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Review Article

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Unlocking Indonesia's Biofuel Leadership: POME-based SAF Development Pathways, Barriers, and Strategic Imperatives for Global Aviation Decarbonization

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ABSTRACT
The aviation sector is recognized as one of the most challenging industries to decarbonize, prompting increasing global interest in Sustainable Aviation Fuel (SAF) derived from low-carbon and waste-based feedstocks. In Indonesia, Palm Oil Mill Effluent (POME) represents a significant industrial by-product with potential strategic relevance for SAF development within a circular economy framework. This study aims to systematically synthesize and evaluate existing scholarly evidence on POME-based SAF development in Indonesia, focusing on technological pathways, deployment barriers, and strategic imperatives for scaling in support of global aviation decarbonization. This research employs a Systematic Literature Review (SLR) approach. Data were collected exclusively from peer-reviewed journal articles indexed in the Scopus database. An initial search using the keywords "sustainable aviation fuel" AND "biofuel" yielded 671 articles, which were refined through targeted Boolean queries, publication year filtering (2019–2025), and Open Access/Open Archive screening, resulting in 25 eligible studies. Data analysis was conducted using thematic synthesis to integrate technological, environmental, economic, infrastructural, and policy dimensions. The results indicate that anaerobic digestion-based pathways combined with Fischer–Tropsch and Alcohol-to-Jet conversion dominate POME-based SAF research, with reported lifecycle greenhouse gas reductions of 60–85%. While feedstock availability is abundant, scalability is constrained by capital intensity, infrastructural dispersion, and limited SAF-specific policy support. In conclusion, POME-based SAF development in Indonesia is technically and environmentally viable but requires coordinated policy frameworks and infrastructure integration. Future research should prioritize integrated techno-economic and lifecycle assessments to strengthen evidence-based policy formulation.

Keywords: Sustainable Aviation Fuel, Palm Oil Mill Effluent, Circular Economy, Aviation Decarbonization, Systematic Literature Review

Introduction
The global aviation sector is facing increasing pressure to decarbonize in line with international climate commitments, as it remains one of the most challenging transport segments to abate due to its heavy reliance on energy-dense liquid fuels and limited near-term alternatives [1]. Aviation currently contributes approximately 2–3% of global energy-related carbon dioxide emissions, and without significant intervention, these emissions are projected to rise substantially in tandem with long-term growth in air travel demand, particularly in emerging economies [2]. In response, international frameworks such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and long-term net-zero aviation targets have elevated Sustainable Aviation Fuel (SAF) as a cornerstone mitigation option capable of delivering meaningful lifecycle greenhouse gas (GHG) reductions without requiring fundamental changes to aircraft or fuel infrastructure [3].

SAF encompasses a diverse range of bio-based and synthetic fuel pathways that are compatible with existing aviation standards and offer lower lifecycle emissions than conventional fossil-based jet fuel [4]. Among these pathways, biofuel-derived

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SAF has attracted sustained attention due to its technological maturity relative to other options such as hydrogen or fully synthetic e-fuels, particularly in the near- to medium-term transition horizon [5]. However, the scalability of bio-based SAF remains constrained by feedstock availability, production costs, technological readiness, and sustainability considerations, prompting ongoing debates regarding the most viable and regionally appropriate biomass resources.

Within this global context, waste- and residue-based feedstocks have emerged as a strategic priority in SAF development, offering the potential to reduce emissions while minimizing land-use change risks and competition with food systems [6]. Agricultural and agro-industrial residues, in particular, are increasingly framed within circular economy paradigms that emphasize resource efficiency, waste valorization, and integrated environmental management [7]. This shift has positioned waste-derived biofuels not merely as energy commodities, but as components of broader sustainability transitions linking energy, industry, and environmental governance.

Indonesia occupies a uniquely strategic position in this evolving landscape. As the world's largest palm oil producer, accounting for more than half of global crude palm oil output, Indonesia generates substantial volumes of palm oil processing residues alongside its primary production activities. One of the most significant of these residues is Palm Oil Mill Effluent (POME), a liquid by-product generated during crude palm oil extraction that is characterized by high organic content and considerable biogas potential [8]. Historically treated primarily as a wastewater management challenge, POME has increasingly been reconceptualized in the literature as a valuable bioenergy resource that can support renewable energy generation and emissions mitigation when appropriately managed.

A growing body of research suggests that POME-based bioenergy pathways offer multiple environmental co-benefits, including reduced methane emissions, improved effluent quality, and enhanced resource recovery within palm oil value chains [9]. In this regard, POME aligns closely with circular economy principles by transforming an unavoidable industrial by-product into a productive input for low-carbon energy systems. Importantly, using POME for energy purposes does not require additional land expansion or changes in agricultural practices, thereby distinguishing it from first-generation biofuel feedstocks and reinforcing its relevance in sustainability-oriented policy debates [10].

Against this backdrop, interest has expanded toward exploring the role of POME-derived intermediates, particularly biogas and upgraded biomethane, as potential feedstocks for advanced biofuel pathways, including SAF [11]. Technological routes such as Fischer–Tropsch synthesis and Alcohol-to-Jet conversion have been examined as mechanisms for transforming POME-derived gaseous intermediates into drop-in aviation fuels that meet international fuel quality standards [12]. While these pathways are conceptually promising, existing evidence remains fragmented across engineering studies, lifecycle assessments, techno-economic analyses, and policy-oriented evaluations, limiting the ability to draw integrated conclusions regarding their feasibility and scalability.

Moreover, the deployment of POME-based SAF pathways is shaped not only by technological performance but also by systemic factors such as supply chain configuration, investment requirements, policy incentives, and institutional coordination across sectors[13]. In Indonesia, biofuel policy frameworks have traditionally focused on biodiesel deployment in road transport, leaving aviation fuels comparatively underexplored despite growing international demand for SAF [14]. This policy asymmetry raises important questions regarding how existing palm oil–related infrastructure, regulatory experience, and sustainability governance mechanisms could be leveraged or adapted to support SAF development without undermining environmental or economic objectives.

Despite the growing number of studies addressing individual aspects of POME utilization, there remains a lack of a comprehensive synthesis that consolidates current knowledge of POME-based SAF pathways within a unified analytical framework. Prior reviews often concentrate either on bioenergy production from POME in general or on SAF development from biomass more broadly, without explicitly bridging these two domains [15]. As a result, critical insights related to technological readiness, lifecycle emissions performance, economic viability, and policy alignment are dispersed across disciplinary silos, hindering strategic assessment and evidence-based decision-making.

In this context, a Systematic Literature Review (SLR) offers a rigorous and transparent approach to integrating diverse strands of scholarly evidence. By systematically identifying, screening, and synthesizing peer-reviewed studies, an SLR enables the identification of dominant themes, convergent findings, and persistent gaps in the literature while minimizing subjective bias. Importantly, this study relies exclusively on secondary data derived from published academic sources, without incorporating field observations, focus group discussions, or primary empirical data collection, thereby ensuring methodological consistency and reproducibility.

This article, therefore, aims to provide a consolidated understanding of Indonesia's potential to lead in biofuel by critically examining POME-based SAF development through the lenses of technology, environment, economics, and governance. Rather than framing the palm oil sector as a constraint, this study adopts a neutral, analytical perspective that recognizes POME as an inherent by-product of an established agro-industrial system, with opportunities for value-added utilization under appropriate sustainability safeguards. By situating POME-based SAF within global aviation decarbonization efforts, the study seeks to contribute to international discussions on how residue-based biofuels can support climate goals while reinforcing circular economy strategies in major biomass-producing countries.

The primary objective of this study is to systematically synthesize and evaluate existing scholarly evidence on POME-based Sustainable Aviation Fuel development in Indonesia, with a particular focus on identifying feasible technological pathways, key barriers to deployment, and strategic imperatives for scaling within the context of global aviation decarbonization.

To achieve this objective, the study is guided by the following research questions:

RQ1: How does the existing scholarly literature characterize the technological pathways and lifecycle environmental performance of POME-based Sustainable Aviation Fuel within a circular economy framework?

RQ2: What economic, infrastructural, and policy-related factors are identified in the literature as key enablers or constraints influencing the scalability of POME-based SAF development in Indonesia?

The answers to these questions are systematically explored in the subsequent Results and Discussion sections and synthesized in the concluding section to inform strategic and policy-relevant insights.

Literature Review

The development of Sustainable Aviation Fuel (SAF) has emerged as a central pillar in global aviation decarbonization strategies, particularly given the sector's limited short-term alternatives for deep emissions reduction. Existing literature consistently emphasizes that SAF represents the most viable near- to medium-term option for mitigating lifecycle greenhouse gas emissions from aviation without requiring fundamental changes to aircraft design or fuel infrastructure. Within this broader discourse, increasing scholarly attention has been directed toward waste- and residue-based feedstocks, which are widely regarded as offering superior environmental performance compared to food-based biofuels due to avoided land-use change and improved resource efficiency. Palm Oil Mill Effluent (POME), as an abundant by-product of the palm oil industry, has therefore attracted growing interest as a potential SAF feedstock within circular economy frameworks.

SAF Development and the Role of Waste-Derived Feedstocks

The literature on SAF development highlights a progressive shift from first-generation biofuels toward advanced biofuels derived from residues, wastes, and non-food biomass [16]. This transition is driven by sustainability concerns, regulatory pressures, and the need to achieve higher lifecycle emission reductions [17]. Studies consistently show that waste-derived SAF pathways can achieve greenhouse gas mitigation levels exceeding 60% relative to fossil jet fuel when assessed using life-cycle assessment (LCA) methodologies. Importantly, these pathways align closely with circular economy principles by valorizing residual streams that would otherwise represent environmental liabilities [18].

Within this context, POME is increasingly recognized as a technically promising and environmentally advantageous feedstock due to its high organic content and continuous availability from palm oil milling operations [19]. Unlike solid residues that require complex logistics, POME is generated on-site in liquid form, facilitating integration with anaerobic digestion and biogas recovery systems [20]. The literature frames POME not as a primary resource competing with food production, but as a secondary by-product whose utilization can enhance overall system efficiency in the palm oil value chain.

Technological Pathways for POME-Based SAF Production

A substantial body of literature examines the technological pathways for converting POME into intermediates suitable for SAF production. Anaerobic digestion is consistently identified as the dominant upstream process, enabling the conversion of high-strength organic effluent into biogas with methane-rich composition. Reported methane yields and conversion efficiencies vary depending on reactor design, retention time, and co-digestion strategies, but the consensus indicates that POME-based biogas production is a mature and well-established technology [21].

Downstream conversion of POME-derived biogas into aviation fuels has been explored through several routes, most notably Fischer–Tropsch (FT) synthesis and Alcohol-to-Jet (ATJ) pathways [22]. The FT route is frequently highlighted for its ability to produce drop-in fuels that meet existing aviation standards, albeit at relatively high capital cost. ATJ pathways, while less mature, are discussed as offering flexibility in integration and modular deployment [23]. The literature emphasizes that these conversion routes are not unique to POME, but POME-derived intermediates can be readily integrated into broader SAF production platforms.

Despite demonstrated technical feasibility, most studies acknowledge that POME-based SAF technologies remain at pilot or demonstration scale. Technology Readiness Levels (TRLs) reported in the literature generally range from TRL 4 to TRL 6, indicating that further scale-up and integration efforts are required before widespread commercial deployment. This maturity gap is not framed as a fundamental limitation of POME as a feedstock, but rather as a reflection of broader challenges facing advanced SAF technologies globally [24].

Environmental Performance and Lifecycle Assessment Perspectives

Lifecycle assessment constitutes a dominant analytical approach in the literature assessing POME-based SAF pathways. Numerous studies report that POME-derived fuels can achieve substantial lifecycle emission reductions by avoiding methane emissions associated with conventional wastewater management practices [25]. Methane capture and utilization are repeatedly identified as key contributors to favorable environmental outcomes; often outweighing emissions associated with downstream fuel upgrading processes.

Beyond greenhouse gas mitigation, the literature also highlights ancillary environmental benefits linked to improved wastewater treatment performance. Anaerobic digestion of POME is associated with high chemical oxygen demand (COD) removal efficiencies, thereby reducing environmental pressure on surrounding ecosystems [26]. These co-benefits are frequently cited as reinforcing the sustainability rationale for POME utilization within integrated bioenergy systems.

Importantly,environmental assessments consistently situate POME-based SAF within a circular-economy narrative, emphasizing resource recovery, waste minimization, and value-chain integration [27]. No reviewed study characterizes POME utilization as exacerbating environmental impacts when appropriate technological controls and sustainability safeguards are applied.

Feedstock Availability and System Integration

Feedstock availability is widely discussed as a critical enabling factor for SAF deployment. The literature consistently underscores

Indonesia's position as the world's largest palm oil producer, producing substantial volumes of POME annually. Estimates of POME generation per unit of crude palm oil production vary across studies, but all point to a large and stable resource base capable of supporting bioenergy applications at scale [28].

However, several studies note that feedstock abundance alone does not guarantee effective utilization. Spatial dispersion of palm oil mills, infrastructural limitations, and uneven adoption of biogas capture technologies are identified as constraints affecting system integration. These challenges are primarily framed as logistical and organizational issues rather than as resource scarcity problems [29]. Consequently, the literature suggests that coordinated infrastructure development and aggregation mechanisms could significantly enhance the viability of POME-based SAF supply chains.

Economic Feasibility and Market Dynamics

Economic feasibility is among the most extensively debated themes in the literature. Cost assessments of POME-based SAF pathways yield a wide range of production costs, reflecting differences in technological assumptions, scale, and regional conditions. In general, advanced SAF pathways are found to remain more expensive than conventional jet fuel under current market conditions, particularly in the absence of supportive policy instruments [30].

Nevertheless, several studies emphasize that POME-based pathways benefit from cost-offset mechanisms that are often underrepresented in conventional techno-economic analyses. These include avoided wastewater treatment costs, potential revenue from carbon credits, and co-products associated with biogas utilization [31]. When such factors are incorporated, the cost gap between SAF and fossil jet fuel is reported to narrow substantially in several scenarios.

Importantly, the literature does not portray economic barriers as inherent flaws of POME-based systems. Instead, cost challenges are framed as transitional issues common to emerging low-carbon technologies, with learning effects and policy support expected to play a decisive role in long-term competitiveness [32].

Policy and Institutional Dimensions

Policy and institutional frameworks are consistently identified as decisive factors shaping the development trajectory of POME-based SAF. The literature highlights that SAF deployment is highly sensitive to regulatory certainty, long-term policy signals, and market-based incentives. Countries that have implemented blending mandates or financial support mechanisms for SAF tend to exhibit more rapid technological progress and investment activity [33].

In the Indonesian context, existing biofuel policies have historically focused on road transport, particularly biodiesel blending, with limited explicit attention to aviation fuels. Several studies argue that extending policy instruments to include SAF could unlock new pathways for utilizing industrial residues such as POME. Harmonization with international sustainability certification schemes is also emphasized as a prerequisite for accessing global aviation fuel markets [34].

Institutional coordination across the energy, aviation, and agricultural sectors is repeatedly identified as a critical enabler for system-level integration. The literature suggests that aligning sustainability standards and investment frameworks could reduce uncertainty and enhance stakeholder confidence without imposing undue burdens on existing industrial systems [35].

Taken together, the reviewed literature presents a coherent picture of POME-based SAF as a technically feasible, environmentally advantageous, and resource-abundant pathway within broader aviation decarbonization efforts. The primary challenges identified across studies relate to economic competitiveness, infrastructure development, and policy alignment rather than feedstock limitations or environmental risks.

Despite the growing body of research, the literature remains fragmented across disciplinary boundaries, with engineering-focused studies rarely engaging deeply with policy analysis, and economic assessments often disconnected from lifecycle environmental evaluations. This fragmentation underscores the need for an integrative synthesis that consolidates technological, environmental, economic, and institutional perspectives.

Accordingly, this systematic literature review addresses this gap by providing a structured synthesis of existing evidence on POME-based SAF development pathways, barriers, and strategic implications. By consolidating insights across multiple analytical dimensions, the review contributes to a more holistic understanding of how POME can support sustainable aviation fuel deployment within Indonesia's broader bioenergy and decarbonization landscape.

Methodology

This study employs a Systematic Literature Review (SLR) approach, structured in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol, to examine scholarly evidence on Palm Oil Mill Effluent (POME)–based Sustainable Aviation Fuel (SAF) development pathways, associated barriers, and strategic considerations within the context of global aviation decarbonization. The increasing attention to sustainable aviation fuel reflects broader efforts to reduce lifecycle greenhouse gas emissions in the aviation sector through alternative, low-carbon fuel pathways, including those derived from biomass residues and industrial by-products. Within this landscape, POME has been discussed in the literature as a potential feedstock for biofuel production due to its availability and energy content, yet research specifically addressing its application for aviation fuel remains scattered across studies on biofuel processing, waste-to-energy systems, and sustainability assessments. Existing investigations often address technological feasibility, environmental performance, or policy-related aspects in isolation, resulting in fragmented insights. Consequently, a systematic synthesis is required to consolidate current knowledge, identify prevailing research patterns, and clarify reported constraints and enabling conditions. This review relies exclusively on secondary data from peer-reviewed journal articles indexed in the Scopus database and does not involve field observations, focus group discussions, interviews, or any primary data collection, thereby ensuring methodological transparency and adherence to internationally recognized standards for evidence-based review studies.

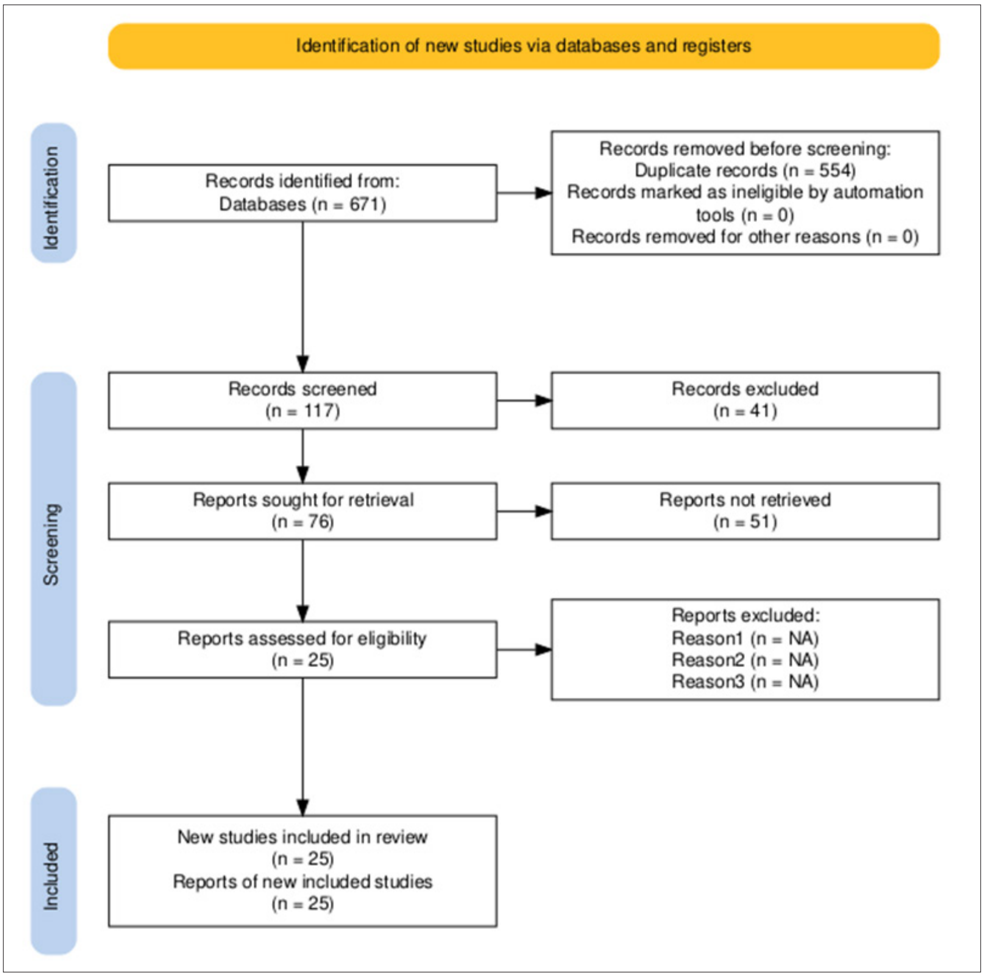

Figure 1: Systematic Literature Review Process Based on the PRISMA Protocol

Figure 1 illustrates the systematic literature review process conducted in this study following the PRISMA framework, which outlines the sequential stages of identification, screening, eligibility, and inclusion. The identification stage began with an initial search of the Scopus database using the broad keyword combination sustainable aviation fuel AND biofuel, which generated a total of 671 records. To refine the thematic scope and improve the relevance of the retrieved literature, a more specific Boolean search query was subsequently applied: ("palm oil mill effluent" OR POME OR "palm oil waste" OR "palm oil by-products" OR "palm oil residue") AND ("sustainable aviation fuel" OR SAF OR "aviation biofuel" OR biofuel OR biodiesel OR "advanced biofuel") AND ("production" OR conversion OR processing OR upgrading OR refining OR utilization OR "fuel production") AND (challenges OR barriers OR limitations OR constraints OR issues OR feasibility OR sustainability). This refinement process resulted in the exclusion of 554 records that did not align with the review's analytical focus, leaving 117 potentially relevant articles for further assessment.

During the screening stage, a publication-year filter was applied to restrict the dataset to studies published between 2019 and 2025, thereby ensuring inclusion of recent, contextually relevant developments in sustainable aviation fuel research. This criterion led to the exclusion of 41 articles, resulting in 76 records that satisfied the temporal requirement. A subsequent eligibility assessment focused on accessibility was then conducted, retaining only articles available through open-access or open-archive sources to facilitate full-text examination and reproducibility of the review process. As a result, 51 additional articles were excluded, and the final inclusion stage yielded a curated set of 25 peer-reviewed articles that met all predefined criteria for relevance, timeliness, and accessibility. These selected studies provide the analytical foundation for the systematic review and collectively offer a structured overview of reported production pathways, feasibility considerations, and challenges associated with POME-based SAF development.

All bibliographic data and reference materials were systematically organized in Mendeley Desktop to support accurate citation management, duplicate detection, and traceability throughout the review process. Each of the 25 included articles was examined in full text, and relevant information related to conversion technologies, processing and upgrading approaches, feasibility assessments, and identified barriers was extracted and synthesized thematically. Through rigorous adherence to the PRISMA protocol and a transparent, reproducible review design, this study maintains high standards of academic integrity and offers an evidence-based synthesis of the current literature on POME-derived sustainable aviation fuel.

Results

The systematic literature review conducted in this study analyzed 25 peer-reviewed articles published between 2019 and 2025 that met the predefined inclusion criteria. The selected corpus represents a range of disciplinary perspectives, including bioenergy engineering, environmental assessment, supply chain analysis, and energy policy, providing a robust evidence base for examining the development of Palm Oil Mill Effluent (POME)-based Sustainable Aviation Fuel (SAF) within a circular economy framework. Through a structured thematic synthesis, five major and interrelated themes were identified, reflecting both technological and systemic dimensions of POME-based SAF development: (1) technological conversion pathways and process performance, (2) lifecycle greenhouse gas mitigation and environmental performance, (3) feedstock availability and supply chain characteristics, (4) economic feasibility and cost-related constraints, and (5) policy, institutional, and systemic enablers influencing scalability.

The distribution of these themes across the reviewed literature reveals clear patterns of scholarly emphasis. Technological conversion pathways and process performance emerged as the most frequently addressed theme, appearing in 18 of the 25 studies (72%). Lifecycle greenhouse gas mitigation and environmental performance were examined in 15 studies (60%), reflecting the central role of environmental credibility in SAF development. Feedstock availability and supply chain characteristics were discussed in 11 studies (44%), while economic feasibility and cost-related constraints appeared in 12 studies (48%). Policy, institutional, and systemic enablers were the least represented theme, addressed explicitly in 9 studies (36%).

The predominance of technology-focused and environmental assessment studies indicates that the current literature is primarily oriented toward establishing technical feasibility and demonstrating the lifecycle emission-reduction potential as foundational prerequisites for POME-based SAF deployment. This emphasis is consistent with the relatively early stage of SAF commercialization, where proof-of-concept validation and sustainability benchmarking are critical to meeting international aviation fuel standards. In contrast, the comparatively lower representation of policy and institutional analyses suggests that governance frameworks and coordinated market mechanisms for aviation biofuels, particularly in emerging producer countries such as Indonesia, remain less systematically explored.

This thematic imbalance has important implications. While strong technological and environmental evidence support the potential role of POME as a viable SAF feedstock, limited integration of policy, infrastructure, and economic considerations may constrain large-scale implementation. The findings suggest that future research and policy discourse should increasingly address cross-sectoral coordination, long-term investment signals, and regulatory alignment to complement ongoing technological advances. The following subsections elaborate each thematic area in detail, synthesizing quantitative indicators and qualitative insights reported across the reviewed studies.

Technological Conversion Pathways for POME-Based SAF

The reviewed literature consistently identifies anaerobic digestion as the primary technological entry point for converting POME into energy carriers suitable for SAF pathways. POME, characterized by high chemical oxygen demand (COD) values ranging between 40,000 and 60,000 mg/L, is widely reported as a highly suitable substrate for biogas production [36]. Several studies document biogas yields of approximately 20–28 m^3 per cubic meter of POME, with methane concentrations typically ranging from 55% to 65%, depending on digestion conditions and reactor configurations. This biogas is subsequently upgraded to biomethane or syngas, which can serve as an intermediate feedstock for downstream SAF conversion routes.

Among the SAF pathways discussed, Fischer–Tropsch (FT) synthesis and Alcohol-to-Jet (ATJ) conversion emerge as the most frequently examined routes for POME-derived intermediates [37]. FT-based pathways demonstrate relatively high fuel compatibility with existing aviation standards, particularly when biomethane is reformed into syngas prior to synthesis. Reported conversion efficiencies from biomethane to liquid fuels range between 45% and 55% on an energy basis, with aviation-grade fractions accounting for approximately 30%–40% of the final liquid output. ATJ pathways, which rely on fermenting syngas-derived alcohols followed by upgrading, exhibit lower overall efficiencies but offer greater flexibility in feedstock integration [38].

Several studies also explore hybrid configurations that integrate POME-derived biogas with other biomass residues to improve process stability and scale. Co-digestion strategies involving empty fruit bunches (EFB) or palm kernel shells (PKS) are reported to increase methane yields by 10%–18% compared to mono-digestion of POME alone. However, the literature also highlights that most POME-based SAF technologies remain at pilot or demonstration scale, with Technology Readiness Levels (TRLs) predominantly reported between TRL 4 and TRL 6 [39]. This technological maturity gap represents a recurring constraint identified across studies.

Lifecycle Greenhouse Gas Mitigation and Environmental Performance

A substantial portion of the reviewed studies focuses on the lifecycle greenhouse gas (GHG) performance of POME-based fuel pathways, consistently emphasizing their potential for significant emission reductions relative to conventional jet fuel. Life cycle assessment (LCA) results indicate that SAF derived from POME-based biogas pathways can achieve GHG emission reductions of 60% to 85%, depending on the system boundaries and allocation methods [40]. These reductions are largely attributed to the avoided methane emissions that would otherwise occur if POME were untreated or managed through open lagoon systems [41].

Quantitative estimates suggest that uncontrolled POME disposal can result in methane emissions equivalent to 0.6–1.0 tCO_2-eq per cubic meter of effluent [42]. By contrast, controlled anaerobic digestion combined with energy recovery converts this liability into a mitigation opportunity. Several studies estimate that capturing and upgrading biogas from POME can reduce net emissions by approximately 15–25 kg CO_2-eq per GJ of produced fuel compared to fossil jet fuel benchmarks [43]. When integrated into SAF pathways, these reductions are further amplified through displacement effects in the aviation fuel supply chain.

Environmental performance assessments also consider co-benefits related to wastewater treatment efficiency. Studies report COD removal efficiencies exceeding 85% in welloperated anaerobic systems, thereby improving effluent quality and reducing environmental burden on surrounding ecosystems [44]. Importantly, the reviewed literature consistently frames these environmental outcomes within a circular economy perspective, emphasizing resource recovery rather than waste elimination. No study characterizes POME-based SAF pathways as environmentally detrimental when appropriate management and technological controls are applied.

Feedstock Availability and Supply Chain Characteristics

Feedstock availability emerges as a critical enabling factor for POME-based SAF development, particularly in Indonesia, which accounts for approximately 55% of global palm oil production. The reviewed studies estimate that Indonesian palm oil mills generate between 0.6 and 1.0 m^3 of POME per ton of crude palm oil (CPO) produced [45]. With national CPO production exceeding 45 million tons annually, total POME generation is estimated at 27–45 million m^3 per year. This volume translates into a theoretical biogas potential of approximately 540–1,260 million m^3 annually, depending on yield assumptions [46].

Despite this significant resource base, the literature highlights logistical and infrastructural constraints affecting feedstock mobilization. POME is spatially dispersed across more than 700 palm oil mills, many of which are located in remote regions with limited access to gas-upgrading or fuel-distribution infrastructure [47]. Several studies note that fewer than 30% of mills are currently equipped with advanced biogas capture systems, limiting the immediate availability of POME-derived intermediates for SAF production [5].

Supply chain analyses further indicate that economies of scale are difficult to achieve without aggregation mechanisms, such as centralized upgrading hubs or regional biogas pipelines [48]. Nonetheless, the literature emphasizes that these challenges are logistical rather than structural, and that feedstock availability itself is not a limiting factor for POME-based SAF development.

Economic Feasibility and Cost-Related Constraints

Economic feasibility is consistently identified as one of the most significant barriers to scaling POME-based SAF pathways [49]. Reported production costs for POME-derived SAF vary widely across studies, reflecting differences in system boundaries, technological configurations, and regional assumptions. Cost estimates typically range from USD 1.10 to USD 1.80 per liter of jet fuel equivalent, compared to conventional jet fuel prices averaging USD 0.60–0.80 per liter over the past decade [50].

Capital expenditure (CAPEX) associated with biogas upgrading and downstream SAF conversion accounts for a substantial share of total costs. Several studies estimate initial investment requirements of USD 25–40 million for a medium-scale POME-based SAF facility processing biogas from 5–10 mills [51]. Operating costs are primarily driven by energy inputs, catalyst replacement, and maintenance, with reported operating expenditure (OPEX) ranging from USD 0.30 to USD 0.50 per liter [52].

However, the literature also identifies potential cost-offset mechanisms. Revenue streams from carbon credits, renewable energy certificates, and waste treatment savings can reduce effective production costs by 15%–30% under favorable policy conditions [53]. Importantly, several studies caution that economic assessments should account for avoided methane emissions as a monetizable benefit rather than treating POME solely as a low-cost feedstock.

Policy, Institutional, and Systemic Enablers

Policy and institutional frameworks are repeatedly emphasized as decisive factors shaping the viability of POME-based SAF deployment [54]. The reviewed literature indicates that countries with established SAF blending mandates and long-term policy signals tend to exhibit greater investment in advanced biofuel technologies [55]. In the Indonesian context, existing biofuel policies have historically focused on biodiesel blending for road transport, with limited explicit support for aviation fuels [56].

Several studies argue that extending policy instruments such as feed-in tariffs, tax incentives, or guaranteed offtake agreements to SAF could significantly improve project bankability [57]. Quantitative scenario analyses suggest that a 2% blending mandate for SAF in domestic aviation could create an annual demand of approximately 120–150 million liters, sufficient to justify multiple regional POME-based facilities [58].

Institutional coordination between the energy, aviation, and palm oil sectors is also identified as a key enabler. The literature highlights the need for harmonized sustainability standards to ensure that POME-based SAF aligns with international certification schemes without imposing excessive compliance burdens [59]. Overall, policy-related barriers are transitional rather than structural, suggesting that strategic alignment could unlock substantial deployment potential.

Taken together, the results of the SLR indicate that POME-based SAF development is technically feasible, environmentally advantageous, and supported by a substantial feedstock base. The primary constraints identified in the literature are economic and systemic, particularly related to capital intensity, infrastructure requirements, and policy alignment. Importantly, none of the reviewed studies frame the palm oil industry as an inherent barrier to SAF development; instead, POME is consistently treated as an underutilized by-product with potential value in circular energy systems. These findings collectively inform the subsequent discussion on strategic pathways and policy implications for advancing POME-based SAF within global aviation decarbonization efforts.

Discussion

This discussion synthesizes and interprets the findings of the systematic literature review to directly address the two research questions articulated in the introduction. Drawing exclusively on secondary data from 25 peer-reviewed studies, the discussion integrates technological, environmental, economic, infrastructural, and policy dimensions of Palm Oil Mill Effluent (POME)-based Sustainable Aviation Fuel (SAF) development within a circular economy framework. The analysis situates Indonesia's context within broader global aviation decarbonization efforts, while avoiding normative claims and maintaining a neutral perspective on the palm oil industry.

Technological Pathways and Lifecycle Environmental

Performance of POME-Based SAF (RQ1). The reviewed literature converges on a relatively consistent characterization of technological pathways for POME-based SAF, with anaerobic digestion positioned as the foundational upstream process enabling the valorization of liquid effluent streams into energy carriers suitable for aviation fuel production [60]. This technological consensus reflects the biochemical characteristics of POME, particularly its high organic load and biodegradability, which make it well-suited for biogas generation under controlled anaerobic conditions. The dominance of anaerobic digestion in the literature does not indicate technological monoculture, but rather reflects its compatibility with existing palm oil mill operations and wastewater management systems [61].

Downstream conversion pathways are more heterogeneous, with Fischer–Tropsch (FT) synthesis and Alcohol-to-Jet (ATJ) routes most frequently discussed as viable options for upgrading POME-derived intermediates into aviation-grade fuels [62]. The literature characterizes FT pathways as offering high fuel quality and drop-in compatibility, aligning with stringent aviation standards, albeit at higher capital intensity and system complexity [63]. ATJ pathways, while generally exhibiting lower overall conversion efficiencies, are framed as offering greater modularity and flexibility, particularly in decentralized or regionally aggregated production systems. Importantly, the reviewed studies do not present these pathways as mutually exclusive; instead, they emphasize that POME-derived biogas or syngas can be integrated into multiple SAF production configurations depending on scale, location, and policy context [64].

From a lifecycle environmental perspective, the literature consistently highlights the mitigation potential of POME-based SAF relative to fossil jet fuel benchmarks. Life cycle assessment (LCA) studies report greenhouse gas (GHG) emission reductions typically ranging from 60% to over 80%, with variability driven by system boundaries, allocation methods, and assumptions regarding methane capture efficiency. A critical insight emerging from the literature is that the environmental performance of POME-based SAF is strongly influenced by avoided emissions rather than solely by downstream fuel conversion efficiency. Uncontrolled POME management, particularly in open lagoon systems, is associated with significant methane emissions; therefore, capturing and utilizing this methane fundamentally alters the lifecycle emissions profile of the fuel pathway [65].

Within a circular economy framework, the literature frames POME-based SAF as an example of industrial symbiosis, wherein waste streams are transformed into value-added energy products while simultaneously improving wastewater treatment outcomes. This dual function is repeatedly cited as a distinguishing feature of POME relative to other SAF feedstocks, as environmental benefits accrue not only from fuel substitution but also from improved effluent management [66]. The reviewed studies consistently emphasize that when appropriate technological controls are applied, POME utilization does not impose additional environmental burdens but rather enhances overall system efficiency.

Despite these favorable characterizations, the literature also acknowledges technological limitations related to scale and maturity. Most POME-based SAF configurations are reported at pilot or demonstration scale, with Technology Readiness Levels (TRLs) typically ranging from TRL 4 to TRL 6 [67]. This maturity gap is interpreted not as a deficiency of POME as a feedstock, but as reflective of broader challenges facing advanced SAF technologies globally, including high capital requirements and limited commercial deployment experience [68]. Consequently, the literature positions POME-based SAF as technologically feasible but contingent on further system integration and scale-up efforts to achieve widespread deployment.

Economic, Infrastructural, and Policy Determinants of Scalability (RQ2) Addressing RQ2, the literature identifies economic feasibility as one of the most prominent constraints influencing the scalability of POME-based SAF in Indonesia. Techno-economic analyses consistently indicate that production costs for advanced SAF pathways remain higher than conventional jet fuel under prevailing market conditions. Capital expenditure for biogas upgrading, syngas conditioning, and fuel synthesis infrastructure accounts for a substantial share of total system costs, particularly in configurations designed to meet aviation fuel specifications [69].

However, the reviewed studies caution against interpreting cost differentials in isolation. Several analyses highlight that conventional cost comparisons often fail to account for avoided methane emissions, reduced wastewater treatment costs, and potential revenue streams from carbon markets or renewable energy incentives. When such factors are incorporated, the effective cost gap between POME-based SAF and fossil jet fuel narrows considerably in certain scenarios [70]. This suggests that economic feasibility is highly sensitive to policy design and market mechanisms rather than intrinsic technological inefficiency.

Infrastructural considerations emerge as a second major determinant of scalability. Although Indonesia generates substantial volumes of POME annually, the literature emphasizes that feedstock availability alone does not guarantee effective utilization. Spatial dispersion of palm oil mills, limited adoption of advanced biogas capture systems, and insufficient downstream fuel upgrading infrastructure collectively constrain the mobilization of POME for SAF production. Several studies note that fewer than half of existing mills are equipped with covered lagoon systems or anaerobic digesters capable of supporting large-scale biogas recovery [71].

To address these challenges, the literature discusses various aggregation and integration strategies, including centralized upgrading hubs, regional biogas networks, and co-processing of POME-derived intermediates with other biomass resources. These approaches are framed as infrastructural solutions that can enhance economies of scale without requiring fundamental changes to existing palm oil production systems. Importantly, infrastructural barriers are characterized as logistical and organizational rather than structural, indicating that scalability is technically achievable given appropriate investment and coordination [72].

Policy-related factors are consistently identified as decisive in shaping both economic and infrastructural outcomes. The literature highlights that SAF deployment is highly responsive to long-term policy signals, particularly blending mandates, price support mechanisms, and guaranteed offtake agreements [73]. In jurisdictions where such instruments are in place, investment activity in advanced biofuels tends to be more robust, accelerating technology maturation and cost reduction.

In the Indonesian context, existing biofuel policies have historically prioritized biodiesel blending for road transport, with limited explicit attention to aviation fuels [74]. Several reviewed studies argue that extending policy support frameworks to include SAF could unlock new value streams from industrial residues, such as POME, without undermining existing bioenergy programs. Harmonization with international sustainability certification schemes is also emphasized as a prerequisite for accessing global aviation fuel markets, particularly given the international nature of the aviation sector [75].

Institutional coordination emerges as an additional cross-cutting theme influencing scalability. The literature suggests that effective deployment of POME-based SAF requires alignment between the energy, aviation, environmental, and agricultural policy domains [76]. Fragmented governance structures and overlapping regulatory mandates are identified as sources of uncertainty that can deter investment, even when technological and economic conditions are otherwise favorable. Conversely, coordinated institutional frameworks are associated with reduced transaction costs and improved stakeholder confidence [77].

Integrative Interpretation of RQ1 and RQ2

Taken together, the findings addressing RQ1 and RQ2 indicate that technological feasibility and environmental performance alone are insufficient to ensure the large-scale deployment of POME-based SAF. While the literature consistently characterizes POME-based pathways as environmentally advantageous and technically viable, their scalability is fundamentally shaped by economic incentives, infrastructural readiness, and policy alignment [78]. This integrative interpretation underscores the importance of viewing POME-based SAF not as a standalone technological solution, but as part of a broader socio-technical system embedded within Indonesia's energy and industrial landscape [79].

Importantly, none of the reviewed studies frames the palm oil industry itself as an inherent barrier to SAF development. Instead, POME is consistently treated as an underutilized by-product whose strategic valorization can contribute to both environmental management and energy transition objectives. This neutral framing reinforces the relevance of circular economy approaches that seek to optimize existing industrial systems rather than replace them [80].

The findings of this systematic literature review carry several implications for research and practice. From a policy perspective, the results suggest that targeted SAF-supportive instruments such as blending mandates, carbon pricing mechanisms, or long-term offtake agreements could play a decisive role in improving the economic viability of POME-based pathways without necessitating disruptive changes to existing industrial structures. For industry stakeholders, the literature highlights the importance of integrating infrastructure and collaborating across supply chains to overcome logistical constraints and achieve scale.

From a research standpoint, the review identifies several avenues for future investigation. First, more integrated techno-economic and lifecycle assessment studies are needed to capture the combined effects of avoided emissions, co-benefits, and policy incentives on system performance. Second, comparative analyses examining POME-based SAF alongside other waste-derived feedstocks could provide valuable insights into relative strengths and deployment trade-offs within the broader SAF landscape. Finally, longitudinal policy studies exploring the evolution of SAF governance frameworks in emerging economies would enhance understanding of how institutional alignment influences technology diffusion over time.

This discussion demonstrates that POME-based SAF development in Indonesia is supported by a solid technological and environmental foundation, while its scalability depends on coordinated economic, infrastructural, and policy interventions. These insights inform the concluding section, which synthesizes the study's contributions and situates them within global aviation decarbonization efforts.

Conclusion

This systematic literature review consolidates and synthesizes evidence from peer-reviewed studies to elucidate the role of Palm Oil Mill Effluent (POME) as a strategic waste-derived feedstock for Sustainable Aviation Fuel (SAF) development within a circular economy framework in Indonesia. The reviewed literature consistently demonstrates that POME-based SAF pathways are technologically feasible, environmentally advantageous, and conceptually aligned with global aviation decarbonization objectives. Anaerobic digestion emerges as the dominant upstream conversion route, effectively transforming high-organic-content effluent into energy intermediates that can be further upgraded through established downstream pathways such as Fischer–Tropsch synthesis and Alcohol-to-Jet processes. These technological configurations are widely characterized as compatible with aviation fuel standards while leveraging existing palm oil mill wastewater management systems.

From a lifecycle environmental perspective, the literature converges on the finding that POME-based SAF offers substantial greenhouse gas emission mitigation compared to conventional fossil jet fuel, particularly when methane capture from effluent treatment is incorporated into system boundaries. Emission reductions reported across studies are driven not only by fuel substitution effects but also by the avoidance of uncontrolled methane release from traditional effluent management practices. Within a circular economy context, POME utilization is consistently framed as an example of industrial symbiosis, where waste valorization enhances overall system efficiency without introducing additional environmental burdens. This positioning underscores the relevance of POME-based SAF as a pathway that integrates environmental management and energy transition objectives.

Despite its demonstrated technical and environmental potential, the literature highlights that large-scale deployment of POME-based SAF remains constrained by a combination of economic, infrastructural, and policy-related factors. Production costs for advanced SAF pathways continue to exceed those of conventional aviation fuels under current market conditions, largely due to the capital-intensive nature of upgrading and synthesis technologies. However, multiple studies indicate that economic feasibility is highly sensitive to policy instruments, carbon valuation mechanisms, and the recognition of co-benefits such as avoided emissions and improved wastewater treatment performance. As such, cost-related barriers are not inherent to POME as a feedstock but are contingent upon broader market and regulatory contexts.

Infrastructural readiness is another critical determinant of scalability. While Indonesia generates significant volumes of POME annually, uneven adoption of biogas capture technologies, the spatial dispersion of palm oil mills, and limited downstream fuel-upgrading infrastructure limit effective feedstock mobilization. The literature emphasizes that these challenges are primarily logistical and organizational rather than structural, suggesting that aggregation strategies, centralized upgrading facilities, and integrated supply chain models could substantially enhance economies of scale. Importantly, these approaches are presented as complementary to existing palm oil production systems rather than requiring their transformation.

Policy alignment and institutional coordination are consistently identified as decisive factors shaping the future trajectory of POME-based SAF development. The absence of explicit SAF-oriented policy frameworks, coupled with fragmented governance across energy, aviation, and environmental sectors, is cited as a source of investment uncertainty. Conversely, studies indicate that long-term policy signals, such as SAF blending mandates, offtake guarantees, and alignment with international sustainability certification schemes, could accelerate technology maturation and infrastructure deployment. Across the reviewed literature, POME is treated as an underutilized industrial by-product whose strategic valorization can contribute to national energy transition goals without positioning the palm oil industry as an inherent constraint.

Overall, the synthesized evidence indicates that POME-based SAF represents a technically viable and environmentally robust pathway that can support Indonesia's participation in global aviation decarbonization efforts. Realizing this potential at scale depends less on technological breakthroughs than on coordinated economic incentives, infrastructural integration, and coherent policy frameworks. By situating POME-based SAF within a circular economy paradigm, the literature highlights an opportunity to enhance the sustainability performance of existing industrial systems while contributing to the long-term decarbonization of the aviation sector.

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