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From Waste Stream to Aviation Decarbonization Asset: Opportunities and Challenges of Palm Oil Mill Effluent (POME)–Based HEFA Sustainable Aviation Fuel Under ICAO CORSIA

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ABSTRACT: Sustainable Aviation Fuel (SAF) is widely viewed as a near- to mid-term pillar of aviation decarbonization because it can function as a drop-in fuel within existing aircraft and fueling infrastructure, while enabling substantial life-cycle greenhouse gas (GHG) reductions when produced from low-carbon feedstocks and robustly accounted for. Under ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), life-cycle accounting, including default and actual life-cycle emissions values, has become central to how airlines can claim emissions reductions from eligible fuels. Recent policy-relevant developments highlight Palm Oil Mill Effluent (POME)—a residue stream from crude palm oil (CPO) processing—as a potentially important SAF feedstock, particularly when POME oil is recovered and converted via hydroprocessed esters and fatty acids (HEFA). Drawing on a qualitative literature review (QLR) and policy-document triangulation, this paper synthesizes the opportunity and challenge landscape for POME-based SAF in supporting global aviation decarbonization. The thematic findings emphasize (i) carbon-accounting advantages linked to residue classification and low default life-cycle emissions factors, (ii) Indonesia's strategic potential as a large-scale residue-based SAF supplier, and (iii) governance requirements for credibility, including traceability, sustainability certification, and fuel accounting systems. Key challenges include supply-chain variability, measurement–reporting–verification (MRV) integrity risks, infrastructure and conversion constraints, and policy coordination across domestic allocation and trade. The paper concludes with policy recommendations focused on building trustworthy traceability and accounting architecture and aligning incentives to scale residue-based SAF without undermining broader sustainability expectations.

KEYWORDS: Sustainable aviation fuel; POME; HEFA; CORSIA; life-cycle assessment; default values; traceability; certification; aviation decarbonization; Indonesia.

1. INTRODUCTION

Aviation faces a difficult decarbonization challenge: demand for air transport is expected to remain structurally important for trade, tourism, and global connectivity, yet liquid hydrocarbon fuels still dominate the sector's energy needs for safety, range, and performance. In this context, Sustainable Aviation Fuel (SAF) has emerged as a key lever for emissions reduction, especially in the short- to medium-term when alternative propulsion options are not yet widely deployable at scale. ICAO's CORSIA framework has further elevated the importance of life-cycle greenhouse gas (GHG) accounting, as airlines' ability to claim emissions reductions depends on how fuels are classified, verified, and quantified under agreed methodologies (ICAO, 2025).

A major implication is that the world not only needs more SAF production capacity; it also needs an expanding portfolio of eligible feedstocks that can deliver credible and measurable life-cycle emissions savings. This paper frames this issue through a global demand narrative, citing projections that SAF demand could reach 515 million tons by 2050, implying intensified competition for sustainable feedstocks that comply with CORSIA criteria. In parallel, Indonesia—already a globally significant palm oil producer—has an opportunity to contribute to SAF scale-up through residues, wastes, and by-products associated with the palm oil value chain, provided that governance and sustainability assurances are credible and internationally accepted(Judijanto, 2025b).

This paper focuses on Palm Oil Mill Effluent (POME) as a residue-based feedstock pathway to SAF via HEFA conversion. POME is formed unavoidably during the processing of fresh fruit bunches (FFB) into CPO, and a portion of oil can be recovered from this stream as "POME oil," which can then serve as a lipid feedstock for HEFA SAF. It highlights a pivotal policy development: ICAO has set a default life-cycle emissions factor for POME-based HEFA SAF at 18.1 gCO_2e/MJ, presented as a global default value that enables substantial claimed reductions relative to a jet fuel baseline of 89 gCO_2e/MJ (Judijanto, 2025c).

Purpose and research questions

Using a qualitative literature review approach (not a systematic literature review), this paper aims to synthesize the opportunity and challenge landscape for POME-based SAF in supporting global aviation decarbonization, with a particular focus on the accounting and governance environment shaped by ICAO CORSIA. The guiding questions are :

1. What are the main opportunity narratives—technical, economic, and policy—supporting POME oil as a residue-based HEFA SAF feedstock?
2. What are the principal challenges—supply chain, MRV integrity, infrastructure, and policy coordination—that could constrain real-world deployment?
3. What governance and policy design elements are most critical to ensure credible scaling of POME-based SAF under CORSIA?

2. LITERATURE REVIEW

2.1 SAF pathways and why HEFA matters for waste/residue feedstocks

SAF is produced through multiple conversion pathways, commonly discussed in terms of ASTM-recognized routes such as HEFA, Fischer–Tropsch (FT), Alcohol-to-Jet (ATJ), and synthesized iso-paraffins (SIP). This paper emphasizes this pathway ecosystem and situates HEFA as a particularly relevant option for lipid-based feedstocks, including waste oils and residues. In the broader academic discourse, recent reviews similarly position SAF as central to aviation decarbonization, while highlighting that scale-up is constrained by feedstock availability, production costs, and policy uncertainty (Wang et al., 2024).

Among SAF pathways, HEFA is often described as closer to commercial maturity than some advanced routes, and it can process lipid feedstocks such as used cooking oil (UCO), tallow, and other residues. This matters for decarbonization because waste/residue feedstocks can reduce life-cycle emissions burdens by avoiding upstream cultivation emissions and induced land-use change (ILUC) in many accounting approaches, though such advantages depend on robust classification and verification(Prussi et al., 2021).

2.2 CORSIA and life-cycle accounting: default values, ILUC, and credibility

CORSIA is designed as a global market-based measure for international aviation, and it includes the use of CORSIA Eligible Fuels (CEFs) as a way to reduce airlines' offsetting requirements by claiming verified life-cycle emissions reductions. ICAO's "Default Life Cycle Emissions Values for CORSIA Eligible Fuels" document specifies general provisions on the use of default values for life-cycle emissions factor (LCEF) calculation and points to associated methodology documents and supporting guidance. This default-value architecture is significant because it standardizes claims at a global scale when project-specific "actual" values are unavailable, but it also shifts attention toward the integrity of feedstock classification, chain-of-custody, and MRV (Prussi et al., 2021).

A central feature emphasized in the literature is that CORSIA's LCA approach incorporates ILUC for relevant feedstocks and differentiates feedstocks by classes, such as main products versus residues/wastes/by-products, which affects whether upstream cultivation burdens are included. The same literature also highlights the global jet fuel baseline used for benchmarking, stating that the average life-cycle GHG intensity baseline for petroleum-derived jet fuel has been set at 89 gCO_2e/MJ (well-to-wake) in the CORSIA context. Complementary evidence underscores that petroleum jet fuel life-cycle emissions vary, which can influence interpretations of "savings" claims and the importance of harmonized baselines for policy comparability(Jing et al., 2022).

2.3 POME as a residue stream and why it enters the SAF conversation

POME is generated in palm oil mills during the processing of FFB to produce CPO, consisting of wastewater, oil, and solids; some oil that is lost during processing can be recovered from POME and is commonly termed "POME oil." From a feedstock-diversification perspective, It frames POME as a residue that ICAO has classified within a positive list of SAF feedstocks, aligning it with the broader "waste/residue/by-product" category that is increasingly emphasized for low-emission SAF options(Mohammad et al., 2021).

The scale question is crucial. ISCC estimates that recoverable POME oil potential can range from 0.76% to 2.88% of processed FFB, depending on mill configurations, implying that national-level volumes could be meaningful when aggregated across Indonesia's palm oil milling network. While such estimates are indicative rather than definitive across all mills, they support the strategic argument that residue-derived lipids could complement other SAF feedstocks, such as UCO and palm fatty acid distillate (PFAD), thereby expanding the domestic "feedstock basket" without relying solely on primary vegetable oils(Mohd Yusof et al., 2023).

2.4 LCA evidence for waste/residue SAF and the importance of default factors

The appeal of residue-based SAF is often expressed in life-cycle terms. In an Applied Energy article on the life-cycle CO_2e intensity of commercial aviation with specific SAFs, the highlights state that SAF derived from recycled cooking oil can reduce life-cycle emissions by 76–97% relative to fossil fuel. Although UCO is not identical to POME oil, the result is relevant because it illustrates the magnitude of reductions that waste-derived lipid feedstocks can achieve in LCA analyses when appropriate accounting assumptions and supply chains are in place (Bell et al., 2025).

For POME specifically, ICAO has set a default LCEF of 18.1 gCO_2e/MJ for POME-based HEFA SAF and interprets this as implying a 79.6% reduction relative to jet fuel at 89 gCO_2e/MJ, with the value applied globally. The same material provides a stage breakdown (collection/pre-treatment, transport, SAF production, SAF transport) and indicates that the default value is an average of two modeling efforts (Indonesia expert team and Hasselt University) that were verified and discussed in ICAO-related processes. In policy terms, this suggests that POME has moved from a "candidate" feedstock to an "accountable" feedstock with a recognized default emissions factor, which can influence investment interest and airline demand for credible low-LCEF SAF(Prayitno et al., 2023).

2.5 Governance, traceability, and accounting: why MRV becomes decisive

Scaling residue-based SAF requires more than technical feasibility. A recurring theme in the governance literature is that sustainability claims depend on chain-of-custody models, data quality, and transparent accounting mechanisms. ICAO's default-values document explicitly references supporting methodology documents and processes for adding new conversion processes or feedstocks, signaling that eligibility is not purely technical but procedurally governed. Additionally, supply chain research emphasizes that SAF supply chains face distinctive configuration challenges and require improved business models and system-level thinking to overcome cost and deployment barriers (Martinez-Valencia et al., 2021a).

Policy instruments such as blending mandates can accelerate SAF uptake but can also impose distributional impacts and cost pressures. A 2024 journal article on the impacts of a SAF mandate on airline-related outcomes explicitly frames SAF deployment as critical to achieving net-zero goals, illustrating that mandates are now a mainstream policy tool under debate in reputable transport-energy scholarship. Taken together, the literature suggests that the success of POME-based SAF hinges on credible traceability, consistent LCA accounting under CORSIA, and policy coordination that reduces uncertainty for investors and airlines (Chen et al., 2024a).

3. METHOD: QUALITATIVE LITERATURE REVIEW (QLR)

3.1 Design rationale

This paper employs a qualitative literature review (QLR) rather than a systematic literature review (SLR). The choice reflects the nature of the topic: POME-based SAF sits at the intersection of rapidly evolving international policy rules (CORSIA eligibility and default values), emerging industrial supply chains, and diverse sustainability narratives. In such contexts, a QLR is suitable for interpretive synthesis—mapping themes, tensions, and policy-relevant storylines—rather than attempting to exhaustively review all empirical studies in a PRISMA-style process.

3.2 Corpus construction

The review draws on: (i) post-2020 peer-reviewed journal literature addressing CORSIA LCA, SAF life-cycle emissions, and SAF supply chain configuration; (ii) select high-authority policy documents from ICAO relevant to CORSIA default values and LCA provisions; and (iii) a policy-anchoring case document describing the POME default value, eligibility framing, and an Indonesia-linked submission timeline. The literature was selected iteratively to represent three complementary lenses: carbon accounting (LCA/CORSIA), techno-economic deployment constraints (SAF supply chain), and governance/credibility (traceability and policy design)(ICAO, 2025).

3.3 Thematic synthesis procedure

Texts were read and coded to identify recurring "opportunity" and "challenge" narratives, followed by axial grouping into higher-order themes: (1) carbon-accounting advantage; (2) supply potential and industrial positioning; (3) governance and MRV integrity; (4) infrastructure and conversion constraints; and (5) policy coordination and market design. The themes were then used to structure the Results and Discussion sections and to derive policy recommendations aligned with CORSIA-aligned credibility requirements.

4. RESULTS: THEMATIC FINDINGS ON OPPORTUNITIES AND CHALLENGES

4.1 Opportunity themes

4.1.1 Carbon-accounting advantage under CORSIA: low default LCEF and residue classification

A key opportunity theme is that POME-based HEFA SAF has been assigned a low default LCEF in ICAO-related documentation, which can materially reduce the offsetting burden airlines face under CORSIA when SAF is used and properly claimed. It is reported that ICAO has established a default LCEF of 18.1 gCO_2e/MJ for POME HEFA, and frames this as a 79.6% reduction relative to a jet fuel baseline of 89 gCO_2e/MJ. In practical terms, lower LCEF values increase the emissions savings an airline can claim per unit of SAF, thereby reducing the volume of offsets required for compliance and improving the economic attractiveness of sourcing low-LCEF fuels (Chiaramonti et al., 2021; Gyandoh, 2025).

This theme is reinforced by the broader CORSIA LCA framework, which holds that residues/wastes/by-products can be treated differently from main-product crops with respect to upstream cultivation emissions and ILUC, which is one reason residue-based pathways are often highlighted as high-performing in LCA comparisons. The opportunity narrative is therefore not merely "POME can make SAF," but "POME can enable SAF that is especially strong in carbon accounting," assuming the residue stream is credibly defined and verified (Ambraziejus, 2025; Prussi et al., 2021).

4.1.2 Indonesia's strategic scale potential: a residue-based contribution to global SAF supply

A second opportunity theme concerns potential scale. It is reported that ISCC-based estimates indicate that recoverable POME oil can range from 0.76% to 2.88% of FFB processed, and present an illustrative national-scale calculation suggesting that, if roughly 1% is recovered across Indonesia's mills, the result could be about 2.5 million tons of POME oil. It has been suggested that, when combined with other lipid residues, such as UCO and PFAD, the total SAF potential in Indonesia could reach 2–3 million kiloliters. While these figures require careful validation against mill-level data and updated industrial statistics, they support a plausible strategic positioning: Indonesia could contribute to global SAF deployment not only through primary oils but also through residues that may carry lower life-cycle burdens in CORSIA accounting(Nugroho et al., 2024; Prabandari, 2024; Prussi et al., 2021).

This positioning is relevant to global aviation decarbonization narratives because global SAF demand projections imply a massive feedstock requirement, and residue-based sources can reduce pressure on land-intensive feedstocks when managed responsibly. The potential "global contribution" framing also matters diplomatically, because CORSIA is an international mechanism and default values are meant to function at a global scale.(ICAO, 2025; Martinez-Valencia et al., 2021a, 2023).

4.1.3 Policy legitimacy and market signaling: the significance of an ICAO default value

A third opportunity theme is the signaling effect that occurs when a feedstock pathway is assigned an ICAO-recognized default emissions factor. It has been described as a structured process of engagement—working papers, expert modeling, verification, and ICAO working group discussions—culminating in the amendment of the document and the establishment of the default value in late 2025. In market terms, such recognition can reduce uncertainty for project developers and airlines by providing a standardized basis for emissions claims, which is particularly important when voluntary or compliance-driven demand depends on verifiable carbon benefits(Haag, 2020; ICAO, 2025).

The governance literature suggests that harmonized methods and default values help reduce disputes over LCA assumptions and thereby facilitate market formation, even though they do not eliminate the need for credible chain-of-custody and verification. For POME, the existence of a default value can thus be interpreted as enabling infrastructure and commercial discussions to proceed with clearer carbon-accounting parameters than would be the case under purely ad hoc, project-specific claims (Chao et al., 2019; Martinez-Valencia et al., 2021a).

4.1.4 Circular-economy and waste-management co-benefits

A fourth opportunity theme is that valorizing POME oil can create incentives for improved waste and residue management at mills. POME is an unavoidable residue stream in CPO production, and notes that recovering oil from POME converts "lost value" into a feedstock for low-emission fuel. This supports a circular-economy narrative: residue recovery can reduce environmental burdens associated with unmanaged effluent and generate an additional revenue stream that may encourage investment in improved mill-level systems and monitoring(Akhbari et al., 2020; Judijanto, 2025a).

In addition, broader SAF supply chain scholarship emphasizes the importance of system-level approaches and the integration of services and business-model improvements to make SAF supply chains viable; residue valorization fits within such "supply chain innovation" narratives (Baxter, 2021; Martinez-Valencia et al., 2021a).

Beyond the direct emissions-accounting advantage, valorizing POME oil for SAF can strengthen mill-level environmental management by converting an unavoidable effluent stream into an auditable, revenue-linked resource that supports improved operational controls. Because POME is generated during FFB-to-CPO processing and contains recoverable oil, establishing recovery systems facilitates tighter monitoring of losses, improved handling of effluent streams, and clearer documentation of material flows, which can later support sustainability claims. In practice, this "waste-to-value" logic can help align environmental compliance incentives with productivity goals at palm oil mills, especially when downstream SAF demand rewards consistent quality and traceable provenance(Firdaus, 2025b; Lopez-Gomez, 2024).

At a system level, circular-economy co-benefits depend on whether POME recovery is embedded into a coordinated SAF supply chain rather than treated as an isolated mill upgrade. The supply chain literature emphasizes that SAF requires deliberate configuration—linking feedstock sourcing, logistics, processing capacity, and business models—so POME valorization can catalyze broader integration across mills, aggregators, and conversion facilities when governance and data systems are aligned. This integration can also reinforce the credibility of residue-based decarbonization narratives by operationalizing traceability and "fuel accounting," rather than merely as policy aspirations, thereby strengthening the long-term legitimacy of POME-based SAF in global markets(Firdaus, 2025a; Martinez-Valencia et al., 2021b).

4.2 Challenge Themes

4.2.1 Supply-chain realism: variability in recovery rates, quality, and logistics

A first major challenge is the variability of POME oil recovery across mills and the logistics of aggregating residue streams into a consistent, certifiable, and industrially usable feedstock. It has been noted that recoverable proportions depend on mill characteristics (e.g., different sterilizer systems), and the implied range (0.76%–2.88% of FFB) indicates that supply estimates can change substantially across facilities. This variability has direct implications for project finance, as HEFA plants require stable volumes and consistent quality specifications, and residue streams can be heterogeneous (Chan & Chong, 2019; Langston & Schult, 2025; Mohd Yusof et al., 2023).

A related issue is collection and transportation. LCA stage framing explicitly includes collection/pre-treatment and transport to a SAF plant, indicating that logistics and handling are nontrivial. Even when transportation emissions constitute a smaller share of the total LCA across many pathways, logistics can dominate operational complexity, especially when residues are distributed across multiple mills and must be consolidated with traceable documentation(Hülagü et al., 2025; Martinez-Valencia et al., 2021b; Saxe & Kasraian, 2020).

POME oil supply is inherently heterogeneous because it depends on mill configurations, operating practices, and the practical recoverability of oil from an effluent stream rather than from a purpose-grown commodity oil chain. It is estimated that recoverable POME oil ranges from 0.76% to 2.88% of processed FFB, depending on mill-system characteristics, implying that upstream variability can materially affect bankable feedstock volumes for HEFA SAF plants. The broader SAF supply-chain literature stresses that feedstock selection and availability are decisive constraints for SAF scaling, making "variable residue streams" operationally more challenging than standardized commodity feedstocks unless aggregation and quality systems are deliberately designed(Ho et al., 2025; Martinez-Valencia et al., 2023).

Logistics and handling further shape feasibility, as residues must be collected, pre-treated, and transported while maintaining an auditable chain of custody and consistent specifications. In the LCA boundary illustration for POME-based SAF, collection/recovery and transportation are explicit life-cycle stages, signaling that real-world deployment must solve material-flow coordination across multiple nodes (mills → transport → conversion → blending → airport). Consistent with this, a review of SAF supply-chain configuration highlights that SAF value chains require tailored network designs—covering biorefinery siting, transportation, and business models—because "one-size-fits-all" renewable fuel logistics do not automatically deliver cost parity or scalable deployment for aviation fuels(Aprilianto & Rau, 2025; Martinez-Valencia et al., 2021b).

4.2.2 MRV integrity, traceability, and the risk of contested "residue" claims

The second challenge theme concerns credibility. Residue-based advantages in LCA accounting depend on correct classification and trustworthy chain-of-custody, because residues can be vulnerable to mislabeling, double counting, or ambiguous boundaries between "by-product," "co-product," and "waste." The CORSIA methodology literature emphasizes that feedstock classification (main product vs. residue/waste/by-product) is important because it defines the LCA boundary, particularly whether upstream cultivation emissions are included. This means that a residue pathway's carbon advantage is only as strong as the governance systems that verify its residue status and track it through conversion and use(Baledon et al., 2023; Prussi et al., 2021).

It has been directly identified this governance requirement by recommending a robust traceability system for POME and regulation aligned with ICAO-recognized sustainability certification schemes, along with the creation of fuel accounting systems for emissions claims. The implication is that "default value recognition" is not the end state; the practical ability to monetize carbon savings depends on auditable records, consistent documentation, and aligned certification and accounting rules(ICAO, 2025; Nik Ibrahim et al., 2022; Rozali et al., 2025).

Residue-based SAF pathways derive a substantial portion of their climate value from classification and boundary-setting in life-cycle accounting, which makes MRV (measurement–reporting–verification) integrity a first-order concern rather than a compliance afterthought. The CORSIA LCA framework has been analyzed as an internationally adopted approach for calculating life-cycle GHG emissions for aviation fuels, underscoring that claims depend on standardized methods and the consistent application of rules across fuels and feedstocks. In parallel, policy research on waste-oil markets highlights how competitiveness and policy incentives can interact with "certification integrity" concerns for waste-derived feedstocks, illustrating that the economics of low-carbon claims can create pressure on verification systems when incentives are strong and oversight is uneven (Pan et al., 2025; Steinbach, 2025).

For POME-based SAF, this risk translates into a governance requirement to demonstrate that POME oil is a legitimate residue stream and to ensure that volumes are tracked from mill recovery through conversion and final fuel delivery without double-counting or misclassification. The recommendations explicitly call for building a robust POME traceability system and developing "fuel accounting systems" aligned with ICAO-recognized sustainability certification schemes to enable credible emissions-saving claims. This emphasis is consistent with the broader CORSIA methodology literature, which treats eligibility and life-cycle quantification as procedural and evidence-based, implying that low default values deliver real decarbonization benefits only when supported by auditable documentation and reliable chain-of-custody controls (Davies et al., 2022; Prussi et al., 2021).

4.2.3 Infrastructure and conversion constraints: HEFA capacity, hydrogen, and distribution to aviation hubs

A third challenge is that even if POME oil is available, conversion capacity and supporting inputs (including hydrogen and utilities) must be developed or repurposed. The CORSIA LCA methodology literature notes that HEFA pathways include energy and material inputs for oil extraction and the HEFA process itself, including hydrogen requirements and other fossil or renewable energy inputs that affect life-cycle results. This highlights a structural constraint: scaling HEFA SAF is not only a feedstock issue but also an industrial infrastructure and energy-system issue(Becken et al., 2023; Prussi et al., 2021; Uddin & Wang, 2025).

Supply chain configuration research further indicates that SAF supply chains differ from road-fuel supply chains and require optimized networks of biorefineries, transportation, and business models to address cost-parity and deployment challenges. In Indonesia's case, this points to the need for integrated planning: residue collection systems, conversion plants, blending logistics, and distribution to airports must be coordinated rather than treated as isolated investments(Kokkinos & Emmanouilidou, 2023; Martinez-Valencia et al., 2021b).

Even when a low-carbon residue feedstock is available, scaling SAF requires industrial capacity and supporting inputs that are not readily available in the right places or at the right scale. The SAF supply-chain configuration literature emphasizes that biorefinery siting, transportation networks, and business-model design are decisive for overcoming cost and deployment barriers, implying that POME-based SAF requires coordinated investments across collection hubs, conversion facilities, and downstream distribution. In the POME-to-SAF LCA boundary definition, the pathway explicitly includes transport to a SAF plant, subsequent transport to blending locations, and transport onward to airports, highlighting that “getting fuel to wing” is a multi-stage infrastructure problem rather than a single-plant problem(Martinez-Valencia et al., 2023; Raab et al., 2024).

Conversion-route constraints also matter because HEFA production is embedded in a broader energy and material system in which hydrogen and process energy can affect costs and life-cycle outcomes. The CORSIA LCA approach is explicitly designed to quantify life-cycle GHG emissions for aviation fuels across pathways, implying that upstream inputs (including processing requirements) must be accounted for consistently to preserve credibility and comparability of SAF claims. A recent analysis of SAF mandate impacts in the airline context further illustrates that policy-driven uptake interacts with real-world supply and operational constraints, so infrastructure readiness (conversion capacity and distribution logistics) becomes central to whether mandates translate into actual fuel switching at airports(Chen et al., 2024b; Jakimovska, 2025; Okunevičiūtė Neverauskienė et al., 2025).

4.2.4 Policy coordination, domestic allocation, and trade classification issues

A fourth challenge theme is policy coordination. It has been highlighted that there is a need to regulate the domestic versus export allocation of POME and to revisit classification issues, such as HS code distinctions, to ensure that POME is uniquely identified and not conflated with similar products. This speaks to a broader governance tension: residue streams can become economically valuable, thereby triggering competing policy objectives (e.g., domestic energy security vs. export revenue) and creating pressure for clear definitions and controls(Yusof et al., 2024).

Policy mandates can also quickly reshape incentives. A 2024 journal article examining the impacts of a SAF mandate indicates that such mandates are increasingly central to SAF deployment pathways and can influence airline costs and system outcomes. For POME-based SAF, this means that national or regional mandates could increase demand for low-LCEF fuels while intensifying scrutiny and competition, making robust governance and public legitimacy even more important(Chen et al., 2024b).

Residue-based SAF scaling can be constrained by regulatory fragmentation—across energy policy, industrial standards, environmental governance, and trade administration—because each layer influences how residues are defined, incentivized, and monitored. In this case, policy coordination issues are explicitly flagged: the need to regulate domestic versus export allocation of POME and the need to review HS code classification so that POME is uniquely distinguished from similar categories to support clearer market governance. These issues matter because inconsistent definitions and weak classification can undermine traceability and invite disputes over whether a feedstock qualifies as an eligible residue stream in international markets(Prussi et al., 2021).

Policy instruments that accelerate SAF demand—such as blending mandates—can also exacerbate coordination challenges by increasing the economic value of eligible feedstocks and intensifying scrutiny of accounting integrity. A recent transport-economics study on the impacts of SAF mandates underscores that mandates are actively debated as a decarbonization tool, with implications for airline outcomes, reinforcing that policy design choices shape both incentives and distributional effects across the aviation system. Within a CORSIA-aligned environment, harmonizing domestic rules (allocation, classification, verification) with internationally recognized life-cycle accounting approaches is a practical requirement to convert “policy recognition” into stable investment signals and credible export opportunities (Chen et al., 2024b).

4.2.5 Competing demand across biofuel sectors

Finally, there are potential trade-offs across sectors. It has been noted that POME can also serve as a biodiesel feedstock, and that if CPO production declines, POME could become an alternative, implying interactions with existing biofuel markets. This highlights a coordination challenge: residue-based resources can be reallocated toward whichever policy regime offers stronger incentives, potentially creating volatility unless rules are aligned and long-term signals are credible (Kacaribu et al., 2025).

Competition for low-carbon lipid feedstocks is intensifying as multiple decarbonization policies reward materials that score well in life-cycle carbon accounting, which can lead to price escalation, supply tightness, and integrity risks in waste/residue markets. Scholarship on SAF supply-chain configuration emphasizes feedstock constraints as a central bottleneck for scaling, implying that any residue stream capable of supporting HEFA (including POME oil) will face strategic allocation decisions when multiple sectors (road fuels, aviation fuels, oleochemicals) compete for the same limited pool. This competitive landscape underscores the importance it treating POME oil not only as a technical option but also as part of a contested low-carbon feedstock economy shaped by policy incentives and verification capacity

(Martinez-Valencia et al., 2021b; Noor et al., 2026; Nur Izzati et al., 2024).

In Indonesia's policy narrative, it has been noted that POME is also noted as a biodiesel feedstock, and it is framed as an alternative resource, particularly when CPO production fluctuates, highlighting the possibility of cross-program competition and substitution. Managing these trade-offs requires rules that clarify priority uses (domestic blending versus export; aviation versus road fuels) while ensuring that carbon claims remain consistent with internationally accepted life-cycle accounting principles. The practical implication is that POME-based SAF strategies should be designed alongside broader biofuel governance—so that incentives do not unintentionally create scarcity, volatility, or integrity challenges that could weaken both emissions outcomes and public legitimacy(Judijanto, 2025c; Martinez-Valencia et al., 2021b).

5. DISCUSSION AND ANALYSIS

5.1 What changes when ICAO sets a default value for POME HEFA?

The establishment of a default life-cycle emissions factor for a specific feedstock–conversion route should be interpreted as an institutional "permission structure" for carbon accounting, rather than as a guarantee of physical scaling. ICAO's default-values document provides the general architecture for the use of default values in LCEF calculations, underscoring that default factors are part of a broader methodological system that also includes actual-value methodologies and eligibility provisions. Within that architecture, it has been reported that the default value for POME HEFA matters is 18.1 gCO_2e/MJ, as it can significantly improve the economics of claims under CORSIA compared to higher-LCEF feedstocks, thereby shaping procurement priorities (ICAO, 2025).

The CORSIA methodology literature underscores that residues/wastes/by-products can be excluded from upstream cultivation burdens within the LCA boundary, and that ILUC is generally not applied in the same way as it is for crop-based pathways. This helps explain why residue-based SAF can appear highly competitive in LCA comparisons and why ICAO-recognized default values can accelerate investor and airline interest: they translate complex modeling into a standardized, claim-ready number(Prussi et al., 2021).

However, default values also increase the importance of governance. When a low LCEF is available, the incentive to classify fuels and feedstocks to obtain that low number increases, thereby elevating fraud risk and reputational exposure if traceability systems are weak. It emphasises traceability; fuel accounting systems are therefore not ancillary but central to the credible use of default values in a credible manner (Wolniak et al., 2026).

5.2 Indonesia's strategic pathway: from residue potential to a credible SAF ecosystem

It has been suggested that Indonesia's residue potential could be substantial and that POME oil, together with UCO and PFAD, could support meaningful SAF volumes. From a strategic standpoint, the country's opportunity is not only to produce SAF but also to position itself as a supplier of low-LCEF SAF that helps airlines reduce compliance costs under international carbon regimes. Achieving this requires building an ecosystem that integrates: (i) mill-level recovery and standardized quality control; (ii) logistics and aggregation infrastructure; (iii) conversion capacity (HEFA plants or co-processing arrangements); and (iv) certification, traceability, and accounting systems accepted by international markets(Martinez-Valencia et al., 2021b).

Supply chain configuration research underscores the need for such an integrated design by emphasizing the distinctiveness of SAF supply chains and the importance of modeling and business-model innovation to overcome cost barriers. Meanwhile, the policy literature on mandates suggests that jurisdictions are increasingly using blending obligations and related instruments, which could create stable demand if Indonesia's SAF meets eligibility and integrity requirements (Chen et al., 2024b).

5.3 The governance core: traceability, certification, and "fuel accounting systems"

Three governance components stand out:

1. **Traceability systems for residues (POME-to-fuel chain-of-custody).** It explicitly calls for a reliable traceability system for POME aligned with ICAO-recognized sustainability certification schemes. In the CORSIA framework, where default values coexist with "actual" value methodologies and eligibility provisions, traceability is the backbone that links a physical feedstock stream to an emissions claim (ICAO, 2025).
2. **Fuel accounting systems for claims.** It calls for fuel accounting systems that are consistent with ICAO standards, underscoring the need for rigorous MRV to operationalize emissions-savings claims. This aligns with the broader CORSIA emphasis on consistent and transparent monitoring of fuel life-cycle GHG intensities(ICAO, 2025).
3. **Policy alignment across sectors and trade.** It is mentioned that the domestic/export allocation and HS code clarity indicate that administrative definitions and trade classification can become bottlenecks when residue streams become valuable and globally traded. Clarity here is part of integrity: markets need to know what is being traded, how it is verified, and how it is counted(ICAO, 2025).

POME is an unavoidable residue of existing CPO processing and underscores that residues/wastes/by-products are particularly valuable for SAF because they can meet low-emission criteria and diversify feedstocks beyond primary oils. At the same time, the CORSIA methodology literature highlights the themes of safeguards and sustainability criteria in ICAO development, suggesting that scrutiny is systemic and not limited to any single feedstock(Prussi et al., 2021).

Thus, a constructive policy posture is to treat POME-based SAF as a pathway that can improve environmental performance and industrial value capture, while simultaneously investing in robust traceability and certification to meet international expectations. In practice, this means that "residue-based" is a strong starting point, but credibility is earned through MRV and governance that withstand external audits and stakeholder scrutiny (Martinez-Valencia et al., 2021b).

6. CONCLUSION AND POLICY RECOMMENDATIONS

6.1 Substantive conclusions

First, POME oil is a plausible and potentially significant residue-based feedstock for HEFA SAF, and its main strategic appeal lies in carbon accounting under CORSIA when a low default LCEF is recognized. The reported ICAO default LCEF of 18.1 gCO_2e/MJ for POME HEFA, interpreted as a 79.6% reduction relative to 89 gCO_2e/MJ for jet fuel, strengthens the incentive for airlines and fuel suppliers to consider POME-based SAF as a high-value decarbonization option.

Second, Indonesia could leverage its palm oil milling ecosystem to scale residue recovery and become a material contributor to global SAF supply, particularly when residue-derived pathways are prioritized to manage ILUC and land-use concerns in LCA narratives. However, the practical feasibility of scaling depends on supply-chain execution, infrastructure development, and, critically, governance systems that protect MRV integrity and enable internationally accepted claims.

Third, the main challenges—supply variability, traceability and accounting integrity, conversion constraints, and policy coordination—are solvable, but only through an integrated strategy and credible institutional design.

6.2 Recommendations (policy-focused)

1. **Establish a national POME traceability architecture aligned with ICAO-recognized sustainability certification schemes**, including standardized definitions, mill-level documentation protocols, and audit-ready data systems.
2. **Develop fuel accounting systems that operationalize emissions claims**, ensuring compatibility with CORSIA default/actual value frameworks and preventing double-counting across compliance and voluntary markets.
3. **Coordinate industrial and infrastructure planning** by linking residue recovery programs, aggregation logistics, and HEFA conversion investments to airport fuel distribution strategies, consistent with the "unique SAF supply chain" insights in the literature.
4. **Clarify domestic allocation and trade classification rules for POME oil**, including clear HS code differentiation where needed, to support transparent markets and policy alignment across energy, industry, and environmental objectives.
5. **Encourage policy stability and predictable demand signals** (e.g., phased blending targets, incentives linked to verified life-cycle savings) while monitoring distributional impacts, consistent with the growing literature on SAF mandates and their system effects.

6.3 Limitations and future research

This QLR synthesizes an evolving evidence base, and future work should add mill-level empirical studies on recovery rates, quality management, and logistics costs for POME oil, as well as comparative analyses of chain-of-custody models under different regulatory regimes. Additionally, more peer-reviewed work is needed on fraud risk mitigation and MRV design for residue-based SAF in international markets, given the strong incentives created by low default LCEF values.

REFERENCES

1. Akhbari, A., Kutty, P. K., Chuen, O. C., & Ibrahim, S. (2020). A study of palm oil mill processing and environmental assessment of palm oil mill effluent treatment. *Environmental Engineering Research*, *25*(2), 212–221. https://doi.org/10.4491/eer.2018.452
2. Ambraziejus, L. (2025). Towards Safe and Sustainable Aviation Decarbonization: The Case for Fewer Flights on Higher Quality SAF [Utrecht University]. https://studenttheses.uu.nl/handle/20.500.12932/49000
3. Aprilianto, H. C., & Rau, H. (2025). A Multi-Objective Optimization Approach for Generating Energy from Palm Oil Wastes. *Energies*, *18*(11), 2947. https://doi.org/10.3390/en18112947
4. Baledon, M. S., Jacobsen, J. A., Clausen, H. H., Holm, P. W., Rauch, B., Enderle, B., Souza, S., & Ulibarri, B. de. (2023). *Report on environmental and operational benefits of SAF*. https://ethanolrfa.org/file/2754/Rpt on Enviro Operational Benefits of SAF_ALIGHT.pdf
5. Baxter, G. (2021). Decarbonizing International Air Cargo Transportation's Carbon Footprint: A Review of the World Air Cargo Carrying Airlines Current and Potential Environment Related Measures and Strategies. International Journal of Environment, Agriculture and Biotechnology, *6*(6), 265–290. https://doi.org/https://dx.doi.org/10.22161/ijeab.66.31
6. Becken, S., Mackey, B., & Lee, D. S. (2023). Implications of preferential access to land and clean energy for Sustainable Aviation Fuels. Science of The Total Environment, 886, 163883. https://doi.org/https://doi.org/10.1016/j.scitotenv.2023.163883
7. Bell, A., Mannion, L. A., Kelly, M., Ghaani, M. R.,

& Dooley, S. (2025). Life cycle CO2e intensity of commercial aviation with specific sustainable aviation fuels. *Applied Energy*, *382*, 125075. https://doi.org/https://doi.org/10.1016/j.apenergy.2024.125075

8. Chan, Y. J., & Chong, M. F. (2019). *Palm Oil Mill Effluent (POME) Treatment—Current Technologies, Biogas Capture and Challenges* (pp. 71–92). https://doi.org/10.1007/978-981-13-2236-5_4
9. Chao, H., Agusdinata, D. B., DeLaurentis, D., & Stechel, E. B. (2019). Carbon offsetting and reduction scheme with sustainable aviation fuel options: Fleet-level carbon emissions impacts for US airlines. *Transportation Research Part D: Transport and Environment*, *75*, 42–56. https://doi.org/10.1016/j.trd.2019.08.015
10. Chen, R., Yang, H., Wang, K., & Jiang, C. (2024a). Impacts of a sustainable aviation fuel mandate on airline competition — Full-service carrier vs. low-cost carrier. *Transportation Research Part B: Methodological*, *190*, 103098. https://doi.org/https://doi.org/10.1016/j.trb.2024.103098
11. Chen, R., Yang, H., Wang, K., & Jiang, C. (2024b). Impacts of a sustainable aviation fuel mandate on airline competition — Full-service carrier vs. low-cost carrier. *Transportation Research Part B: Methodological*, *190*, 103098. https://doi.org/10.1016/j.trb.2024.103098
12. Chiaramonti, D., Talluri, G., Vourliotakis, G., Testa, L., Prussi, M., & Scarlat, N. (2021). Can lower carbon aviation fuels (LCAF) really complement sustainable aviation fuel (SAF) towards EU aviation Decarbonization? *Energies*, *14*(19), 6430. https://doi.org/10.3390/en14196430
13. Davies, E., Deutz, P., & Zein, S. H. (2022). Single-step extraction–esterification process to produce biodiesel from palm oil mill effluent (POME) using microwave heating: a circular economy approach to making use of a difficult waste product. *Biomass Conversion and Biorefinery*, *12*(7), 2901–2911. https://doi.org/10.1007/s13399-020-00856-1
14. Firdaus, M. I. (2025a). Palm Oil Industry. In *The Palm Oil Export Market: Trends, Challenges, and Future Strategies for Sustainability* (p. 32).
15. Firdaus, M. I. (2025b). The Challenges in Upstream-Midstream Supply Chain of Palm Oil Industry: A Review of Literature in Indonesian Case. In *The Palm Oil Export Market: Trends, Challenges, and Future Strategies for Sustainabilityt Market* (1st ed., p. 10). Routledge Taylor & Francis Group. https://www.taylorfrancis.com/chapters/edit/10.4324/9781003518600-4/challenges-upstream-midstream-supply-chain-palm-oil-industry-muhammad-iqbal-firdaus
16. Gyandoh, E. S. (2025). *Techno-Economic Analysis (TEA) and Life-Cycle Assessment (LCA) of Sustainable Aviation Fuel (SAF) Production Through Circular Economy (CE) Practices: A Focus on Supply Chain Optimization and Policy Implications* [The University of New Mexico]. https://www.proquest.com/openview/ba9c3dbd9ac9ba31da6f551f22230d77/1?pq-origsite=gscholar&cbl=18750&diss=y
17. Haag, K. (2020). International action and the role of ICAO. In *Aviation and Climate Change: Economic Perspectives on Greenhouse Gas Reduction Policies* (1st ed., p. 13). Routledge Taylor & Francis Group. https://www.taylorfrancis.com/chapters/edit/10.4324/9781315572406-6/international-action-role-icao-karlheinz-haag
18. Ho, Q. N., Lau, W. J., Jaafar, J., Othman, M. H. D., & Yoshida, N. (2025). Membrane Technology for Valuable Resource Recovery from Palm Oil Mill Effluent (POME): A Review. *Membranes*, *15*(5), 138. https://doi.org/10.3390/membranes15050138
19. Hülagü, S., Dullaert, W., Eruguz, A. S., Heijungs, R., & Inghels, D. (2025). Integrating life cycle assessment into supply chain optimization. *PLOS ONE*, *20*(1), e0316710. https://doi.org/10.1371/journal.pone.0316710
20. ICAO. (2025). *ICAO Document: CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels*. https://www.icao.int/sites/default/files/environmental-protection/CORSIA/Documents/CORSIA Eligible Fuels/ICAO-document-06-Default-Life-Cycle-Emissions-June-2025.pdf
21. Jakimovska, N. (2025). *Sustainable Aviation Fuels (SAF) and its Importance: Could it be a Solution for Skopje's Air Quality Improvement and Emission Reduction?* [Haaga-Helia University]. https://www.theseus.fi/handle/10024/896669
22. Jing, L., El-Houjeiri, H. M., Monfort, J.-C., Littlefield, J., Al-Qahtani, A., Dixit, Y., Speth, R. L., Brandt, A. R., Masnadi, M. S., MacLean, H. L., Peltier, W., Gordon, D., & Bergerson, J. A. (2022). Understanding variability in petroleum jet fuel life cycle greenhouse gas emissions to inform aviation decarbonization. *Nature Communications*, *13*(1), 7853. https://doi.org/10.1038/s41467-022-35392-1
23. Judijanto, L. (2025a). A Review of Palm Oil Valorization Technologies. *International Journal of Engineering, Science and Information Technology*, *5*(4), 172–180. https://doi.org/10.52088/ijesty.v5i4.1171
24. Judijanto, L. (2025b). POME-based Sustainable Aviation Fuel (SAF) as a Game Changer in Sustainable Renewable Energy. *Journal of Petroleum, Gas, and Chemical Engineering*, *2*(1), 1–9.

https://www.wecmelive.com/open-access/pomebased-sustainable-aviation-fuel-saf-as-a-game-changer-in-sustainable-renewable-energy.pdf

25. Judijanto, L. (2025c). Treasure from Palm Oil Waste: POME as Low-Emission Fuel for Aviation. *Journal of Scientific Engineering Advances*, *1*(2), 1–11. https://doi.org/10.63721/25JSEA0104
26. Kacaribu, A. A., Aisyah, Y., Febriani, & Darwin. (2025). Development of wastewater treatment methods for palm oil mill effluent (POME): A comprehensive review. *Resources Chemicals and Materials*, *4*(4), 100130. https://doi.org/10.1016/j.recm.2025.100130
27. Kokkinos, N. C., & Emmanouilidou, E. (2023). Waste-to-energy: applications and perspectives on sustainable aviation fuel production. In *Renewable Fuels for Sustainable Mobility* (pp. 265–286). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-9325-1_14
28. Langston, S. E., & Schult, H. T. (2025). Sustainable Aviation Fuel: A Comprehensive Review of Feedstocks, Conversion Pathways, and Decarbonization Potential in the Aviation Sector. *Energy Conversions and Managements*, *101*(July). https://energyconversions.org/index.php/ecm/P1V1ECM
29. Lopez-Gomez, M. (2024). *Value chain for the implementation in use and production of Sustainable Aviation Fuel (SAF) in Colombia* [Universidad de los Andes Colombia]. https://hdl.handle.net/1992/74775
30. Martinez-Valencia, L., Garcia-Perez, M., & Wolcott, M. P. (2021a). Supply chain configuration of sustainable aviation fuel: Review, challenges, and pathways for including environmental and social benefits. *Renewable and Sustainable Energy Reviews*, *152*, 111680. https://doi.org/https://doi.org/10.1016/j.rser.2021.111680
31. Martinez-Valencia, L., Garcia-Perez, M., & Wolcott, M. P. (2021b). Supply chain configuration of sustainable aviation fuel: Review, challenges, and pathways for including environmental and social benefits. *Renewable and Sustainable Energy Reviews*, *152*, 111680. https://doi.org/10.1016/j.rser.2021.111680
32. Martinez-Valencia, L., Peterson, S., Brandt, K., King, A. B., Garcia-Perez, M., & Wolcott, M. (2023). Impact of services on the supply chain configuration of sustainable aviation fuel: The case of CO2e emission reductions in the U.S. *Journal of Cleaner Production*, *404*, 136934. https://doi.org/10.1016/j.jclepro.2023.136934
33. Mohammad, S., Baidurah, S., Kobayashi, T., Ismail, N., & Leh, C. P. (2021). Palm Oil Mill Effluent Treatment Processes—A Review. *Processes*, *9*(5), 739. https://doi.org/10.3390/pr9050739
34. Mohd Yusof, M. A. Bin, Chan, Y. J., Chong, C. H., & Chew, C. L. (2023). Effects of operational processes and equipment in palm oil mills on characteristics of raw Palm Oil Mill Effluent (POME): A comparative study of four mills. *Cleaner Waste Systems*, *5*, 100101. https://doi.org/10.1016/j.clwas.2023.100101
35. Nik Ibrahim, N. A., Ahmad Tarmizi, A. H., Selvaduray, K. R., & Kuntom, A. (2022). Sustainability and Traceability in the Malaysian Oil Palm Industry. In *Recent Advances in Edible Fats and Oils Technology* (pp. 425–461). Springer Singapore. https://doi.org/10.1007/978-981-16-5113-7_16
36. Noor, N. A., Pandyaswargo, A. H., Rumbayan, M., & Onoda, H. (2026). Technology Readiness of Biomass Waste-to-Energy in Indonesia: A Multistakeholder Assessment of Anaerobic Digestion of Palm Oil Mill Effluent and Municipal Organic Waste. *Energies*, *19*(1), 255. https://doi.org/10.3390/en19010255
37. Nugroho, D. A., Sitompul, M. R., & Widadi, N. (2024). Sustainable aviation fuel development: case study in Indonesia. *IOP Conference Series: Earth and Environmental Science*, *1294*(1), 012032. https://doi.org/10.1088/1755-1315/1294/1/012032
38. Nur Izzati, Y., Rizqi Alika, N., & Yunarzad Prasetya, E. K. (2024, September 24). Commercialization Analysis of POME (Palm Oil Mill Effluent) With AOP (Advance Oxidation Process) Nanobubble Using Business Model Canvas. *Proceedings of the International* Conference on Industrial Engineering and Operations Management. https://doi.org/10.46254/AU03.20240119
39. Okunevičiūtė Neverauskienė, L., Sikorskaitė-Narkun, E., & Tvaronavičienė, M. (2025). The Economics of Sustainable Aviation Fuels: Market Trends and Policy Challenges in Selected EU Countries. *Sustainability*, *18*(1), 127. https://doi.org/10.3390/su18010127
40. Pan, L., Huo, B., & Hong, X. (2025). Blockchain traceability and agri-food appeal: A task-technology fit perspective. *Food Quality and Preference*, *126*, 105400. https://doi.org/10.1016/j.foodqual.2024.105400
41. Prabandari, A. P. (2024). Sustainable Aviation Fuel in Indonesia: A Comprehensive Overview. *Pakistan Journal of Life and Social Sciences (PJLSS)*, *22*(2). https://doi.org/10.57239/PJLSS-2024-22.2.001118
42. Prayitno, Ramadhan, D., & Fikri, A. (2023). Establishing Regional Regulation to Enhance the Utilization of Palm-Oil Based Sustainable Aviation Fuel (SAF) in ASEAN Aviation Industry.

Proceedings of the CAFEO 41 Engineering Conference, *41*(1), 95–99. https://repository.unkris.ac.id/id/eprint/3084/1/Full Prosiding Engineering Conference CAFEO41 - min.pdf

43. Prussi, M., Lee, U., Wang, M., Malina, R., Valin, H., Taheripour, F., Velarde, C., Staples, M. D., Lonza, L., & Hileman, J. I. (2021). CORSIA: The first internationally adopted approach to calculate life-cycle GHG emissions for aviation fuels. *Renewable and Sustainable Energy Reviews*, *150*, 111398. https://doi.org/10.1016/j.rser.2021.111398
44. Raab, M., Dietrich, R.-U., Philippi, P., Gibbs, J., & Grimme, W. (2024). Aviation fuels of the future − A techno-economic assessment of distribution, fueling and utilizing electricity-based LH2, LCH4 and kerosene (SAF). *Energy Conversion and Management: X*, *23*, 100611. https://doi.org/https://doi.org/10.1016/j.ecmx.2024.100611
45. Rozali, N. L., Ramli, U. S., Singh, R., Syed Jaafar, S. N., Weckwerth, W., Azizan, K. A., & Othman, A. (2025). Omics Technologies: A Strategy to Expedite the Geographical Traceability and Authenticity of Palm Oil. *Food and Bioprocess Technology*, *18*(5), 4101–4128. https://doi.org/10.1007/s11947-024-03673-w
46. Saxe, S., & Kasraian, D. (2020). Rethinking environmental LCA life stages for transport infrastructure to facilitate holistic assessment. Journal of Industrial Ecology, *24*(5), 1031–1046. https://doi.org/10.1111/jiec.13010
47. Steinbach, S. (2025). The used cooking oil dilemma: Feedstock competitiveness, certification integrity, and U.S. biofuel policy. *Food Policy*, *134*, 102907. https://doi.org/10.1016/j.foodpol.2025.102907
48. Uddin, M. N., & Wang, F. (2025). Sustainable Aviation Fuels: A Review of Current Techno Economic Viability and Life Cycle Impacts. *Energies*, *18*(20), 5510. https://doi.org/10.3390/en18205510
49. Wang, B., Ting, Z. J., & Zhao, M. (2024). Sustainable aviation fuels: Key opportunities and challenges in lowering carbon emissions for aviation industry. *Carbon Capture Science & Technology*, *13*, 100263. https://doi.org/https://doi.org/10.1016/j.ccst.2024.100263
50. Wolniak, R., Jonek-Kowalska, I., & Grebski, W. W. (2026). The Implementation of Open Innovation in Energy Recovery Towards Sustainable Development. *Energies*, *19*(3), 652. https://doi.org/10.3390/en19030652
51. Yusof, M. A. B. M., Chan, Y. J., Chong, D. J. S., & Chong, C. H. (2024). In-ground lagoon anaerobic digester in the treatment of palm oil mill effluent (POME): Effects of process parameters and optimisation analysis. *Fuel*, *357*, 129916. https://doi.org/https://doi.org/10.1016/j.fuel.2023.129916