subsequent production years. Evidence from soil-decomposition and residue-management research suggests that carbon responses can differ among treatments and horizons, reinforcing the need for long-term field observation [33,27,15].

Additionality should not be equated with the existence of an unused feedstock. A project creates a credible additional mitigation outcome only relative to a defensible reference situation and with appropriate recognition of displaced production, induced activity

and upstream burdens. This principle also affects competing uses: manufacturing durable materials from trunk fractions may temporarily store biogenic carbon or displace carbon-intensive products, whereas conversion to fuel may substitute for fossil aviation fuel. Neither pathway is always superior; results depend on service life, replacement materials, process emissions, market response and system boundary. An OPT cascade-use assessment would therefore compare integrated options rather than predetermine fuel as the socially optimal use [7,9,14,15].

Technology Portfolios and Commercial Feasibility

Indonesia could reduce investment risk by considering a portfolio of OPT utilisation routes rather than regarding all trunk fractions as a homogeneous input for a single large refinery. An initial research track should characterise fibre, sap, lignin and moisture distributions and assess their competing material uses. A second track should compare integrated pilot conversion pathways, including alcohol-to-jet, thermochemical routes and the catalytic upgrading of lignin-derived intermediates, with transparent product and energy balances. A third should establish actual LCA and techno-economic performance under representative Indonesian electricity mixes, transport distances and plantation-management conditions. Reviews of biomass SAF technologies identify process integration, catalysts, moisture management and feedstock flexibility as persistent obstacles to commercial scaling [43,39,42,49,46].

Commercial feasibility is sensitive to material handling and the timing of plantation replanting. A refinery requires sufficiently stable supply, whereas trunks arise in irregular geographical cohorts and degrade when stored or transported under unsuitable conditions. Aggregating across plantations can moderate the discontinuity, but it may raise transport distance, handling expenses and documentation costs. Decentralised preprocessing might reduce the movement of wet biomass at the price of additional distributed equipment and quality-control requirements. These trade-offs must be evaluated against regional geography, potential multi-feedstock operations, conversion scale and offtake contracts. Recent SAF supply-chain modelling research confirms that optimising one criterion alone can produce inferior financial or environmental outcomes when availability, logistics, certification and emissions are considered together [16,25,52,24].

Policy credibility also requires resisting the substitution of aspiration for demonstrated fuel qualification. Producing ethanol or bio-oil from OPT is not identical to supplying qualified aviation fuel at an airport. There are intermediate upgrading stages, energy inputs, catalyst demands, testing and chain-of-custody requirements. Demonstration data should therefore distinguish carbon conversion efficiency, intermediate product yield, finished SAF yield and airport-delivered cost. If a company presents only laboratory fermentation titres or theoretical syngas yields, investors and policymakers should regard the commercial jet pathway as unproven. Cross-pathway reviews document significant differences between technology maturity and production-cost projections, supporting stringent evidence thresholds [51,31,57,45].

Indonesia Evidence and Governance Roadmap

An Indonesia-specific roadmap should begin with a transparent regulatory dossier that describes exactly how trunks arise, why replanting is the independent driver of generation, how alternative uses are currently distributed and what elasticity of supply can reasonably be expected. This dossier should accompany monitoring of the CAEP/14 and WG5 decisions and the published ICAO source documents. A provisional national claim that OPTS belongs to the residue class may support technical dialogue, but it should remain explicitly conditional on the institutional process. A well-structured dossier could also identify which trunk fractions, farm types or supply chains might require different treatment because their economic functions differ [10,11].

Fieldwork should then use representative plantation clusters across regions and producer types, recording replanting year, trunk density, moisture, nutrient concentrations, soil class, current trunk disposal practices, transport access, tenure and use alternatives. Paired comparisons of retained and removed biomass, combined with long-run soil observation, would provide the baseline needed for sustainable-extraction guidance. Such work should deliberately include smallholder nutrient constraints and soil-management practices rather than assume industrial-estate parameters are nationally representative. Research on smallholder fertilisation, replanting productivity and sustainable livelihoods makes this representativeness requirement especially important [35-37,53].

Figure 4 organises the roadmap into five mutually reinforcing workstreams: regulatory, biophysical, supply-chain, technology and climate assessment. Independent verification connects the workstreams to a certifiable product. The diagram highlights an important ordering principle: attractive classification treatment should trigger empirical investigation, not bypass it. The pathway also makes clear that local universities, research institutes, regulators, certification bodies, operators and smallholder associations must share standards and data; no single organisation can establish the entire lifecycle and governance case. Digital tools can assist with provenance and emissions records but are effective only when field measurements and oversight institutions are credible [54,24,58,55].

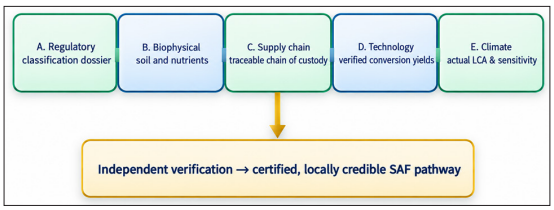


Figure 4: Five mutually reinforcing evidence workstreams for an Indonesian OPT-to-SAF development roadmap. Conceptual synthesis developed by the author

A phased implementation plan follows. During the first phase, authorities and researchers should clarify the decision status, produce technical definitions, map availability and establish a baseline protocol. The second phase should involve monitored pilot extraction, nutrient and carbon trials, representative conversion tests and externally reviewed actual LCA. The third phase should integrate certified chain-of-custody systems, reliable contracted feedstock supply, technology validation and conditional scale-up. An annual reassessment should examine changes in feedstock value and use, soil-monitoring results and any alterations to ICAO sustainability criteria. Such adaptive

governance responds to the evolving SAF-policy environment and uncertainty about large-scale supply ambitions [3,57,50,23].

Distributional Safeguards and Cross-Sector Policy Coherence
Developing a new aviation-fuel market from plantation residues raises questions of ownership, benefit sharing and long-term soil stewardship. Trunk biomass arises on land that may be held by industrial estates, operated through partnerships or controlled by independent smallholders. A transparent procurement contract should state who holds title to the trunk, who pays for felling and collection, who bears nutrient-replacement costs, how volumes are measured and how compliance premiums are distributed. Without these provisions, downstream fuel buyers may capture most of the value while farmers retain the costs of fertility management and certification. Studies of oil-palm livelihoods and certification show how documentation and transaction costs can determine which producers are able to participate in sustainability-labelled markets [54,53,55].

Value creation should also be coherent with Indonesia's wider palm sector, biodiversity commitments and low-carbon industrial development. A national SAF strategy that incentivises excessive biomass export at the expense of plantation productivity could undermine long-term agricultural sustainability. Conversely, policies that indiscriminately ban residue utilisation could forgo innovation and viable rural income. The appropriate objective is to identify win–win operating ranges, compensate necessary ecological stewardship and distinguish genuine new mitigation from shifts of emissions to other sectors. A distributional and system-wide lens is especially relevant in global aviation markets where fuel buyers and credit claimants may be far removed from the landscapes bearing production consequences [34,53,15,31].

Monitoring should include non-carbon indicators alongside lifecycle emissions: soil organic carbon, nutrient balance, yield response, erosion risk, smallholder income, contract transparency, verified material-use displacement and audit exceptions. Reporting such indicators prevents a narrow CO_2-equivalent metric from crowding out the mechanisms that generate climate performance. It also helps decision-makers identify cases were retaining particular trunk fractions, using them in longer-lived materials or returning process residues offers higher total value than full fuel conversion. Integrative SAF pathway assessment research demonstrates that technology and policy choices are best assessed through multi-criteria frameworks rather than assuming an emissions number alone can determine social acceptability [14,3,22,59].

Conclusion

Synthesis and Practical Recommendations

The proposed classification of oil palm trunk as an agricultural residue could open a strategically important avenue for sustainable aviation fuel development in Indonesia. Its value lies in clarifying how a stream generated during plantation renewal may be treated within the international fuel-governance system. However, classification must not be confused with approval of a specific production facility, fuel-conversion route or emissions value. Nor does it imply that all extracted trunk material is ecologically dispensable. Regulatory recognition creates an opportunity to produce evidence; it does not replace the obligation to produce that evidence.

The main conclusion is that a credible OPT pathway requires separate demonstrations of appropriate feedstock classification, sustainable availability, robust actual lifecycle emissions, technically qualified fuel production and independently verified supply-chain integrity. The distinction between prescribed indirect land-use changes treatment and real-world carbon and nutrient consequences is central. Failure to maintain it risks both scientific overstatement and reputational damage to legitimate circular-bioeconomy innovation. Successful development instead requires matching the evidentiary standard of the claim: policy status through official decisions, soil effects through field measurements, fuel performance through integrated conversion trials and carbon intensity through transparent lifecycle assessment.

Indonesia should prioritise five actions. First, establish an authoritative record of the ICAO classification process and applicable terminology. Second, map replanting-derived OPT and quantify recoverable, ecologically sustainable fractions rather than relying on gross biomass potential. Third, run long-term soil-carbon and nutrient-balance trials that represent industrial estates and smallholders. Fourth, support pilot conversion projects with verifiable process inventories and full airport-delivered fuel balances. Fifth, build interoperable traceability and certification systems that protect biomass ownership, distribute compliance costs fairly and prevent duplicate environmental claims.

Near-term policy should therefore remain conditional: an OPT designation is best interpreted as a possible regulatory enabling step, followed by actual LCA, sustainability verification and technology-specific certification. Medium-term pilots should test the economic and ecological trade-offs of collecting partial trunk fractions, returning organic residues and using hybrid biomass portfolios. Long-term scale-up should depend on independently reviewed field results, stable contracts, appropriate qualification pathways and documented benefits that remain robust under conservative assumptions.

The review is limited by the scarcity of published integrated OPT-to-SAF trials and by its interpretive, non-systematic selection of 2020–2026 literature. It does not calculate a national SAF production forecast or claim a measured OPT carbon intensity, because the necessary physical and commercial data are not available in the source materials. Future work should examine dynamic carbon accounting, supply-elasticity thresholds, soil-specific removal limits, comparative cascade-use options and distributional impacts under real certification conditions. With those safeguards, OPT could become a meaningful component of a diversified and scientifically defensible aviation decarbonisation strategy rather than a label-driven carbon claim.

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