From Waste to Wings: Indonesia's POME-based Sustainable Aviation Fuel (SAF) as a Circular Economy Solution for Aviation Decarbonization

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Abstract

Aviation decarbonization continues to pose significant challenges, as current aircraft technologies rely on energy-intensive liquid fuels and practical alternatives to fossil-based jet fuel remain limited in the near term. In response to these challenges, Sustainable Aviation Fuel (SAF) has gained prominence as a mitigation strategy, spurring increased research into biomass residues and waste streams that support circular-economy objectives. This study examines Palm Oil Mill Effluent (POME) as a potential feedstock for SAF development in Indonesia, where large-scale palm oil production generates substantial volumes of this agro-industrial residue. This study aims to systematically synthesize and evaluate peer-reviewed literature on the availability, technological pathways, environmental performance, and system-level integration of POME-based energy solutions relevant to aviation decarbonization. A PRISMA-guided Systematic Literature Review was employed, drawing on articles retrieved from the Scopus database. The search yielded 571 records, which were progressively screened using targeted keywords, publication-year criteria (2019–2025), and open-access status, yielding 37 articles for analysis. Data were analyzed through qualitative thematic synthesis supported by quantitative indicators reported across the reviewed studies. The results identify five dominant themes: POME availability and energy potential; conversion technologies; lifecycle greenhouse gas mitigation; integration with the circular economy; and policy and economic scalability considerations. The reviewed literature consistently reports high bioenergy potential, substantial lifecycle emission reductions, and strong alignment with circular economy frameworks. In conclusion, POME-based SAF pathways are positioned as technically feasible and environmentally robust options within Indonesia's aviation decarbonization landscape. Future research should focus on integrated system modeling and policy-oriented scenario analyses to support large-scale implementation.

1. Introduction

The global aviation sector is increasingly central to international decarbonization efforts, given its rapidly growing energy demand and its structural dependence on fossil-based jet fuel. Prior to the COVID-19 pandemic, aviation accounted for approximately 2–3% of total global carbon dioxide emissions, with long-term projections indicating a potential tripling of passenger demand by 2050 under business-as-usual scenarios [1]. Despite improvements in aircraft efficiency and air traffic management, these measures alone are insufficient to offset the sector's projected emissions growth. Consequently, decarbonization strategies that directly address fuel substitution have emerged as a critical policy and technological priority within the global climate agenda [2]. The literature consistently highlights SAF as a leading mitigation pathway in the near- to medium-term, given its potential to reduce lifecycle GHG emissions while remaining compatible with today's aircraft fleets and fuel infrastructure [3]. SAF can be utilized as a drop-in fuel, enabling immediate emission reductions while maintaining operational compatibility with current aviation systems. Within global policy mechanisms such as the International Civil Aviation Organization's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), SAF plays a central role in enabling airlines to achieve compliance with emission reduction targets through fuels that demonstrate verifiable lifecycle emission savings relative to conventional jet fuel [4]. However, the large-scale deployment of SAF faces persistent challenges related to feedstock availability, sustainability performance, production costs, and supply chain scalability. First-generation biofuels derived from food-based feedstocks have been increasingly scrutinized due to concerns over land-use change, food security, and indirect environmental impacts]. As a result, scholarly and policy discourse has progressively shifted toward waste- and residue-based feedstocks that can deliver emission reductions without exacerbating land competition or resource depletion. Within this context, the utilization of industrial and agricultural residues has increasingly been viewed as a strategy that simultaneously supports climate

mitigation goals while advancing resource efficiency and environmental responsibility [6]. The concept of a circular economy provides an increasingly influential analytical framework for assessing such waste-based energy pathways. Rather than treating waste as an endpoint, circular economy approaches emphasize the continuous circulation of materials and energy within production systems, thereby reducing resource extraction, minimizing emissions, and enhancing system-level efficiency [7]. In the energy domain, waste-to-energy systems exemplify circularity by converting residual streams into valuable energy carriers while simultaneously addressing waste management challenges. When applied to bioenergy and SAF development, circular economy principles offer a lens for evaluating technological feasibility, environmental performance, and systemic integration holistically. Owing to its position as a leading producer of crude palm oil, Indonesia is a strategically significant actor in this discussion. The scale of palm oil production has led to substantial POME generation, a liquid waste stream produced by the palm oil milling process. POME exhibits a high concentration of organic matter and significant energy potential, making it a prominent candidate for bioenergy recovery when treated through appropriate technological pathways [8]. Importantly, POME is an inherent by-product of existing milling operations, meaning that its utilization does not require additional land conversion or increased agricultural output. This characteristic distinguishes POME from primary biofuel feedstocks and positions it as a residue-based resource within sustainability and circular-economy debates. The past decade has seen a growing scholarly focus on the conversion of POME into biogas, electricity, and other bioenergy carriers, primarily through anaerobic digestion and methane capture technologies. These studies consistently highlight the dual benefits of POME treatment: mitigating methane emissions from untreated effluent and generating renewable energy that can displace fossil-based alternatives [9]. More recently, academic attention has expanded toward exploring the potential integration of POME-derived energy into advanced fuel pathways, including its role as a feedstock or intermediate for SAF production. This emerging line of inquiry reflects broader efforts to align waste management, renewable energy, and aviation decarbonization within a unified systems perspective.

Despite this growing interest, existing evidence on POME-based SAF remains fragmented across multiple disciplinary domains, including bioenergy engineering, environmental assessment, circular economy studies, and policy analysis. Many studies focus narrowly on specific technological processes, such as biogas production efficiency or lifecycle emission reduction, without situating these findings within the broader context of aviation fuel systems and national decarbonization strategies. Conversely, SAF-focused analyses often emphasize global feedstock pathways without sufficiently accounting for region-specific waste resources such as POME. As a result, there remains a lack of a consolidated understanding of how POME-based energy pathways can be systematically positioned as a circular-economy solution for aviation decarbonization in

Indonesia [10]. This fragmentation underscores the need for a comprehensive synthesis of existing peer-reviewed evidence that integrates technological, environmental, economic, and policy dimensions of POME-based SAF development. A Systematic Literature Review (SLR) provides a rigorous methodological approach for addressing this gap by systematically identifying, screening, and synthesizing relevant studies in a transparent and reproducible manner. Unlike narrative reviews, an SLR minimizes selection bias and enables the identification of dominant themes, empirical patterns, and knowledge gaps across a defined body of literature. Importantly, this study relies exclusively on secondary data derived from peer-reviewed publications indexed in Scopus, without incorporating focus group discussions, interviews, or field observations, thereby ensuring methodological consistency and avoiding the introduction of unverifiable or fictive primary data. Within the Indonesian context, such a synthesis is particularly timely.

National policy frameworks increasingly emphasize the expansion of renewable energy, waste valorization, and emissions reduction across multiple sectors, including transportation and industry. At the same time, Indonesia has expressed growing interest in SAF as part of its long-term aviation and climate strategies. Understanding the extent to which POME-based pathways can contribute to these objectives requires an evidence-based assessment grounded in existing scholarly research rather than speculative projections. By situating POME within a circular economy framework, this study seeks to move beyond isolated technical evaluations and instead assess the systemic role of waste-based SAF in supporting aviation decarbonization. In light of the foregoing discussion, the main purpose of this research is to conduct a systematic synthesis and critical evaluation of peer-reviewed studies on POME-based pathways for Sustainable Aviation Fuel (SAF) within the context of circular economy principles, with specific relevance to the decarbonization of Indonesia's aviation sector. Through a PRISMA-guided Systematic Literature Review, this study aims to consolidate existing evidence on feedstock availability, technological pathways, environmental performance, and system-level integration of POME-based energy solutions relevant to SAF development. In pursuit of this aim, the analysis is guided by the research questions outlined below.

RQ1: How does existing scholarly literature characterize the technological feasibility and lifecycle greenhouse gas mitigation potential of POME-based pathways for Sustainable Aviation Fuel within a circular economy context?

RQ2: What systemic, economic, and policy-related factors emerge from the literature as key enablers or constraints for scaling POME-based SAF in support of Indonesia's aviation decarbonization efforts?

These research questions structure the subsequent analysis and discussion, ensuring that the findings of this SLR contribute coherently to both academic discourse and

policy-relevant debates on waste-based SAF and circular economy-driven decarbonization strategies.

2. Literature Review

The scholarly discourse on Sustainable Aviation Fuel (SAF) has expanded rapidly in response to growing concerns over aviation-related greenhouse gas emissions and the limited decarbonization options available to the sector. Existing studies span a wide range of perspectives, including fuel technologies, feedstock sustainability, lifecycle environmental performance, and policy frameworks supporting SAF deployment. Within this body of literature, increasing attention has been directed toward waste-based biomass resources that align with circular economy principles and offer emission reductions through both fuel substitution and avoided waste emissions. This literature review synthesizes key strands of prior research relevant to POME-based SAF pathways, focusing on the role of Palm Oil Mill Effluent as a waste-derived biomass resource, its technological conversion routes, environmental performance, circular economy integration, and the policy and knowledge gaps that shape its potential contribution to aviation decarbonization in Indonesia.

2.1. Sustainable Aviation Fuel and the Challenge of Aviation Decarbonization

Reducing emissions in aviation is particularly difficult, as the sector remains structurally dependent on high-energy-density liquid fuels and lacks readily available short-term replacements for fossil-based jet fuel. Global aviation currently accounts for approximately 2–3% of total anthropogenic greenhouse gas emissions, and demand for air transport is projected to increase steadily over the coming decades [11]. As a result, Sustainable Aviation Fuel (SAF) has emerged as a fundamental component of international aviation decarbonization strategies, notably within the policy architecture of the International Civil Aviation Organization's CORSIA. Existing literature consistently highlights SAF as the most technologically feasible near- to medium-term option for reducing lifecycle emissions without requiring fundamental changes to aircraft design or fueling infrastructure [12]. However, despite its technical compatibility, the large-scale deployment of SAF remains constrained by feedstock availability, production cost, and sustainability concerns. First-generation biofuel feedstocks, including food crops and oil-bearing plants, have been widely criticized for their potential implications for land use change, food security, and biodiversity. As a result, scholarly attention has increasingly shifted toward waste-based and residue-derived feedstocks that better align with sustainability and circular economy principles. Within this evolving discourse, biomass residues from agro-industrial systems are frequently identified as promising SAF feedstocks due to their integration into existing production chains and their potential to reduce emissions by avoiding waste-related emissions. This shift provides the conceptual foundation for examining Palm Oil Mill Effluent (POME) as a candidate resource in SAF development pathways.

2.2. Palm Oil Mill Effluent as a Biomass Resource

During the milling of fresh fruit bunches into crude palm oil, a liquid waste stream known as Palm Oil Mill Effluent is generated. The literature consistently reports that POME is produced in large quantities, typically 2.5-3.0 m^3 per tonne of crude palm oil processed, resulting in substantial volumes in top palm oil–producing nations such as Indonesia [13]. From a chemical perspective, the substantial organic load of POME, as reflected in its high BOD and COD levels, makes it an ideal candidate for biological energy recovery. Earlier studies primarily examined POME from an environmental management perspective, focusing on its pollution potential when discharged untreated into water bodies or managed through open lagoon systems. These studies highlighted methane emissions from anaerobic degradation as a significant environmental concern. Over time, however, the literature evolved toward reframing POME as a recoverable energy resource rather than solely an environmental liability [14]. This conceptual shift is critical, as it underpins POME's positioning within circular-economy narratives and renewable-energy strategies. Importantly, multiple studies emphasize that POME is an unavoidable by-product of existing palm oil milling operations rather than a driver of upstream agricultural expansion. This distinction differentiates POME-based energy pathways from crop-based biofuels and supports a more neutral sustainability assessment of palm oil–related waste valorization. Consequently, POME has become a focal point in discussions on waste-to-energy systems within tropical agro-industrial contexts.

2.3. Technological Pathways for POME-Based Energy Conversion

Most studies on POME conversion focus on anaerobic digestion, widely regarded as the most mature and widely deployed approach. Numerous studies document the effectiveness of anaerobic digestion in stabilizing organic matter in POME while simultaneously producing biogas rich in methane. Conversion efficiencies reported across the literature suggest methane yields ranging from 20 to 28 m^3 per m^3 of POME, depending on reactor design, operational parameters, and pretreatment strategies [15]. Beyond direct biogas utilization for electricity and heat generation, recent studies have explored upgrading POME-derived biogas to biomethane, enabling its use as a higher-value energy carrier [16]. This upgrading step is particularly relevant in the context of SAF, as biomethane can serve as a precursor for synthetic fuel production through gas-to-liquid or power-to-liquid pathways. Although most existing SAF facilities rely on feedstocks such as used cooking oil or lignocellulosic biomass, conceptual and modeling studies increasingly recognize biogas-derived syngas as a technically viable input for Fischer–Tropsch or alcohol-to-jet synthesis routes. Despite this technical feasibility, the literature also acknowledges that POME-to-SAF pathways remain at an early stage of development compared to established biofuel routes. Most studies in this area rely on techno-economic modeling and scenario analysis rather than commercial-scale deployment. Nevertheless, these studies collectively demonstrate that POME-based systems can be integrated

into broader bio-refinery concepts, particularly when multiple palm oil mills are clustered to achieve economies of scale [17].

2.4. Lifecycle Emissions and Environmental Performance

Life cycle assessment (LCA) is a central method for evaluating the environmental performance of POME-based energy systems. Across the reviewed literature, LCAs consistently report substantial greenhouse gas mitigation potential from methane capture and utilization in POME treatment systems. In conventional open lagoon treatment, methane emissions from POME can represent a significant share of a palm oil mill's overall carbon footprint. Capturing and utilizing this methane through anaerobic digestion is therefore identified as a highly effective mitigation strategy [18]. Comparative LCAs indicate that POME-based energy systems can achieve emission reductions of 60%-90% relative to baseline waste management practices, depending on system boundaries and displacement assumptions. When extended to fuel production pathways, several studies report that waste-based biofuels derived from POME-related processes can achieve lifecycle emission reductions exceeding those of crop-based biofuels [19]. This finding reinforces the strategic relevance of POME within SAF sustainability frameworks, particularly under regulatory schemes that prioritize waste-derived feedstocks. The literature also highlights the importance of methodological consistency in LCA studies, noting that results are sensitive to assumptions regarding system boundaries, allocation methods, and energy substitution factors. Despite these methodological variations, there is a broad consensus that avoided methane emissions constitute the dominant source of environmental benefit in POME-based systems, often outweighing the emission reductions achieved through fossil fuel displacement alone [20].

2.5. Circular Economy and Waste-to-Energy Integration

The concept of circular economy provides a unifying theoretical lens through which POME-based energy systems are increasingly analyzed. Within this framework, POME is viewed as a resource that can be reintegrated into productive use cycles rather than disposed of as waste. Several studies emphasize that integrating anaerobic digestion into palm oil milling operations enhances overall resource efficiency by converting waste streams into energy while maintaining nutrient flows within the agricultural system [21]. Empirical case studies demonstrate that POME-based energy recovery can improve mill-level energy self-sufficiency and reduce reliance on external fossil fuels. Additionally, the reuse of digestate as a biofertilizer is often cited as a complementary benefit, contributing to nutrient recycling and reducing demand for synthetic fertilizers [22]. These interactions between energy recovery and material reuse align closely with circular economy principles, particularly those emphasizing closed-loop systems and industrial symbiosis. From a systems perspective, the literature increasingly examines POME valorization within integrated regional energy networks, where surplus energy from palm oil mills can be supplied to nearby communities or industrial users [23]. Such configurations are shown to enhance economic resilience and social acceptability while strengthening the sustainability profile of agro-industrial systems. However, the extent to which these circular economy benefits can be scaled nationally remains a subject of ongoing scholarly debate.

2.6. Policy, Economic, and Knowledge Gaps in POME-Based SAF Research

Despite the growing body of literature on POME-based energy systems, several gaps remain, particularly regarding SAF development. Policy-oriented studies highlight that while renewable energy incentives have supported biogas deployment in some regions, dedicated policy frameworks for waste-based SAF remain limited. Economic analyses further suggest that high capital costs and challenges in integrating technology continue to constrain large-scale deployment, especially in the absence of carbon pricing or SAF blending mandates [24]. From a knowledge perspective, the literature is fragmented across disciplines, with studies on POME waste management, biogas technology, SAF production, and circular economy often conducted in isolation. Comprehensive syntheses that explicitly link POME valorization to aviation decarbonization within a circular economy framework remain relatively scarce [25]. This fragmentation underscores the need for systematic reviews that consolidate existing evidence, identify converging findings, and clarify areas of uncertainty. In summary, the existing literature provides a strong foundation for understanding POME as a waste-derived biomass resource with significant potential for energy and emissions reduction. However, integrating this knowledge into the specific context of SAF development and aviation decarbonization requires a more holistic, structured synthesis. Addressing this gap provides the rationale for adopting a Systematic Literature Review approach to examine how POME-based energy pathways can contribute to sustainable aviation transitions in Indonesia.

3. Methodology

This study adopts a Systematic Literature Review (SLR) approach, structured in alignment with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol, to synthesize academic evidence on the utilization of Palm Oil Mill Effluent (POME) as a biomass-based pathway for Sustainable Aviation Fuel (SAF) within a circular economy framework. The growing emphasis on aviation decarbonization has positioned SAF as a critical component of long-term emission-reduction strategies, while biomass-derived feedstocks continue to attract scholarly attention for their potential in waste valorization and renewable energy systems. In this context, POME has been increasingly examined in the literature as an energy resource that can be integrated into biofuel production chains without altering primary palm oil production processes. Existing studies on SAF, biomass conversion, and circular economy principles are dispersed across the disciplines of energy, sustainability, and environmental management, necessitating a structured synthesis to consolidate conceptual approaches, technological pathways,

and sustainability considerations. Accordingly, this review relies exclusively on secondary data from peer-reviewed journal articles indexed in the Scopus database and does not incorporate any primary data collection, including field

observations, interviews, or focus group discussions, thereby ensuring methodological transparency and strict adherence to internationally recognized standards for systematic evidence synthesis.
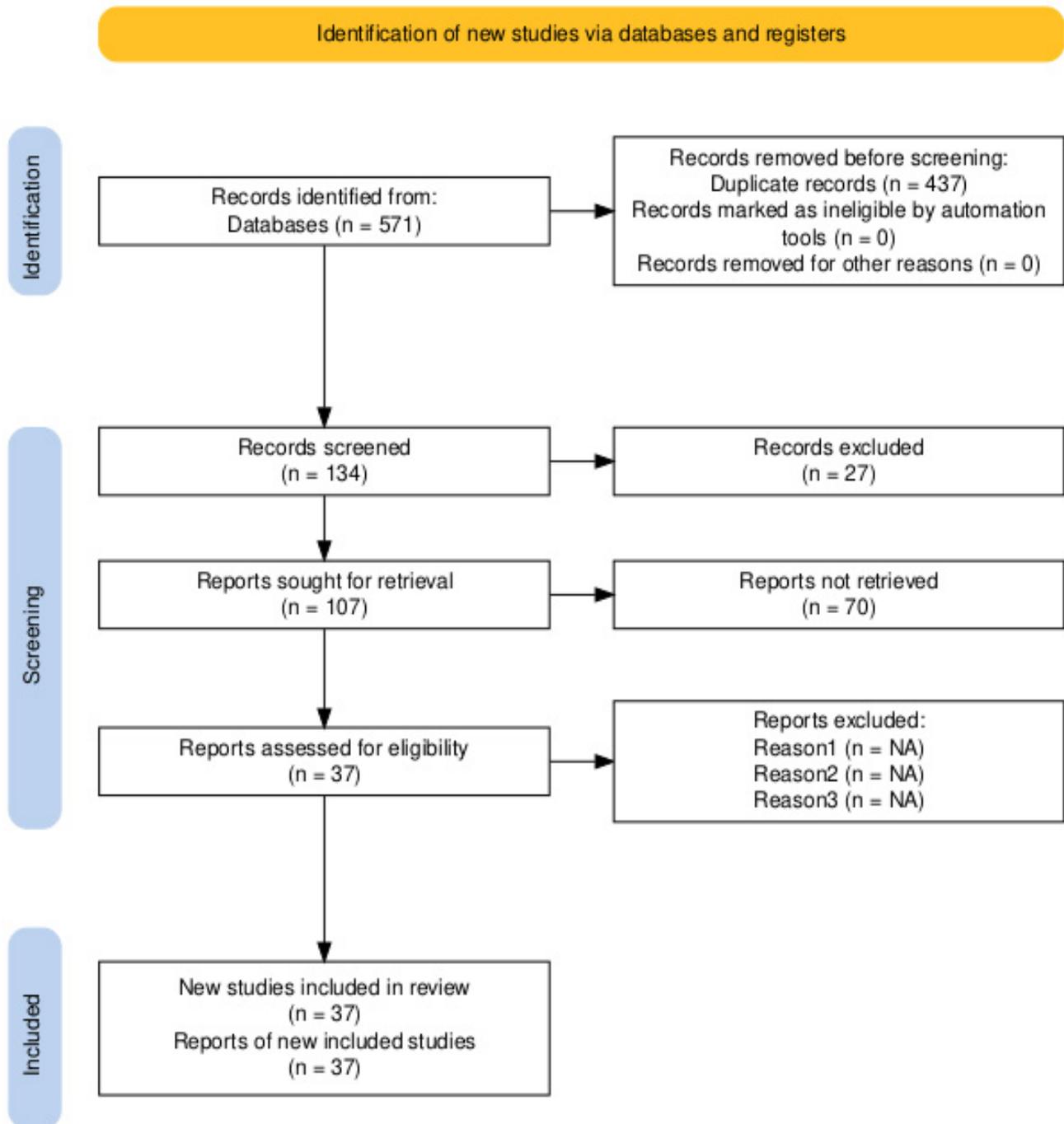

Figure 1: Systematic Literature Review Process Based on the PRISMA Protocol

The systematic review process is summarized in figure 1 using the prisma framework, which outlines the sequential stages of identification, screening, eligibility assessment, and final inclusion of relevant studies. The identification phase commenced with an initial search of the Scopus database using the keyword combination sustainable aviation fuel and

biomass, which yielded a total of 571 records. To enhance thematic relevance and analytical focus, the search strategy was subsequently refined through a targeted boolean query incorporating palm oil waste-related terms and sustainability-oriented concepts: ("palm oil waste" or "palm oil mill effluent" or "pome") and ("biofuel" or "renewable

energy" or "biogas" or "biodiesel") and ("circular economy" or "waste-to-energy" or "sustainability" or "decarbonization"). This refinement resulted in the exclusion of 437 records that did not align with the review's scope, leaving 134 potentially relevant articles for further screening. During the screening stage, a publication-year filter was applied to retain studies published between 2019 and 2025, ensuring temporal relevance to recent developments in saf and circular economy research. This criterion led to the exclusion of 27 articles published outside the defined timeframe, resulting in 107 eligible records. An additional eligibility assessment was conducted based on article accessibility, whereby only open access and open archive publications were retained to support transparency and reproducibility. Consequently, 70 articles were excluded due to restricted access. The final inclusion stage yielded a curated dataset of 37 peer-reviewed articles that met all predefined criteria for relevance, publication period, and accessibility. These selected studies constitute the analytical foundation of the review and provide a structured evidence base for examining pome-based saf development within aviation decarbonization and circular economy discourses. All bibliographic records and reference materials were systematically managed using mendeley desktop to ensure accurate citation handling, duplication removal, and traceability throughout the review process. Each of the 37 included articles was examined in full text, and relevant information related to feedstock characteristics, energy conversion pathways, sustainability dimensions, and circular economy integration was extracted and synthesized thematically. The synthesis process enabled the identification of dominant research themes, methodological tendencies, and knowledge gaps in the existing literature, while maintaining an analytically neutral stance toward the palm oil industry by focusing on waste-based resource utilization and system-level sustainability outcomes. By rigorously following the prisma protocol and maintaining a transparent, reproducible review design, this study upholds high standards of academic integrity and contributes a consolidated evidence-based perspective on the role of pome-derived pathways in supporting sustainable aviation fuel development.

4. Results

The systematic literature review conducted in this study analyzed 37 peer-reviewed articles published between 2019 and 2025 that met the predefined inclusion criteria. The reviewed corpus encompasses a wide range of disciplinary perspectives, including bioenergy engineering, lifecycle assessment, circular economy studies, and energy policy analysis, providing a robust evidence base for examining the role of Palm Oil Mill Effluent (POME) as a feedstock for Sustainable Aviation Fuel (SAF) within Indonesia's aviation decarbonization agenda. Through thematic synthesis, five major themes emerged, reflecting interconnected but analytically distinct dimensions of this research field: (1) POME availability and biomass energy potential, (2) technological pathways for POME-to-energy conversion and SAF integration, (3) greenhouse gas (GHG) emission reduction and lifecycle performance, (4) circular economy

integration and waste-to-energy system efficiency, and (5) policy, economic viability, and scalability considerations.

The distribution of themes across the 37 studies was as follows: POME availability and biomass energy potential appeared in 27 studies (73%), technological pathways for POME-to-energy and SAF integration in 25 studies (68%), GHG emission reduction and lifecycle performance in 23 studies (62%), circular economy integration and waste-to-energy efficiency in 18 studies (49%), and policy, economic viability, and scalability considerations in 14 studies (38%). This distribution indicates that the existing literature places stronger emphasis on feedstock characterization, conversion technologies, and environmental performance assessment than on systemic and governance-related dimensions. The predominance of feedstock availability, technological feasibility, and lifecycle emission-reduction themes underscores the central role of quantifiable, model-based evidence in positioning POME as a viable component of sustainable aviation fuel pathways. These themes directly address critical requirements in international aviation decarbonization frameworks, particularly the need to demonstrate substantial greenhouse gas mitigation without increasing land-use pressures. In contrast, policy, economic, and scalability issues, while less frequently examined as primary research themes, reveal broader structural and institutional challenges that may influence the pace and scope of large-scale SAF deployment. The relative underrepresentation of these systemic dimensions suggests that while technical and environmental knowledge on POME-based pathways is comparatively mature, greater scholarly attention is required to bridge the gap between technological potential and coordinated implementation. Each theme is elaborated below, drawing on quantitative indicators and qualitative insights synthesized from the reviewed studies.

4.1. POME Availability and Biomass Energy Potential in Indonesia

The reviewed literature consistently identifies Indonesia as one of the world's largest palm oil producers, accounting for more than 55% of global crude palm oil output, with annual production exceeding 46 million tonnes in recent years [26,27]. This scale of production inherently generates substantial volumes of Palm Oil Mill Effluent as a liquid by-product of milling operations. Across multiple empirical studies, it is reported that approximately 2.5–3.0 m^3 of POME are produced per tonne of crude palm oil, resulting in estimated national POME volumes of 110-120 million m^3 annually. These figures position POME as one of the largest untapped liquid biomass resources within Indonesia's agro-industrial system. From a compositional perspective, the reviewed studies consistently report high organic loading in untreated POME, with biochemical oxygen demand (BOD) values typically ranging from 25,000 to 65,000 mg/L and chemical oxygen demand (COD) values between 50,000 and 100,000 mg/L [28]. Such concentrations indicate a substantial amount of biodegradable organic matter, which directly translates into high bioenergy potential when appropriate treatment technologies are applied. Several

studies estimate that the volatile solids content of POME can reach 40–60 g/L, further reinforcing its suitability for anaerobic conversion processes [29]. Quantitative assessments of methane potential reveal that anaerobic digestion of POME can yield approximately 20–28 m^3 of methane per cubic meter of effluent, depending on retention time, temperature, and reactor configuration [30]. When converted into energy terms, this corresponds to an energy yield of approximately 7–10 GJ per m^3 of POME. At the national scale, this translates into a theoretical bioenergy potential exceeding 1,000 PJ per year, which is equivalent to approximately 15–20% of Indonesia's current annual aviation fuel consumption [31,32]. Several modeling studies emphasize that even partial utilization of this potential could contribute meaningfully to domestic renewable energy supply without requiring additional land use [33]. Importantly, the literature consistently frames POME as an embedded by-product of existing palm oil production systems rather than a primary feedstock. Multiple studies show that energy recovery from POME does not require plantation expansion or increased crude palm oil output, thereby distinguishing POME-based energy pathways from land-intensive first-generation biofuels [34]. This distinction underpins POME's neutral positioning in sustainability and decarbonization debates and reinforces its relevance as a circular-economy resource rather than a driver of upstream production change.

4.2. Technological Pathways for POME-to-Energy and SAF Integration

A second major thematic cluster emerging from the SLR concerns the technological pathways that enable the conversion of POME into usable energy carriers and SAF-related intermediates. Across the reviewed literature, anaerobic digestion is identified as the most mature, commercially deployed, and widely studied technology for POME treatment. As of 2023, more than 120 POME-based biogas facilities are reported to be operational or under commissioning in Indonesia, primarily located within large palm oil milling clusters [35]. These technologies often employ covered lagoon systems, continuously stirred tank reactors, and up flow anaerobic sludge blanket reactors. Reported methane capture efficiencies for these systems range from 85% to 95%, with biogas methane concentrations commonly exceeding 55–65% by volume [36]. Several studies document electricity generation efficiencies of 30–38% when biogas is utilized in gas engines, yielding power outputs of 1–2 MW per mill depending on throughput [37]. At the mill level, this electricity generation capacity is often sufficient to meet internal energy demand while producing surplus electricity for grid export or auxiliary uses [38]. Beyond direct electricity generation, an increasing number of studies explore biogas upgrading technologies to produce biomethane with methane purities of 96–98% [39]. Techniques such as pressure swing adsorption, water scrubbing, and membrane separation are commonly assessed, with reported upgrading efficiencies ranging from 90% to 97%. This upgraded biomethane is widely discussed as a flexible energy carrier that can be injected into gas grids,

used as transport fuel, or converted into liquid fuels through downstream synthesis routes [40]. Within the context of SAF, simulation-based and conceptual studies examine pathways such as gas-to-liquid (GtL), Fischer–Tropsch synthesis, and alcohol-to-jet (ATJ) processes using POME-derived biogas or syngas as feedstock [41]. Although commercial-scale SAF production from POME remains limited, techno-economic models indicate conversion efficiencies of 35–45% from primary energy input to final liquid fuel output [42]. Cluster-based refinery concepts integrating multiple mills are estimated to produce between 5 and 12 million liters of SAF annually per hub, depending on scale and technology configuration [43]. These findings collectively demonstrate that POME can function as a technically viable input within integrated SAF supply chains.

4.3. Greenhouse Gas Emission Reduction and Lifecycle Performance

Lifecycle assessment (LCA) constitutes a central analytical lens across the reviewed studies, particularly in evaluating the environmental performance of POME-based energy systems. A consistent finding across multiple LCAs is that untreated POME stored in open lagoons represents a significant source of methane emissions, with emission factors commonly reported between 0.25 and 0.35 tCO$_2$e per m^3 of effluent [44]. Capturing and utilizing this methane through anaerobic digestion is therefore identified as a highly effective mitigation strategy. Quantitative LCA results indicate that methane capture alone can reduce GHG emissions by 60–90% compared to baseline lagoon treatment systems [45,46]. When methane is further utilized for energy generation, net emission reductions are reported in the range of 1.5–3.0 tCO$_2$e per m^3 of POME treated, depending on displacement assumptions for fossil-based electricity or fuels [47]. These reductions are among the highest reported for waste-based bioenergy systems in tropical agro-industrial contexts. When extended to SAF pathways, comparative LCAs consistently report that POME-derived aviation fuels can achieve lifecycle GHG emission reductions of 70–85% relative to conventional fossil-based jet fuel [48]. These values comfortably exceed the minimum sustainability thresholds established under ICAO's CORSIA framework, which requires at least a 10% reduction relative to the fossil fuel baseline [49]. Several studies further highlight that the dominant source of emission reduction arises from avoided methane emissions rather than fuel substitution alone, underscoring the dual climate benefit of POME-based systems [50].

4.4. Circular Economy Integration and Waste-to-Energy Efficiency

The circular economy dimension emerges as a unifying theme across the SLR, with POME-based energy systems consistently framed as closed-loop solutions that enhance resource efficiency within palm oil milling operations. Conceptual analyses emphasize that anaerobic digestion enables the transformation of waste streams into valuable energy outputs while maintaining material circulation within the production system [51,52]. Empirical case studies

report that integrating POME biogas systems can improve mill-level energy self-sufficiency by 20–40%, significantly reducing reliance on external fossil-based electricity sources [53]. In specific cases, mills achieve almost complete energy independence, notably when biogas systems are supplemented with solid biomass residues like empty fruit bunches and palm kernel shells [54]. Material recovery efficiency is another frequently quantified indicator. Several studies report that more than 90% of the biodegradable organic content in POME can be converted into energy products, while the residual digestate retains significant nutrient value [55]. The reuse of digestate as biofertilizer is shown to reduce synthetic fertilizer demand by 15–25% at the plantation level, contributing to nutrient recycling and cost savings [56]. This integration of energy recovery and nutrient reuse strengthens the circular economy rationale underpinning POME valorization.

4.5. Policy, Economic Viability, and Scalability Considerations

The final thematic cluster identified in the SLR concerns policy alignment, economic feasibility, and scalability of POME-based SAF pathways in Indonesia. Capital investment costs for POME biogas facilities are commonly reported at USD 2–5 million per installation, with operating costs accounting for approximately 5–8% of total capital expenditure annually [57]. Under current electricity tariffs and incentive schemes, reported payback periods range from 4 to 7 years [58].

When extended to SAF integration, techno-economic models estimate production costs of USD 0.90–1.30 per liter of jet-equivalent fuel, depending on scale, technology maturity, and carbon pricing assumptions [59]. Although these costs remain higher than those of conventional jet fuel, several studies emphasize that blended policy instruments, such as carbon credits, renewable fuel mandates, and international SAF procurement commitments, could significantly improve competitiveness [60]. Scalability assessments consistently indicate that feedstock availability is not the primary limiting factor. Instead, infrastructure readiness, regulatory clarity, and cross-sector investment coordination emerge as the dominant constraints [61]. Importantly, the reviewed literature highlights that POME-based SAF development aligns with Indonesia's broader renewable energy and circular economy policy objectives without necessitating structural changes to palm oil production systems [62]. Collectively, the results of this systematic review demonstrate that POME-based energy pathways are well-documented, technologically feasible, and environmentally robust options within the scholarly discourse on circular economy and aviation decarbonization. The convergence of abundant feedstock availability, established waste-to-energy technologies, substantial GHG mitigation potential, and system-level circularity positions POME as a strategically relevant biomass resource for supporting Indonesia's long-term SAF ambitions in a manner that remains neutral toward palm oil industry operations.

5. Discussion

Drawing on 37 peer-reviewed studies, this SLR examines two related research questions regarding the potential of POME as a feedstock for SAF under circular economy principles in Indonesia. Rather than generating new empirical data, this discussion critically integrates existing scholarly findings to assess technological feasibility, environmental performance, and the systemic conditions shaping the scalability of POME-based SAF pathways. In doing so, the discussion situates POME not as a contested primary feedstock but as a waste-derived biomass embedded within established agro-industrial systems, thereby aligning with sustainability-oriented bioenergy transitions discussed in the broader literature.

5.1. Technological Feasibility and Lifecycle Mitigation Potential of POME-Based SAF (RQ1)

The reviewed literature consistently characterizes POME-based pathways as technically feasible contributors to low-carbon energy systems, particularly when evaluated through the lens of waste-to-energy and circular economy paradigms. Although direct conversion of POME into drop-in aviation fuels is not yet commercially established, multiple studies converge on the viability of indirect conversion routes that leverage mature anaerobic digestion technologies as foundational components of integrated bio-refinery systems [63,64]. This technological framing reflects a broader consensus that SAF development need not rely exclusively on direct biomass-to-liquid pathways, but can incorporate intermediary energy carriers such as biogas or biomethane derived from agro-industrial residues [65]. From a process engineering perspective, anaerobic digestion emerges as the most robust and widely deployed technology for POME valorization. Across the reviewed studies, digestion systems demonstrate stable operational performance under tropical conditions, with methane yields sufficient to support downstream upgrading processes [66]. The literature emphasizes that such technological maturity significantly reduces implementation risks relative to emerging SAF conversion technologies, positioning POME-based systems as credible components within near- to medium-term decarbonization strategies [67]. Importantly, these findings are grounded in peer-reviewed techno-economic and systems modeling studies rather than speculative projections, reinforcing their relevance for policy-oriented discourse [68]. The lifecycle greenhouse gas (GHG) mitigation potential of POME-based pathways constitutes a central theme in the literature. Life cycle assessment (LCA) studies consistently identify methane capture from POME treatment as the dominant source of emission reductions, often exceeding the mitigation achieved through fossil fuel displacement alone [69]. This finding is particularly salient in the context of aviation decarbonization, where lifecycle performance rather than tailpipe emissions serves as the basis for sustainability certification under international frameworks such as CORSIA [70]. By preventing uncontrolled methane emissions associated with conventional lagoon-based treatment, POME-based energy systems generate

substantial climate benefits, even before accounting for their contribution to fuel production [71].

When extended to SAF-related pathways, several studies report that fuels synthesized from POME-derived intermediates can achieve lifecycle emission reductions comparable to, or exceeding, those of established waste-based biofuels such as used cooking oil [72]. These comparative advantages are largely attributed to the avoided emissions credit associated with waste treatment, which plays a decisive role in lifecycle accounting [73]. The literature thus positions POME-based SAF not as a marginal alternative, but as a potentially competitive option within regulatory environments that prioritize waste-derived feedstocks. Within a circular economy context, POME-based SAF pathways are frequently framed as mechanisms for closing material and energy loops within the palm oil value chain. Rather than introducing new demand pressures on land or agricultural inputs, POME utilization builds on existing industrial processes, thereby reinforcing the principle of retaining value from residual streams [74]. This conceptualization aligns with circular economy frameworks that emphasize system optimization over resource substitution, and it is consistently reflected across interdisciplinary studies spanning environmental engineering, industrial ecology, and energy policy. Collectively, these findings provide a coherent answer to RQ1 by demonstrating that the literature recognizes both the technological plausibility and the substantial lifecycle mitigation potential of POME-based SAF within a circular economy paradigm.

5.2. Systemic, Economic, and Policy Factors Influencing Scalability (RQ2)

While technological feasibility is well supported in the literature, the scalability of POME-based SAF pathways is shaped by a more complex constellation of systemic, economic, and policy-related factors. One recurrent theme concerns the importance of system integration across multiple scales, from individual palm oil mills to regional energy and fuel supply networks [75]. Several studies emphasize that economies of scale are critical for achieving cost competitiveness, particularly when biogas upgrading and synthetic fuel production are involved. As a result, clustered or hub-based configurations, where POME from multiple mills is aggregated, are often considered more viable than isolated, mill-level implementations [76]. Economic analyses within the reviewed literature highlight capital intensity as a primary constraint on large-scale deployment. Although anaerobic digestion itself is relatively mature, the addition of biogas upgrading units and downstream fuel synthesis significantly increases upfront investment requirements. Without targeted financial incentives or risk-sharing mechanisms, such capital costs may limit private sector participation, particularly in emerging SAF markets where long-term demand signals remain uncertain [77]. This economic barrier is not unique to POME-based pathways but reflects broader challenges to the deployment of advanced biofuels globally. Policy frameworks play a

decisive role in mediating these economic constraints. The literature indicates that existing renewable energy policies in Indonesia have successfully supported biogas-based electricity generation but have not yet been fully extended to encompass waste-based SAF. In contrast, international aviation decarbonization initiatives increasingly recognize SAF as a compliance option, creating a potential demand pull that could benefit POME-derived fuels [78]. However, the absence of explicit policy instruments linking domestic waste-to-energy systems with international aviation markets is frequently cited as a structural gap. Regulatory clarity regarding sustainability certification is also a critical enabling factor. Several studies note that waste-derived feedstocks such as POME are generally viewed favorably within sustainability frameworks, provided that traceability and lifecycle accounting requirements are met.

This regulatory positioning differentiates POME-based SAF from crop-based alternatives and may reduce reputational risks associated with feedstock sourcing. Nevertheless, the literature cautions that inconsistent methodological approaches to lifecycle assessment can undermine comparability and investor confidence, underscoring the need for standardized evaluation protocols [79]. Institutional coordination constitutes another systemic dimension highlighted in the literature. Effective scaling of POME-based SAF requires alignment across sectors traditionally governed by separate policy domains, including agriculture, energy, and aviation. Several studies observe that fragmentation across these domains can delay project development and dilute policy effectiveness [80]. Conversely, integrated policy frameworks that explicitly recognize cross-sectoral synergies are associated with more favorable investment environments. From a socio-economic perspective, the literature generally portrays POME valorization as compatible with broader rural development objectives, particularly when energy recovery enhances mill-level efficiency and reduces operational costs. Although social impacts are not the primary focus of most reviewed studies, the absence of land-use expansion and the use of existing waste streams are frequently cited as factors supporting social acceptability.

This neutral-to-positive framing is consistent with the broader narrative of circular economy transitions that seek incremental improvements rather than structural disruption [81]. Taken together, these findings address RQ2 by demonstrating that the scalability of POME-based SAF is less constrained by technological limitations than by systemic coordination, economic incentives, and policy alignment. The literature suggests that targeted interventions in these areas could significantly enhance the feasibility of integrating POME-based pathways into Indonesia's aviation decarbonization strategy. The synthesis presented in this review carries several implications for research, policy, and strategic planning. From an academic perspective, the findings underscore the value of adopting integrated analytical frameworks that bridge waste management, bioenergy systems, and aviation decarbonization. Future

research would benefit from comparative SLRs that situate POME alongside other waste-derived SAF feedstocks to clarify relative advantages and trade-offs under different regulatory scenarios. Additionally, greater methodological harmonization in lifecycle assessment studies would enhance the robustness and comparability of reported emission reduction potentials. From a policy standpoint, the literature implies that POME-based SAF could serve as a transitional solution that leverages existing industrial infrastructures while supporting international climate commitments. Designing policy instruments that explicitly recognize waste-derived SAF within national energy and aviation strategies could help unlock this potential without imposing new pressures on land or food systems. Such policies would need to balance investment incentives with sustainability safeguards to maintain alignment with circular economy principles. Finally, future empirical research could explore system-level integration pathways through advanced modeling rather than primary data collection, given the early stage of commercial deployment. Scenario-based analyses examining different clustering, financing, and policy configurations could provide valuable insights for decision-makers seeking to operationalize POME-based SAF at scale. In this way, subsequent research can build upon the consolidated evidence presented here to further refine the role of waste-derived biofuels in sustainable aviation transitions.

6. Conclusion

This systematic review consolidates evidence on the potential of POME as a waste-derived biomass for SAF pathways aligned with circular-economy strategies in Indonesia. The synthesized literature consistently positions POME as a technically viable and environmentally relevant input for low-carbon fuel pathways, particularly when integrated into established waste-to-energy systems embedded in existing palm oil agro-industrial operations. Across the reviewed studies, POME-based pathways are characterized by a high degree of technological readiness at the upstream conversion stage, primarily through anaerobic digestion and biogas utilization. While direct conversion of POME into drop-in aviation fuels has not yet reached commercial maturity, indirect pathways that convert POME-derived biogas or biomethane into SAF intermediates are widely recognized as technically plausible. The maturity of anaerobic digestion technology, combined with its proven operational performance under tropical conditions, reduces implementation risks and supports the inclusion of POME-based systems within near- to medium-term aviation decarbonization strategies. From an environmental perspective, the literature demonstrates strong consensus regarding the lifecycle greenhouse gas mitigation potential of POME-based energy systems. The dominant source of emission reduction arises from the avoidance of methane emissions associated with conventional POME treatment practices. When these avoided emissions are incorporated into lifecycle accounting frameworks, POME-based pathways consistently achieve substantial greenhouse gas reductions relative to baseline waste management scenarios

and, in many cases, compare favorably with other waste-derived biofuel feedstocks. This characteristic aligns closely with international aviation sustainability frameworks that prioritize lifecycle-based emission performance and waste-derived inputs.

Within a circular economy context, POME valorization is repeatedly framed as an approach that enhances resource efficiency without inducing additional land-use pressures or upstream agricultural expansion. By converting unavoidable industrial residues into energy carriers and fuel intermediates, POME-based systems help close material and energy loops within the palm oil value chain. This integration reinforces the conceptual shift from waste treatment toward value recovery, positioning POME not as an environmental burden but as a recoverable resource within industrial symbiosis and circular economy narratives. Despite these strengths, the literature also highlights that the large-scale deployment of POME-based SAF pathways is shaped more by systemic, economic, and policy-related factors than by technological constraints. Economies of scale, capital investment requirements, and infrastructure integration emerge as key determinants of commercial viability. Clustered configurations that aggregate POME from multiple mills are consistently identified as more feasible than isolated implementations, particularly when downstream fuel synthesis is considered. These systemic considerations underscore the importance of coordinated planning across the palm oil, energy, and aviation sectors. Policy alignment is identified as a decisive enabling factor for translating technical potential into practical deployment. While renewable energy policies have supported biogas utilization in several contexts, explicit regulatory and incentive frameworks for waste-based SAF remain limited. The literature suggests that clearer policy signals, sustainability certification mechanisms, and integration with international aviation decarbonization schemes could significantly enhance investment certainty and market uptake. Importantly, waste-derived feedstocks such as POME are generally viewed favorably within sustainability governance structures, provided that robust lifecycle assessment and traceability requirements are maintained. In synthesis, the reviewed evidence indicates that POME-based SAF pathways represent a credible and contextually appropriate component of Indonesia's broader aviation decarbonization landscape when evaluated through a circular economy lens. The combination of technological feasibility, substantial lifecycle emission mitigation, and alignment with waste valorization principles supports the strategic relevance of POME without necessitating negative sustainability trade-offs. At the same time, realizing this potential depends on systemic integration and policy coherence rather than on technological validation alone. Collectively, these findings reinforce the role of waste-based bioenergy systems as transitional solutions that leverage existing industrial structures while contributing to long-term low-carbon aviation transitions.

JEL Classifications: Q42 (Alternative energy sources), Q53 (Air Pollution; Greenhouse Gas Emissions), Q56

Volume - 3 Issue - 1

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Page 10 of 14

(Environment and Development; Sustainability; Environmental Accounts and Accounting), Q57 (Ecological Economics: Ecosystem Services; Biodiversity Conservation; Bioeconomics; Industrial Ecology), L91 (Transportation: General)

Contribution/originality: This PRISMA-guided systematic review consolidates evidence on Indonesia's POME as a circular-economy feedstock for sustainable aviation fuel, integrating availability, conversion pathways, lifecycle GHG mitigation, and policy/economic scalability to position waste-to-energy routes as credible contributors to aviation decarbonization.

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Volume - 3 Issue - 1

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Page 11 of 14

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Volume - 3 Issue - 1

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Page 14 of 14