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When Is POME a Residue? Definitional Boundaries, Carbon Accounting and Policy Integrity in Sustainable Aviation Fuel

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ABSTRACT

This qualitative literature review examines the definitional controversy surrounding palm oil mill effluent (POME) and its recovered oil as sustainable aviation fuel (SAF) feedstocks. Drawing on 52 cited peer-reviewed journal articles from 2020–2026 and official ICAO and certification documents, it distinguishes unavoidable wastewater, genuinely recovered residual lipids and deliberately diverted primary palm oil. The review interprets the CORSIA POME-HEFA default core lifecycle value of 18.1 g CO_2e/MJ, derived from two modelling estimates, without conflating its assigned indirect land-use change treatment with measured system-wide climate effects. Five thematic findings concern classification boundaries, model-dependent emissions, wastewater methane interactions, plausible recovered-oil supplies and an auditable chain of custody. An origin-and-function framework is proposed to preserve legitimate feedstock eligibility while preventing inappropriate relabelling, duplicate emissions claims and undocumented changes in oil flows. The discussion differentiates official fuel lifecycle accounting from supplementary assessment of methane management and displaced product markets. It recommends mill-level mass balances, independent verification, measured conversion inputs and an adaptive Indonesian policy roadmap. Definitional precision is necessary for regulatory credibility, but cannot substitute for reliable environmental performance or certified fuel production.

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Introduction

Aviation Decarbonisation and the Institutional Significance of Feedstock Identity

Commercial aviation has no immediate, universal substitute for liquid fuel in the long-haul segment. Sustainable aviation fuel (SAF) therefore occupies a prominent place in near- and medium-term decarbonisation strategies, but the term is not a guarantee of environmental benefit. Lifecycle greenhouse-gas emissions depend on feedstock origin, collection, conversion configuration, process energy, transportation and the rules for allocating burdens among products. These multiple dependencies become especially important when aviation fuel is claimed to arise from industrial waste. A waste label may correctly describe an unavoidable material stream while still concealing substantial processing emissions, or it may be misapplied to marketable oil deliberately diverted from normal production. For aviation regulators, the material definition is consequently an accounting input and a governance test, rather than a substitute for verified performance [1-5].

Palm oil mill effluent (POME) is produced during the extraction of crude palm oil (CPO) from fresh fruit bunches (FFB). It is primarily a high-moisture wastewater with substantial suspended and dissolved organic material, and its management affects both water pollution and methane emissions. An oil fraction can be separated from some POME-related streams; that fraction has a plausible role as lipid feedstock for the hydroprocessed esters and fatty acids (HEFA) route to SAF. Nevertheless, the wastewater, its residual oil and commercial CPO are not interchangeable substances. Studies of residual oil recovery and treatment technologies reveal substantial differences in composition, recoverability and process requirements. A policy that uses the common expression 'POME' without identifying which stream is being certified invites operational disagreement and weakens auditability [6-9].

The regulatory debate carries exceptional weight for Indonesia and Malaysia because palm oil mills constitute extensive, geographically dispersed industrial infrastructures. Their wastewater systems may include fat pits, settling tanks, anaerobic ponds, separate oil-recovery units and downstream polishing. Some facilities operate modern biogas systems, whereas others retain older configurations with different capture performance. The feasibility of recovering residual oil varies with equipment and operating practices, and certification costs vary with the maturity of record-keeping. A national SAF assessment cannot therefore apply a single mass-recovery percentage or carbon value without specifying its population of mills. Research on sustainable energy systems and process economics underscores why local infrastructure, wastewater operations and relative end-use prices shape both supply and emissions performance [10-12].

From POME-HEFA Approval to the 2026 Definitional Debate

The IPOSS presentation analysed for this review portrays the 2025 decision on the POME-HEFA route as a regulatory achievement and

describes the October 2026 Steering Group agenda as a process of consolidation rather than a renewed approval contest. The presentation identifies POME as a processing residue, reports an assigned zero indirect land-use change (ILUC) component and records a default core lifecycle emissions value of 18.1 grams of CO_2 equivalent per megajoule. The presentation, however, places the wording of POME's definition under scrutiny. The issue is not whether all industrial safeguards should be discarded, but whether terms such as unavoidable wastewater, sludge, residual lipid, acid recovery and diversion are sufficiently precise to distinguish authentic oil from re-labelled primary production. As a stakeholder working document, the presentation indicates the debate's framing; official ICAO documents determine the operative accounting methodology [13-17].

ICAO's supporting lifecycle methodology makes the emissions number more interpretable. Two modelling teams estimated core values of 18.98 and 17.15 g CO_2e/MJ for the POME-HEFA pathway, using different geographical and process assumptions. Their midpoint, rounded under the applicable procedure, yielded 18.1 g CO_2e/MJ. The analysis also records a correction of 5.6 g CO_2e/MJ if hydrogen for the HEFA process is produced from coal. These figures represent a specified modelled pathway and correction rule, not a measurement demonstrating that all mills or all recovered oils have identical carbon intensities. The range in transport and production contributions shows why a transparent pathway definition is needed before a default is transferred into commercial representations or national forecasts [18-20].

The importance of clarity becomes sharper when additional demand changes the price and treatment of formerly marginal material. A feedstock legitimately generated as an unavoidable residue may acquire commercial value without instantly losing that identity, but increased value can encourage extra collection, new extraction steps and stronger incentives to merge streams that were previously kept apart. Those responses create classification and verification questions even when neither deforestation nor deliberate CPO diversion is demonstrated. Contemporary SAF economics identifies logistical scale, transaction costs and access to certified volumes as determinants of investment viability. The central research problem is consequently how to recognise real wastewater-origin lipids while preventing misclassification and maintaining an environmental accounting boundary that does not award the same benefit twice [21-24].

Research Questions and Contributions

This article asks whether a defensible operational definition can identify POME wastewater and legitimately recovered POME oil without permitting a normal CPO stream to be relabelled. It asks how the economic character of the stream influences supply response, how official core lifecycle and assigned ILUC accounting should be interpreted, and how methane capture interacts with oil removal. Further questions concern plausible recoverable volumes, chain-of-custody assurance, competition among energy and treatment uses, and policies that support Indonesia's legitimate access to international SAF markets. Rather than making an empirical claim about national output, the article integrates these questions into an evidence-based decision architecture. The contribution is a conceptual and policy synthesis that separates physical classification, lifecycle performance, counterfactual effects and certification integrity [25,26].

Literature Review

A process-based Ontology of POME and Residual Oil

The terms product, co-product, by-product, processing residue and waste describe different relationships between production purpose, economic value and material generation. They should not be assigned solely from the colour, acidity or contamination of an oil sample. In palm milling, FFB intake initiates sterilisation, stripping, digestion, pressing, clarification and separation, while wastewater from several stages accumulates in a POME system. Residual oil may be dispersed in emulsions, attached to solids or recovered at identifiable liquid-treatment steps. For credible certification, the relevant questions include when the material entered the wastewater system, whether it was independently generated as part of routine milling, and whether other oil was later added. Recovery technology alone does not settle these origin questions [27,28].

A useful physical distinction separates bulk POME wastewater from oil recovered from POME and from other palm-oil-mill residues. Empty fruit bunch oil, pressed-palm-fibre oil, palm fatty acid distillate and sludge-associated fats can differ by origin, process and existing product definitions, even where commercial labels are similar. A recovered oil can have high free-fatty-acid content without automatically satisfying a specific POME-oil definition. Conversely, a stream may remain a legitimate residue after concentration or acidulation if the entire pathway from an eligible source is documented. Regulatory and certification evaluations must therefore trace the underlying origin rather than infer it from downstream chemical characteristics. The classification question is one of process provenance, material causality and auditable separation.

The IPOSS presentation describes POME as unavoidable wastewater and sludge streams arising from oil extraction and refers to a residual lipid fraction that can occur as free oil, emulsified oil or other fatty material. This wording provides an inclusive physical description but also creates an audit challenge: broad words may be useful for heterogeneous mills, yet fail to establish a precise negative boundary around intentional CPO diversion. International sustainability-certification guidance provides a comparator by distinguishing POME and POME oil while explicitly prohibiting the mislabelling of commercial oils. The institutional regimes should not be conflated, because CORSIA and ISCC have their own governing instruments. Nevertheless, the principle that the feedstock's origin must be documented is transferable and consistent with the broader literature on circular resource recovery [29].

Residue Status, Economics and Supply Elasticity

Residue status cannot be reduced to a claim that a substance has zero economic value. Historically underused POME oil may command a significant price when SAF markets reward documented low-carbon feedstocks, and this price can finance improved recovery technology. Such commercialisation is not necessarily inconsistent with resource efficiency. What requires scrutiny is whether rising demand induces additional primary oil production, new extraction from previously marketed CPO, or the deliberate adjustment of operations to produce more supposedly waste-derived material. The distinction between unavoidable generation and demand-responsive production may be tested through historical mass balances, FFB throughput, recovery method, sales records and input-output elasticities. Economic analysis of POME valorisation demonstrates that recovery opportunities are highly dependent on the physical mill configuration.

Material flows should be differentiated along at least three dimensions: the reason they arise, the step at which they are removed, and the economically feasible alternatives at the time of recovery. A treatment stream generated after routine milling has

a stronger prima facie residue claim than oil deliberately routed away from a profitable primary production system. This distinction is particularly useful when comparing sludge oil, trapped oil and oily wastewater that subsequently undergoes separation. The analytical test should allow genuine changes in recovery efficiency, since technology may reduce losses without changing primary output. It should also demand evidence that apparent yield increases do not arise from strategic relabelling. Such an approach simultaneously protects investment incentives and the credibility of sustainability claims [30].

Regulated Core LCA, ILUC and the Counterfactual

Lifecycle accounting begins by defining the functional unit, system boundary and applicable allocation rules. Under the CORSIA framework, the lifecycle value of an eligible fuel combines prescribed core emissions and the relevant land-use change component, with credits or adjustments where specifically permitted. A residue-classification rule may prescribe zero assigned ILUC for the eligible stream; this is not a universal declaration that the processing chain has zero emissions or that all downstream land and market effects are absent. POME-HEFA core emissions can arise through pumping, separation, chemicals, transport, hydrotreatment, hydrogen supply, utilities and fuel distribution. Additional environmental effects from wastewater management may be important but must not be inserted into a compliance calculation unless the operative methodology authorises their treatment. This separation prevents policy analysis from becoming misreported regulatory arithmetic.

Attributional and consequential lifecycle methods answer different questions. The regulated core calculation characterises the specified fuel pathway using prescribed allocation and inventory procedures, while consequential evaluation asks what changes if oil is removed, wastewater operations are modified or new markets emerge. These questions overlap but cannot be collapsed. Methane capture from anaerobic treatment, for example, can reduce emissions from wastewater management, yet an avoided-methane claim may already be embodied in another product's accounting or credited project activity. Similarly, displacement of an existing material use can change emissions outside the jet-fuel supply chain without becoming a separate permitted compliance credit. Rigorous reporting should keep the official CORSIA result distinct from supplementary sensitivity studies and disclose the rationale for both sets of boundaries.

Wastewater Treatment, Methane and Lipid Recovery Interactions

POME has high organic content and can produce methane under anaerobic conditions, making wastewater treatment a significant part of a palm oil mill's environmental profile. Covered digesters and biogas recovery systems can capture methane for power, process heat or upgrading, whereas uncontrolled ponds may permit more fugitive releases. Oil and long-chain fatty acids within POME can also influence anaerobic digestion stability; excessive concentrations may inhibit microbial activity and alter methane yield. Consequently, removing residual lipids may change wastewater treatment performance even before those lipids enter an aviation-fuel pathway. An integrated assessment should measure residual chemical oxygen demand, biogas production, fugitive emissions, energy replacement and final effluent quality. It should not assume that the oil-extraction and methane-management systems can be optimised independently without any interactions Recent experiments also show that biochar amendments and conductive carbon media can change digestion efficiency, microbial activity and methane production, reinforcing the need to establish a measured treatment baseline rather than infer emissions from feedstock labels alone. [31-35].

Alternative treatment technologies complicate the assumption that one baseline represents all mills. Membranes, advanced oxidation, aerobic polishing, microbial processes and biogas upgrading can materially change the carbon, energy and pollution profile of the residual water. Oil recovery before digestion might improve some operational outcomes while removing biodegradable material relevant to gas production, depending on the system. The energy and chemical burdens of separation or downstream purification can be equally significant. Because advanced technologies have distinct cost and maturity profiles, a useful policy framework should require mill-specific records rather than presume an idealised universal wastewater system. This is especially relevant when describing carbon savings associated with a hypothetical baseline that a particular mill had already abandoned Pilot-scale reactor research and comparative inoculum experiments further demonstrate that wastewater performance varies substantially with operating conditions and microbial communities, limiting the transferability of generic methane assumptions. [36-40].

The value of an integrated treatment approach extends beyond fuel. Biogas, water reuse, recovered nutrients, hydrogen production and other products compete for investment and operational attention. A mill with limited capital may prioritise methane capture and reliable water discharge over residual-oil recovery, while another may already have treatment infrastructure that permits additional recovery at modest marginal cost. A single product-specific financial model can omit these alternatives and consequently overstate the incremental attractiveness of SAF feedstock. Comparative life-cycle cost-benefit analysis of POME biogas systems illustrates the importance of local policy, engineering design and operational reliability. This supports evaluating oil recovery through a wider system perspective while carefully documenting which benefits actually accrue to the certified fuel Co-digestion experiments involving POME and empty-fruit-bunch pressing wastewater also illustrate the diversity of recoverable resource streams and why distinct materials should not be combined into a single unexamined POME-oil definition [41-43].

HEFA Technology, Traceability and Market Institutions

The HEFA route converts suitable lipids through hydrogen-consuming processing, upgrading and separation into jet-range hydrocarbons and other products. Its established technological base makes recovered POME oil an attractive potential input, but the oil must be characterised for water, solids, contaminants, acidity and other parameters relevant to pretreatment, catalyst performance and yield. The amount of usable finished SAF will be smaller than the gross wet mass collected from wastewater systems. Conflating wastewater tonnes, recovered oil tonnes, total hydrocarbon products and finished aviation-fuel output produces misleading supply estimates. Process comparisons should consequently report consistent units and measured conversion yields. Broader work on SAF technology identifies the feedstock-to-finished-fuel distinction as critical for transparent lifecycle and investment analysis [44,45].

Traceability makes classification operational. A credible chain of custody can connect each shipment to the originating mill, FFB throughput period, recovered stream, separation equipment, inventory movements and conversion batch. Mass-balance records can then be checked against plausible recovery ratios and independently verified source histories. Digital systems can

improve record continuity but are not independently reliable without physical measurements, trained auditors and rules for reconciling losses and mixing. Anti-diversion controls matter because higher regulatory or market value for a certified waste stream can motivate substitution. They also protect legitimate suppliers against unfair competition from incorrectly labelled primary products. In this sense, traceability is part of both technical quality assurance and economic governance [46].

Methodology: Critical Qualitative Literature Review

Study Design, Materials and Evidence Hierarchy

This study employs a critical qualitative literature review (QLR), not a systematic literature review or a quantitative meta-analysis. Its objective is to interpret conceptual ambiguities, policy choices and empirical mechanisms across disciplines that rarely share the same boundary conditions. Literature was purposively assembled from peer-reviewed articles published from 2020 through the information cut-off on 15 October 2026, with thematic searches concerning POME, POME oil, SAF, HEFA, methane, lifecycle assessment, residue classification, sustainability certification and supply-chain integrity. Relevant citations were followed iteratively to identify complementary evidence. No PRISMA count or claim of exhaustive database coverage is made. The review is designed to produce a transparent interdisciplinary narrative and research agenda, not a pooled emissions value or statistically representative estimate of feedstock supply.

A hierarchy of sources was used to prevent the elevation of advocacy into operative law. Official ICAO documents were treated as primary sources for CORSIA methodology and reported default calculations. The IPOSS briefing was treated as a stakeholder account of policy discussions and Indonesian strategic priorities; any unresolved CAEP/14 item remains a discussion until an authoritative institutional decision is published. ISCC documentation was used as a comparison of auditing and terminology in a distinct certification context, not as automatic evidence of ICAO rule equivalence. Peer-reviewed engineering articles supplied process mechanisms, treatment performance and economic analyses. Broader SAF studies were used analogically only where their transferability to POME could be explained. This distinction limits both institutional misstatement and cross-feedstock extrapolation.

Interpretive Synthesis and Safeguards

The analysis was organised around six themes: material identity, economic production response, compliance carbon accounting, wastewater-system consequences, engineering feasibility and certification governance. An initial reading identified definitions, variables, modelling assumptions and claimed benefits; a second reading examined contradictions, particularly between inclusive feedstock wording and anti-fraud safeguards. Evidence was assessed for physical proximity to a POME oil-recovery process, geographic relevance, transparency of functional units, treatment of uncertain baselines and explicit recognition of allocation rules. Priority was given to studies reporting mechanisms or operational data rather than unsupported market claims. Where results related to a different waste oil or fuel route, they were used to frame methodological principles rather than to impute a specific POME value.

Three safeguards guided interpretation. First, the 18.1 g CO_2e/MJ default was reported only for the documented POME-HEFA configuration and not as a general environmental score for wastewater treatment. Second, the assigned zero ILUC component was distinguished from both direct core emissions and broader system reactions. Third, no automatic credit was assigned for avoided methane or displaced CPO unless the specified boundary and additionality test would justify that credit. These limitations are particularly important where industrial data are commercially confidential or measurements of oil recovery are incomplete. The resulting contribution is an evidence framework for subsequent independent validation, rather than an investment-grade feasibility study or a certification opinion.

Results: Thematic Findings

Finding I: POME and POME Oil Require Distinct Names and Negative Boundaries

The literature consistently treats bulk POME as a wastewater management challenge, while much of the liquid fuel opportunity lies in recovering its relatively small lipid component. A legally and economically meaningful definition therefore needs a two-stage description. The first stage identifies the eligible wastewater or sludge origin within routine milling; the second identifies the oil recovery process and materials that must be excluded. This avoids the ambiguity of describing all recovered oil as the same substance. The essential negative condition is that oil intentionally diverted from the primary CPO stream, oil purchased elsewhere and other independently classified residues should not qualify merely because they are mixed into a tank called POME. The physical and documentary evidence must be congruent [47].

Figure 1 illustrates the proposed decision logic. It follows material streams from FFB processing into normal CPO output and wastewater-associated residuals, then separates genuine recovery from inappropriate re-routing. The eligibility branch is deliberately conditional: even properly sourced oil requires lifecycle and certification evaluation before SAF claims follow. The rejection branch does not imply that diverted or separately classified oil has no legitimate industrial use; it states that it cannot acquire the same waste-origin claim without satisfying the relevant rules for its actual class. The key innovation is to define the boundary negatively as well as positively, creating an auditable method that does not depend on the downstream chemical similarity of oils.

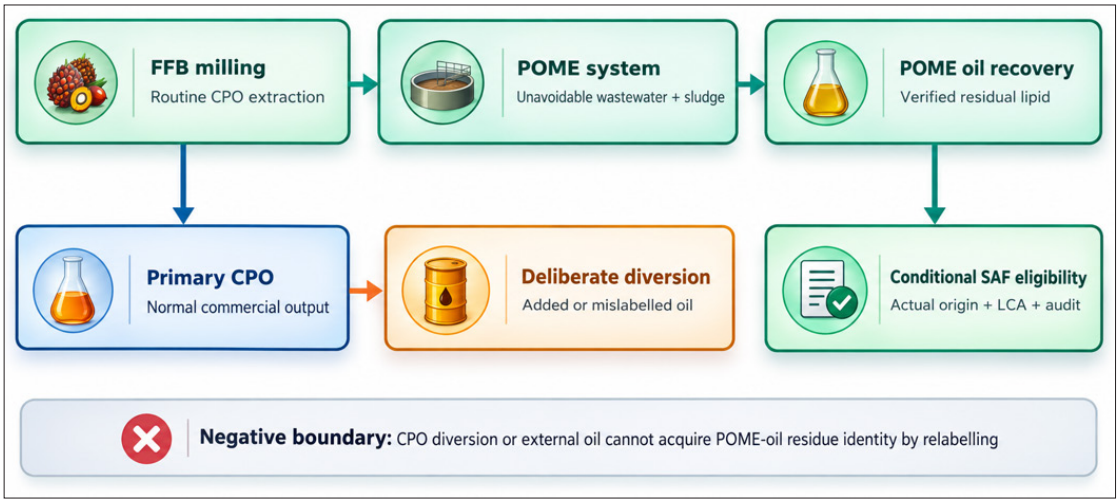


Figure 1: Source-and-Function Test Distinguishing Original Pome Wastewater, Recovered Pome Oil and Ineligible Primary-Oil Diversion

Conceptual Synthesis Developed by the Author

This distinction also clarifies the policy dispute about acid recovery. Acidulation or related processing can change acidity, phase separation and physical appearance without changing the original source of the oil. Conversely, a chemically similar acid oil can originate in a different refinery or processing stream. An eligibility framework should specify allowable transformations while requiring records that prove the feed material entered from permitted wastewater-origin streams. Technology neutrality is defensible only when paired with provenance specificity. An overly narrow ban on named processes may exclude genuine recovered residues, while a broad label based only on a final fatty-acid test could permit the laundering of higher-value oils. Process flow and mass-balance evidence are therefore more robust than chemical inspection alone. Table 1 sets out the corresponding material classes and audit evidence.

Table 1: Analytical Material Classifications and the Evidence Needed to Support a POME Feedstock Claim

Stream	Material identity	Primary audit test
POME wastewater	Unavoidable oil-mill effluent and sludge	Mill origin, process flow, physicochemical characterisation
Recovered POME oil	Residual lipid recovered from eligible effluent	Equipment, tank tracing, paired flow records
Transformed residue oil	Recovered oil after documented separation or acidulation	Prove continuous origin and no external additions
Primary CPO / external oil	Saleable main product or separately sourced oil	Cannot be re-labelled as POME oil by mixing

Table 1 turns these definitions into an evidence matrix that can be applied across different mill technologies. Its categories are intended for analytical comparison, not as a substitute for binding classification rules. The table makes explicit that plausible recovery and documentation requirements differ for original wastewater, residual oil, a transformed recovered fraction and a diverted commercial oil. That distinction also enables regulators to add specific anti-fraud controls without treating every form of wastewater oil recovery as suspect. The result is an administrable framework in which a project can know which supporting records are required before seeking certification or making public claims about climate benefits (Khan et al., 2025; Tang et al., 2024; Ding et al., 2026).

Finding II: A Low Default Core Value is Conditional, not Automatic

The 18.1 g CO_2e/MJ POME-HEFA default is supported by an identifiable modelling procedure rather than a single unexplained headline. The Indonesian expert estimate of 18.98 and the Hasselt University estimate of 17.15 g CO_2e/MJ reflect differences in feedstock collection, transport, conversion location and energy input assumptions. ICAO's supporting document describes their method and the rounded midpoint. The limited spread between these model estimates supports the internal consistency of the prescribed default calculation but not a guarantee that a particular producer's inputs match those assumptions. If a facility uses coal-derived hydrogen, the official sensitivity analysis specifies an additional 5.6 g CO_2e/MJ correction. Carbon intensity should consequently be reported with the applicable feedstock and pathway qualifiers, avoiding both unjustified precision and unqualified claims that every product meets the headline result.

The engineering importance of hydrogen source is not a minor reporting technicality. HEFA requires hydrogen to remove oxygen and adjust hydrocarbon properties, and the carbon footprint of that hydrogen depends on natural gas processing, coal, electricity or other inputs. Transport distance, preprocessing heat and energy mixes also change emissions, while feedstock impurities may affect pretreatment requirements. This helps explain why a residue's nominally low upstream land-use accounting component does not fully determine the finished fuel footprint. Investment screening should therefore ask for documented actual inputs or a defensible basis for using the published default, as well as clear fuel output and co-product allocation. Technology-specific calculations are more credible than generalised claims that all wastewater-derived aviation fuel is intrinsically carbon neutral [48].

The distinction from palm fresh fruit bunches and CPO-based HEFA is equally important. Those crop-oil pathways raise different questions about land demand, cultivation emissions and indirect land-use change. A modelled ILUC estimate for the main palm-oil route should not be applied to wastewater-derived oil as if the physical and economic feedstocks were identical. At the same time, this accounting distinction does not licence reclassification of primary palm oil as waste to escape an unfavourable crop-oil accounting result. The integrity of zero assigned ILUC depends on defending the feedstock's origin. A separate pathway identity must be preserved in the records, technical models and claims. This is why supply-chain origin documentation is an essential complement to lifecycle methodological sophistication.

Finding III: Recovery, Methane Capture and Water Quality Create Joint Effects

The physical treatment system links the aviation-feedstock discussion to the pre-existing problem of POME methane. The amount of residual oil that can be removed, the residual biodegradable load, the anaerobic reactor configuration and the fate of captured biogas jointly influence total mill emissions. Removing oil may in some cases reduce inhibitory long-chain fatty acid concentrations and assist digestion, while in other cases it removes organics that could have generated methane for energy use. These effects cannot be settled by feedstock classification alone. Empirical work on oil-related anaerobic process imbalance indicates that microbial responses are sensitive to composition and concentration. Scenario evaluation should therefore measure conditions before and after recovery instead of presuming a universal additional benefit The experimental evidence from alternative microbial and material-assisted digestion designs also indicates that methane yield is condition dependent, making a no-change assumption especially difficult to defend without paired measurement.

Figure 2 formalises the difference between a regulated fuel-system calculation and a supplementary wastewater-and-market analysis. The top branch contains the certified feedstock and finished SAF lifecycle within the prescribed boundary. The lower branch follows residual wastewater, methane emissions, biogas utilisation, process-energy displacement and possible product-market responses. Arrows indicate potential causal effects rather than an instruction to add every avoided emission to the official value. The separate branches allow policymakers to examine whether the overall intervention has net environmental benefits while keeping the compliance result methodologically coherent. This is particularly relevant when wastewater treatment improvements and SAF recovery are jointly financed but supported by different incentives or sustainability declarations.

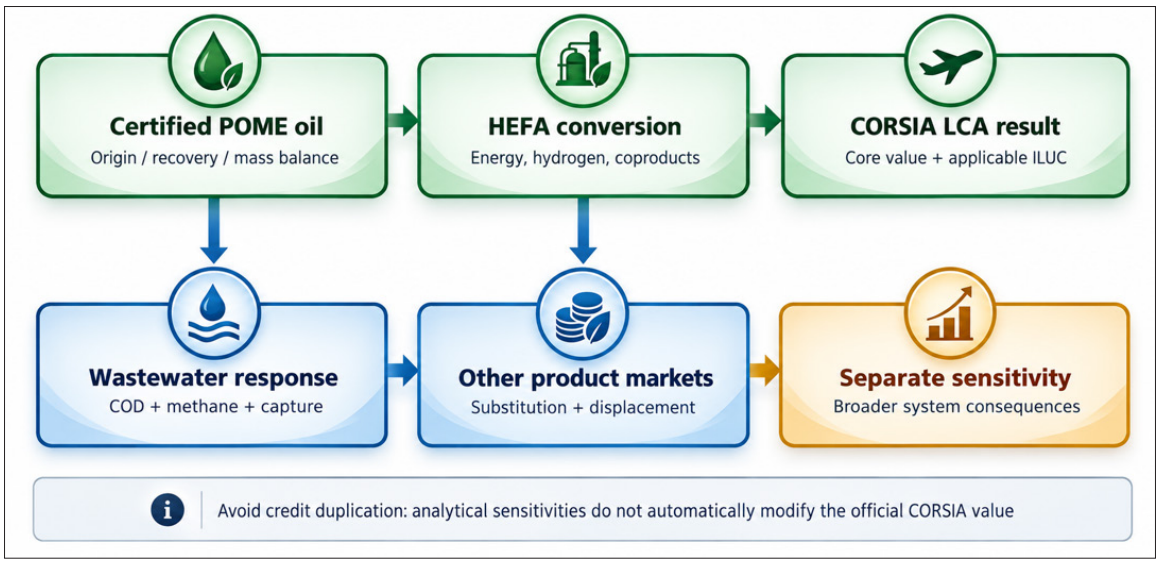


Figure 2: Complementary Regulated Fuel Lifecycle Accounting and Wastewater/Market Response Analysis, with an Explicit Boundary Against Double Counting. Conceptual Synthesis Developed by the author

Industrial resource-recovery research suggests that integrated approaches may offer benefits unavailable to isolated recovery systems, but only where operating conditions are appropriate. Membrane processes can support water reuse and biogas upgrading, oxidation can improve effluent treatment under particular conditions, and engineered anaerobic reactors can convert organic matter into useful energy. Each adds its own material and energy inventory. A systems perspective prevents an oil-recovery assessment from overlooking changes in downstream effluent quality or the fate of captured methane. It also discourages dual treatment of the same avoided emission as both a fuel credit and a separate mill-level reduction. Empirical monitoring, meter calibration and attribution rules are needed to determine which improvements are genuinely incremental. The compliance and supplementary questions are separated in Table 2 to avoid treating illustrative scenarios as automatically allowable credits.

Table 2: Compliance Variables and Supplementary Environmental Sensitivities Relevant to Pome-Based Hefa

Domain	Question	Recommended evidence
Fuel core LCA	Energy, hydrogen, treatment and transport inventory?	Pathway-specific audited inventory / default qualifiers
Assigned ILUC	Does the eligible feedstock meet prescribed residue rules?	Regulatory classification and origin evidence
POME methane	What changes after residual-oil extraction?	Paired COD, biogas and leakage measurements
Other products	Is another fuel/material use displaced?	Explicit market and counterfactual sensitivity
Attributes	Is a benefit counted or transferred more than once?	Claim ownership, retirement and traceability records

Table 2 lists the principal compliance and consequential sensitivities. It emphasises that a change in hydrogen source is a direct fuel-production inventory question, whereas altered lagoon methane or a displaced biodiesel outlet may require broader scenario analysis. A complete comparison also considers whether additional recovery modifies chemical demand, sludge volumes, final wastewater treatment or electricity generation. None of these pathways should be assigned an invented numerical credit in the absence of measurement and an applicable allocation rule. The purpose of the matrix is to guide data collection and reproducible analysis, not to imply that all listed mechanisms occur at every mill. The table also identifies the type of evidence that would permit a future transition from conceptual discussion to quantitative evaluation.

Finding IV: Gross Wastewater Production is not a Measure of Certifiable SAF Supply

Recoverable POME oil is bounded by the volume and composition of wastewater, the amount of oil genuinely entering an eligible stream, the installed recovery system and losses during pretreatment. Estimating eligible volume directly from national FFB throughput without separate checks can therefore exaggerate supply. Milling efficiency, equipment, process temperature, operator decisions, feedstock quality and treatment conditions change the percentage recovered. A genuinely successful improved separation process could raise recovery from previously lost oil without increasing CPO diversion, but the increase should be explainable through process records and engineering changes. Conversely, unexplained jumps in certified oil production above plausible site-specific yields are warning signals rather than evidence of extraordinary circular performance. The correct denominator, reference period and material balance are essential.

Figure 3 proposes a plausibility-and-custody architecture. It begins with verified FFB intake and the main CPO balance, proceeds through wastewater generation and source-specific recovery equipment, and reconciles recovered oil against storage and shipment records. A horizontal chain-of-custody layer follows the same batch into pretreatment and HEFA conversion; an independent audit loop tests anomalous ratios and unrecorded transfers. The diagram does not assign a universal maximum percentage, because genuine recovery differs among technologies and mill designs. Instead, it treats the plausible range as an evidence-based, revisable indicator conditional on measured process conditions. Such a design can identify likely misclassification without penalising operators who document innovative recovery efficiencies.

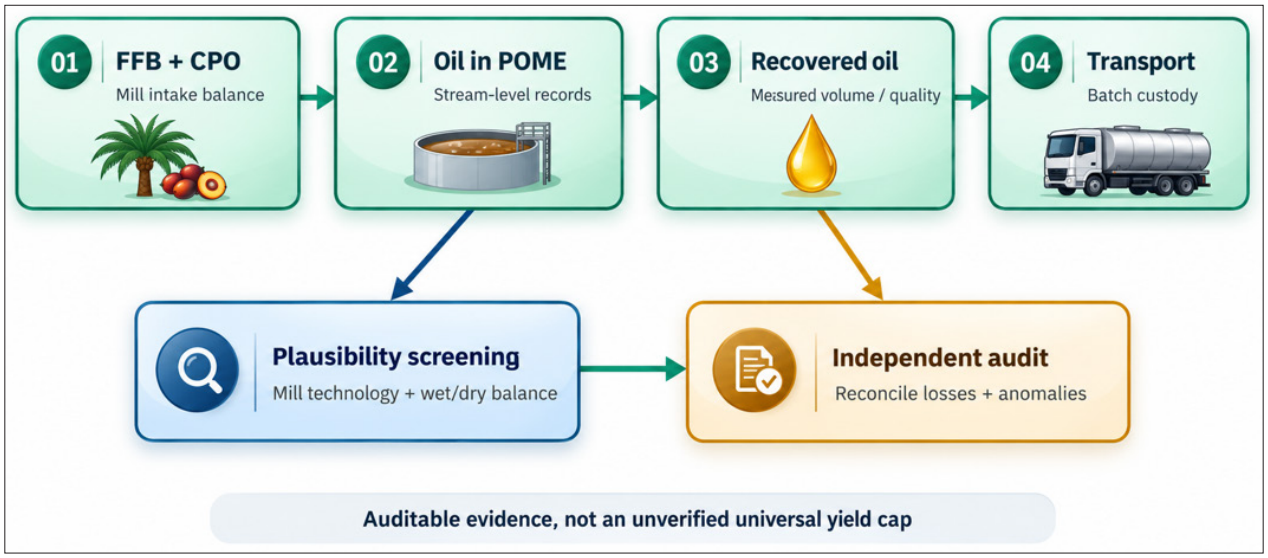


Figure 3: Mill-level Plausibility and Chain-of-Custody arcHitecture for Residual POME Oil, Culminating in Independent Verification. Conceptual Synthesis Developed by the Author

A risk-based audit should distinguish ordinary measurement uncertainty from material inconsistencies. Minor moisture variation may explain differences between wet-volume and dry-mass reports, whereas unexplained oil input from a CPO storage tank signals a different classification issue. Required records could include time-stamped flow measurements, sampling results, tank inventories, invoices, process diagrams, wastewater characteristics and independent laboratory confirmation. Source audits should also be repeated when equipment changes or prices substantially increase the incentive to divert oil. Digital ledgers can assist but cannot reconstruct missing physical evidence after the fact. Verification should therefore combine documentary reconciliation, in-person inspection and analytical testing rather than relying only on declarations or a centralised platform.

Finding V: Certification Design Affects Competitiveness and Inclusion

Certification is not simply a label affixed to a technically produced fuel. It determines which actors can demonstrate their feedstock origin, how conversion facilities allocate attributes, whether competing claims are compatible and which producers can access buyers. If the cost of origin verification is prohibitive, well-capitalised mills may gain preferential market access while less-resourced suppliers remain excluded. At the same time, weak verification could allow high-value palm oil to be sold under a residual-oil name, undermining the legitimacy of the entire market. Research on palm certification and smallholder supply structures demonstrates that documentation, transaction costs and bargaining power influence who receives the benefits of sustainability policies. A proportionate assurance regime needs strong physical tests and accessible compliance support [49].

The risks of double claiming extend beyond physical mislabelling. A producer may seek to claim avoided wastewater methane, a downstream supplier may attribute low-emission energy to another product and an airline may seek the benefit of certified fuel use. These can be compatible only under documented scope, ownership and cancellation rules that prevent identical environmental attributes from being counted repeatedly. Co-processing and book-and-claim systems add another layer of records, because fuel molecules and claimed sustainability attributes may not always travel together. International aviation accounting thus creates a strong demand for interoperable certification documents. It also justifies distinguishing emissions calculated for one functional unit of finished SAF from broader corporate decarbonisation achievements at the same mill.

Discussion and Analysis

Defining POME Without Replacing Science by Terminology

An expansive POME definition is attractive because wastewater systems are heterogeneous and rigid descriptions can exclude legitimate recovery technologies. However, breadth without safeguards may allow a commercially valuable stream to receive residue treatment through a change of label rather than a change in physical origin. An extremely narrow definition can generate the opposite distortion by excluding material genuinely extracted from a qualifying wastewater stream simply because the equipment is located before a traditional pond. The defensible middle course is a function-and-origin definition: identify the unavoidable mill wastewater mechanism, specify eligible residual lipid sources and processes, and prohibit additions or intentional diversion of primary saleable oil. This focuses on causality and mass continuity instead of prescribing one historical treatment technology for every country.

The definition should further distinguish a necessary environmental performance test from the classification test itself. A stream can be genuinely generated as a residue yet perform poorly as a fuel if hydrogen or process energy is carbon intensive. Conversely, an oil may have a favourable chemical profile and attractive process yield without being entitled to a particular residue classification. Treating both decisions separately makes official oversight more predictable: the first layer tests origin and economic generation; the second tests approved fuel pathway emissions and certification. Keeping these gates conceptually independent is especially useful when comparing different mills, because variance in process efficiency should not automatically redefine the ontology of material arising from routine operations.

A Dual-Track Carbon-Accounting and Environmental-Integrity Model

The proposed governance model uses two complementary but non-interchangeable tracks. The compliance track applies the currently recognised CORSIA pathway, valid default or permitted actual LCA calculation, any specified hydrogen correction and independent batch certification. The system-integrity track considers alternative wastewater baselines, observed methane leakage, diverted material markets, changes in CPO recovery and the possibility that apparently residual volumes respond to new fuel prices. The second track is valuable for strategic planning and environmental due diligence, but its results should not be presented as adjustments to an international compliance calculation unless rules expressly allow that treatment. Such transparency avoids creating arbitrary emissions credits while permitting robust interrogation of the broader climate case.

A central counterfactual question is what would have happened to the same oily wastewater in the absence of the SAF project. If the mill already captures methane, a comparison with an uncontrolled lagoon may overstate additional mitigation. If oil extraction changes digester performance, an analysis assuming unchanged methane output may miss a material trade-off. If recovered oil would otherwise be sold into a different biofuel market, its diversion to aviation might induce replacement production. These possibilities call for paired operating records, site-specific process inventories and market scenarios rather than generic waste assumptions. Attributional compliance remains necessary, but consequential sensitivity identifies vulnerabilities that can determine whether a formally eligible pathway advances broader decarbonisation objectives Laboratory enhancements in anaerobic conversion further suggest that feedstock recovery and wastewater treatment must be analysed against feasible site-specific operational alternatives.

For communication, policymakers should report several separate quantities instead of one undifferentiated ‘carbon-saving’ number. These include the feedstock’s documented classification, the prescribed lifecycle value of the certified SAF batch, measured wastewater methane improvements, any separately accounted energy displacement and the sensitivity of the result to alternative product markets. Each quantity has a different reference system and evidentiary burden. Combining them in a marketing claim without indicating potential overlap invites confusion. It is especially important not to use the relatively low POME-HEFA core default as a universal indicator of the environmental performance of palm oil cultivation or all CPO pathways. More specific reporting strengthens rather than weakens the legitimate climate contribution of high-integrity residual feedstocks.

Policy Trade-Offs in Indonesia and International SAF Markets

For Indonesia, international recognition of legitimately recovered POME oil can stimulate investment in collection, wastewater management, pretreatment and SAF supply chains. Those opportunities should nevertheless be evaluated against infrastructure constraints; domestic alternative uses and the distribution of additional value. A workable policy should protect the eligibility of genuine residues while enabling enforcement against mislabelled products. This requires clear origin definitions, country-specific mill datasets, mechanisms for independent audit and technical dialogue with international regulators. It also requires avoiding unnecessarily politicised comparisons in which any verification request is characterised as exclusionary or any residue application is automatically described as greenwashing. An evidence-based position can defend market access and scientific credibility simultaneously [50].

Technology choice affects the same policy problem. Some mills may recover POME oil with minor changes to existing separation equipment; others would need substantial capital expenditure for pretreatment, heating, transport and improved water handling. Centralised HEFA facilities can achieve scale economies but may increase shipment distances or create dependency on a small number of buyers. Distributed recovery can reduce wastewater transport but multiply quality-control locations and administrative costs. Published SAF supply-chain analyses show that spatial configuration and financing materially alter netback and environmental performance. The policy objective should be to create conditions for transparent comparison of configurations, not to predetermine a single industrial architecture before independent measurement.

The Indonesian approach can also connect POME residue policy with broader palm-sector sustainability without collapsing them into the same accounting category. The environmental liabilities of plantation expansion and CPO processing should be evaluated under their respective applicable rules. POME recovery can improve use of a stream generated by existing industrial operations, but that potential does not by itself certify plantation practices or resolve biodiversity and land-tenure issues. Procurement and certification systems should therefore preserve relevant upstream sustainability conditions where required while clearly identifying the distinct emission benefits associated with the fuel pathway. Small and medium suppliers need technical support to satisfy quality and documentation requirements, reducing the chance that a high-integrity certification market becomes inaccessible except to the largest vertically integrated firms [51].

The Evidentiary Roadmap: From Disputed Terminology to Auditable Fuel

Figure 4 arranges an Indonesian implementation roadmap into four successive but revisable phases. The first establishes a shared, origin-based regulatory dossier and maps actual mill flows. The second measures representative recovery and wastewater-treatment effects across multiple configurations. The third validates real conversion yields, full process inventories and mass-balance documentation under independent review. The fourth connects compliant fuel batches to certification and requires periodic updating when technologies or incentives change. This ordering ensures that classification is not treated as the sole investment risk or the final climate accomplishment. The arrows also permit feedback, because field evidence may reveal that definitions or audit practices require refinement before larger-scale implementation.

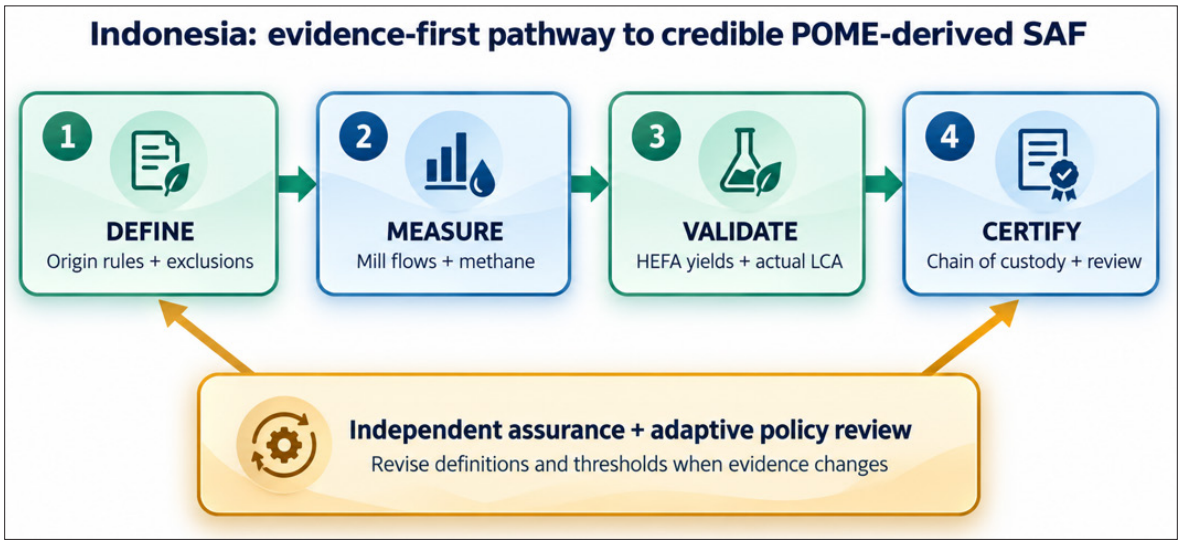


Figure 4: Four-Stage Evidence, Conversion and Certification Roadmap for Indonesian Pome-Derived Saf, Subject to Continuous Regulatory and Empirical Review.
Conceptual Synthesis Developed by the Author

The first phase should include a cross-agency technical group and a carefully documented discussion of the operative text in ICAO and other relevant schemes. Indonesia can support international engagement with evidence on how POME oil is recovered from fat pits, sludge, separation systems and downstream treatment units. The dossier should include explicit process maps and an exclusion protocol for CPO or oil from outside the defined stream. Differences between facilities should be documented rather than forced into a technologically obsolete template. The immediate product would be a decision-ready reference package: definitions, boundary diagrams, plausible recovery bands conditioned on mill type, and an auditable list of input-output records needed by certification bodies.

The second phase should establish representative monitoring at mills that differ in size, region, recovery technology and methane-treatment configuration. Field teams should record FFB intake, CPO output, oil-bearing effluent quantity, recovered residual oil, chemical oxygen demand, methane capture, treatment energy and recovered product specifications. Recovery yields should be expressed with transparent denominators and uncertainty ranges; chain-of-custody transfers should be testable against physical measurement. Paired comparisons before and after recovery would help quantify whether additional oil collection changes biogas or water-treatment performance. The resulting evidence should support a fair plausibility envelope, thereby separating genuine technological efficiency improvements from anomalous or unexplained production volumes.

The third phase needs independent process validation and a pathway-specific actual LCA where required or analytically valuable. Producers should disclose fuel yields, hydrogen and heat sources, transport, pretreatment inputs and co-product handling under the applicable approved methodology. The official default provides a useful benchmark and reporting route, but projects considering unusual energy supplies or process configurations should test whether its assumptions remain appropriate. An additional consequential assessment can evaluate the wastewater and displaced-oil scenarios without confusing those outcomes with the compliance score. Expert replication and methodological transparency are particularly important when studies are used to defend national policy positions or inform investment commitments.

In the final phase, certification and commercial procurement should be conditional on performance across several independently testable dimensions. Feedstock origin must be documented, material balances plausible, product quality compliant, lifecycle records complete and environmental attributes exclusively allocated. Auditors should be authorised to investigate unusual discrepancies or upstream changes in operations, and suppliers should have a clear procedure to challenge erroneous decisions. Annual reassessment is warranted because new technology and price changes may alter what is recoverable and how production responds to demand. This framework makes market entry predictable while maintaining adaptive enforcement, strengthening the prospects for authentic POME-derived SAF without permitting classification terminology to substitute for verifiable environmental results.

Limitations, Transferability and The Unresolved Research Agenda
The published evidence is stronger for POME wastewater treatment, biogas recovery and general lipid-fuel technology than for an independently observed, nationally representative set of POME-oil-to-SAF supply chains. The IPOSS presentation clarifies policy concerns but does not provide a public mill-by-mill database of physical recovery rates or audited diversion tests. Some engineering findings concern biodiesel production or water remediation rather than qualified aviation fuel; their relevance is mechanistic rather than a direct commercial certification result. The article's qualitative methodology also cannot establish the prevalence of any fraud allegation or the national quantity of eligible feedstock. These evidentiary limits are consequential because certification rules are often shaped by extreme or disputed cases, which may not represent ordinary industrial practice.

Future research should link industrial engineering, accounting and institutional analysis using consistent mill identifiers and transparent functional units. Priorities include quantifying the relationship between recovery incentives and physical oil routing; identifying robust analytical markers for source verification where practicable; testing how oil removal changes methane generation; and comparing multiple hydrogen pathways within actual SAF conversion inventories. Publicly replicable ranges would be more useful than a single optimistic estimate of national potential. Research should also examine how small or geographically remote mills can participate without disproportionate compliance costs. The strongest evidence will combine physical sampling, independent records, well-described scenarios and policy comparison, enabling revisions to definitions without eroding the central goal of preventing deliberate primary-oil diversion [52-66].

Conclusion

The discourse on POME as a sustainable aviation fuel feedstock is fundamentally a question about the relationship between material identity, regulatory accounting and environmental integrity. POME wastewater, oil genuinely recovered from that wastewater and commercially produced palm oil require distinguishable definitions. An inclusive origin-based framework can preserve legitimate resource recovery while excluding intentionally diverted primary oils. Classification as a residue is consequential, but it does not independently establish low-emission fuel performance or confer unrestricted certification eligibility. A successful policy must use unambiguous provenance rules together with measured physical flows and independently reviewed lifecycle calculations.

The established POME-HEFA core default gives stakeholders a concrete regulatory reference, yet its correct use requires recognition of pathway boundaries, process assumptions and specified corrections. Methane-management benefits, wastewater treatment outcomes and displaced material uses should be assessed in their appropriate accounting systems, with safeguards against multiple claims to one environmental improvement. Policy should not equate a zero assigned ILUC value with an absence of upstream or downstream environmental effects. Clear separation of these claims will make resulting carbon information more credible to regulators, purchasers, financiers and the wider research community.

Indonesia should prioritise a shared classification dossier, representative mill-level data, source-specific mass-balance guidance, monitoring of methane and wastewater conditions, and independent conversion and carbon audits. A staged process can allow legitimate recovery pathways to expand where robust data support eligibility while promptly addressing anomalous volumes or inappropriate labelling. The strategy should also recognise the costs imposed on smaller mills and create proportionate, technically defensible verification arrangements. International engagement will be most effective when it demonstrates repeatable evidence rather than relying on assertions of residue status alone.

This review is constrained by the absence of a comprehensive public dataset on mill-specific recovery and by the interpretive nature of qualitative evidence synthesis. It does not claim to quantify Indonesia's certifiable POME-oil volume, calculate an alternative official CORSIA default or establish the compliance outcome of any individual project. Future work should investigate source-specific recovery limits, methane-counterfactuals, hydrogen systems and potential market responses through independently replicable studies. With these safeguards, POME-derived SAF can be discussed as a conditional and potentially significant circular-bioeconomy opportunity rather than an unexamined consequence of a favourable feedstock label.

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