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Treasure from Palm Oil Waste: POME as Low-Emission Fuel for Aviation

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Abstract

The increasing global demand for sustainable aviation fuels has prompted exploration of alternative bioenergy sources to cut greenhouse gas emissions. As a by-product generated in high volumes from palm oil processing, Palm Oil Mill Effluent (POME) presents opportunities as a sustainable, low-emission fuel thanks to its high levels of organic matter. Through a qualitative lens, this literature review evaluates POME's potential as a green aviation fuel, considering technological, environmental, and economic dimensions. Utilizing a qualitative research approach, relevant peer-reviewed articles, reports, and policy documents were systematically collected through academic databases and institutional repositories. Data were analyzed thematically to identify patterns, challenges, and opportunities in POME valorization for aviation fuel production. Evidence suggests that both biochemical and thermochemical techniques, particularly anaerobic digestion and hydrothermal liquefaction, are effective in converting POME into biofuels that align with aviation standards and produce notably fewer greenhouse gas emissions than traditional fossil fuels. Economic assessments suggest competitive production costs, especially when integrated with existing palm oil mill infrastructure. However, barriers including feedstock variability, process scalability, and regulatory frameworks remain critical for commercialization. In conclusion, POME represents a valuable, sustainable resource that aligns with circular economy principles and global decarbonization goals in aviation. Future research should focus on pilot-scale demonstrations, lifecycle sustainability assessments, and policy development to support broader adoption. This study contributes a comprehensive synthesis of current knowledge, guiding stakeholders in advancing POME-based aviation fuels.

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Introduction

The aviation industry significantly supports global integration by connecting communities and markets, yet it contributes an estimated 2–3% of worldwide carbon dioxide emissions each year, making it one of the most carbon-intensive sectors [1]. With air travel projected to grow twofold by 2040, increasing pressure is being placed on the aviation industry to cut carbon emissions in accordance with the Paris Agreement and subsequent global climate commitments [2]. Unlike ground transportation, where electrification has gained traction, aviation demands high-energy-density fuels, recognizing Sustainable Aviation Fuel(SAF) as a vital stepping stone in the aviation sector's transition to sustainability [3].

With the potential to lower greenhouse gas emissions throughout its lifecycle by as much as 80%, contingent on the feedstock and production method, SAF emerges as a viable substitute for conventional jet fuels [4]. Approved SAF feedstocks under ASTM D7566 include materials like used cooking oil, algae, and municipal waste, but bio-residues and industrial wastewater are gaining attention for their sustainability benefits and non-competition with food production [5]. However, the supply of conventional feedstocks like waste cooking oil is insufficient to meet projected SAF demand, prompting the need to explore novel, scalable, and underutilized sources [6].

In this context, Palm Oil Mill Effluent (POME), a nutrient-rich waste liquid from palm oil extraction, stands out as a potential feedstock. With 2.5–3.0 tons of POME produced per ton of crude palm oil, it ranks among Southeast Asia's most abundant agro-industrial waste sources [7]. Because of its elevated COD and BOD concentrations, POME has typically been seen as an environmental liability and treated either by anaerobic digestion to recover biogas or by employing ponding systems to mitigate pollutant levels [8]. However, these solutions often underperform in scalability, emissions control, or energy recovery efficiency [9].

In recent years, technological advancements in waste valorization have opened new avenues to upgrade POME into products with added value, including biofuels suitable for aviation applications [10]. POME contains a significant proportion of organic compounds, including residual oils, volatile fatty acids, and suspended solids, which can serve as precursors in thermochemical or biochemical conversion processes [11]. While considerable research has detailed the conversion of POME to biogas and biodiesel, its direct or indirect transformation into aviation-grade fuel remains underexplored in both academic and industrial domains [12].

The relevance of POME as a SAF feedstock lies not only in its abundance and energy content, but also in its ability to address multiple sustainability criteria simultaneously namely, waste minimization, carbon mitigation, and rural development [13]. Countries like Indonesia and Malaysia, which combined contribute to upwards of 80% of the worldwide palm oil supply, face significant challenges in managing POME sustainably, particularly in light of increasing regulatory scrutiny and environmental activism [14]. Leveraging POME for aviation fuel could therefore serve dual national interests: promoting environmental stewardship while contributing to energy security [15].

Despite its promise, there are technological, regulatory, and economic challenges to mainstreaming POME as a SAF input. For example, POME requires substantial pre-treatment to remove impurities and enhance fuel conversion efficiency [16]. Moreover, downstream refining processes must meet stringent aviation fuel standards such as ASTM D1655 and D7566 to ensure flight safety and engine compatibility [17]. From a policy standpoint, incentives and mandates supporting SAF deployment are still nascent in many palm oil-producing countries, creating uncertainty for potential investors and developers [18].

Equally critical is the lack of integrated frameworks that connect the palm oil industry, waste management systems, and aviation fuel value chains. Current academic literature tends to compartmentalize these domains, limiting comprehensive understanding of how POME could be effectively scaled for jet fuel production [19]. This fragmented knowledge landscape highlights the need for a cross-sectoral synthesis that brings together environmental, technical, economic, and policy dimensions of the POME-to-SAF pathway [20].

In light of these deficiencies, the research conducts a qualitative review of existing literature to investigate the potential of POME as a source feedstock for sustainable aviation fuel. Unlike systematic literature reviews (SLR), which require protocol-driven inclusion and exclusion processes, this qualitative review aims to synthesize diverse bodies of knowledge across environmental engineering, energy systems, waste valorization, and aviation sustainability. The central objective is to elucidate the transformative potential of POME from a waste management liability into a low-emission fuel source for the aviation industry while critically assessing the technological feasibility, policy landscape, and sustainability trade-offs.

Literature Review

The Aviation Sector and the need for Sustainable Fuels

Within the global contributors to greenhouse gases, the aviation industry is expanding at a particularly rapid pace. Despite representing a relatively small fraction of total emissions, its radiative forcing and non-CO_2 effects significantly amplify its climate impact [21]. With projected increases in global air traffic and limited electrification potential for long-haul flights, the integration of sustainable aviation fuels (SAFs) is now recognized as a crucial route to achieve decarbonization in aviation [22]. Unlike traditional biofuels, SAFs must meet stringent criteria regarding energy density, thermal stability, and their ability to integrate seamlessly with established jet engines and infrastructure [23].

Multiple feedstocks have been investigated for SAF production, including used cooking oil, algae, municipal solid waste, and lignocellulosic biomass. However, many of these feedstocks face supply constraints, food vs. fuel debates, or high production costs [24]. Hence, attention has increasingly shifted to underutilized waste streams that are abundant, low-cost, and environmentally burdensome. Among them, Palm Oil Mill Effluent (POME) stands out as a potential resource [25].

Palm Oil Mill Effluent (POME): Composition and Characteristics

As a fluid by-product created during the palm oil manufacturing process, POME is produced in large amounts by mills predominantly found in Southeast Asia. It is characterized by a high organic load, comprising residual oils, cellulose, proteins, and volatile fatty acids, making it both a pollution threat and a bioenergy resource [26]. Typical palm oil mills release around 2.5 to 3.0 tons of POME for every ton of crude palm oil extracted, amounting to millions of tons of waste on an annual basis [27].

Containing predominantly water (95–96%), along with 2–4% suspended solids and 0.6–0.7% oil and grease, POME exhibits high Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD) levels, often exceeding 50,000 mg/L and 25,000 mg/L, which make untreated discharge an environmental hazard [28]. However, this organic richness also provides a strong foundation for bioconversion processes if properly managed [29].

Conventional Uses and Limitations of POME Valorization

Historically, the majority of POME has been managed via anaerobic ponding systems, resulting in partial methane recovery and minimal energy yield [30]. Although this method is low-cost, it is land-intensive and contributes to uncontrolled methane release if not properly captured [31]. More recently, POME has been utilized in biogas production through anaerobic digestion and in biodiesel via transesterification of its residual oil fraction [32]. However, these applications remain limited in scale, often confined to pilot plants or off-grid energy projects.

Challenges persist regarding the variability in POME composition, pretreatment requirements, and low oil recovery rates. These factors constrain the scalability and consistency of energy conversion outcomes [33]. Moreover, most POME-to-energy projects are designed for electricity or heat generation rather than liquid transportation fuels, especially jet fuels [34].

Pathways from POME to Sustainable Aviation Fuel (SAF)

The transformation of POME into aviation-grade biofuel remains at a nascent stage. However, several conversion pathways show promise. One approach involves the separation of residual oils followed by hydroprocessing to produce hydrocarbons aligned with jet fuel specifications [35]. Alternatively, POME can be subjected to fermentation or gasification to produce syngas, which is then converted into SAF via Fischer-Tropsch synthesis [36].

Another avenue lies in integrating POME with hydrogen-rich co-feedstocks in hydrothermal liquefaction (HTL) systems to improve energy yields and fuel quality. The key technical bottlenecks include tar formation, water management, and sulfur contamination, all of which must be resolved to meet ASTM D7566 and D1655 standards [37]. While laboratory experiments have demonstrated the technical feasibility of such processes, commercial deployment is hindered by high capital costs and uncertain policy incentives [38].

Policy and Regulatory Landscape

Regional policy frameworks for SAF vary considerably. The European Union's ReFuelEU Aviation initiative, for example, obligates blending SAF into aviation fuels by 2030, thereby encouraging the use of innovative feedstocks like POME [39]. In a similar vein, ICAO's CORSIA program incentivizes lowering lifecycle greenhouse gas emissions, a target that POME-based fuels might help achieve with appropriate certification.

However, palm oil and its derivatives face complex scrutiny in global markets due to concerns about deforestation and land-use change. It is therefore critical that POME, as a waste by-product rather than a dedicated crop, be differentiated in sustainability certifications [40]. This distinction can open pathways for POME inclusion in global SAF supply chains while addressing environmental integrity concerns.

Research Gaps and Synthesis

Despite growing interest in SAF and bio-based waste valorization, literature specifically addressing POME as a SAF feedstock remains fragmented. Most studies have focused on biogas or biodiesel applications, with only a limited number exploring its potential for jet fuel production. Moreover, few studies examine the entire lifecycle of POME-to-SAF conversion, including feedstock logistics, pretreatment technologies, emissions performance, and economic viability in an integrated manner.

The lack of unified frameworks and cross-sectoral assessments inhibits strategic decision-making, both in policy and investment. Furthermore, comparative evaluations of POME against other SAF feedstocks in terms of emissions, land-use neutrality, and cost-effectiveness are notably scarce.

Conceptual Position of the Present Study

In response to these gaps, this study provides a qualitative literature review to synthesize and evaluate the technological pathways, sustainability potential, and policy contexts associated with converting POME into aviation-grade fuel. By drawing on academic literature across waste management, bioenergy, and aviation sectors, this review contributes an integrated understanding of how an abundant, underutilized industrial effluent like POME could support aviation decarbonization goals. This analysis will inform researchers, policymakers, and industry stakeholders of the strategic opportunities and challenges associated with this waste-to-fuel transition.

Methodology

This study employs a qualitative research method with a descriptive and analytical literature review approach. This approach was chosen to systematically examine, synthesize, and critically evaluate existing scientific literature concerning the prospect of Palm Oil Mill Effluent (POME) being employed as a low-emission, sustainable fuel for aviation. Employing a non-empirical approach, the study depends exclusively on secondary information sources like peer-reviewed articles, scientific reports, books, and relevant policy texts, with no primary data or fieldwork conducted. The primary instrument of this study is a conceptual framework designed to guide the selection and analysis of literature, focusing on technological, environmental, and policy aspects related to POME and sustainable aviation fuels. Data collection was conducted systematically by searching reputable academic databases such as Scopus, Web of Science, and Google Scholar using predefined keywords related to POME, biofuel, sustainable aviation fuel, and carbon emissions. Selected literature was critically appraised for its relevance, credibility, and contribution to understanding the use of palm oil by-products as a source for biofuel production. The collected data were analyzed thematically through coding and categorization processes aimed at identifying patterns, economic, and policy dimensions of POME's potential as an aviation fuel to produce a comprehensive and integrative understanding. By employing this method, the study offers an in-depth conceptual synthesis without conducting field interventions or primary data gathering, ensuring the validity of findings through reliance on credible, peer-reviewed academic sources. This qualitative literature review approach enables the generation of insights that can serve as a foundation for advancing environmentally friendly alternative fuel technologies and sustainable energy policies in the aviation sector.

Results

Data Collection Overview

Data for the research were obtained exclusively from secondary literature through structured database searches in Scopus, Web of Science, and Google Scholar, employing keywords including 'Palm Oil Mill Effluent (POME)," "biofuel," "sustainable aviation fuel," "low emission fuel," and "aviation biofuel" were used to gather relevant peer-reviewed articles, reports, and policy documents. A total of 120 articles were initially identified. After screening for relevance, duplication, and quality, 80 articles were selected for in-depth analysis, ensuring a comprehensive coverage of technological, environmental, and economic aspects of POME valorization. The distribution of sources spanned publications from 2015 to 2025, highlighting the recent increase in academic focus on this topic [41, 42].

Characteristics and Composition of POME Relevant to Biofuel Production

Analysis of the collected literature reveals that POME contains approximately 95–96% water, 2–4% suspended solids, and 0.6–0.7% residual oil content, which can be converted into various biofuels [43]. The average Chemical Oxygen Demand (COD) of POME ranges between 40,000 to 60,000 mg/L, with a Biological Oxygen Demand (BOD) of 25,000 to 30,000 mg/L, indicating a high organic load favorable for bioconversion processes [44]. These characteristics make POME a potent substrate for anaerobic digestion, fermentation, and hydroprocessing pathways.

Data shows that producing one ton of crude palm oil leads to the generation of 2.5 to 3.0 tons of POME, which equates to nearly 7.5 million tons per year in Indonesia, the top palm oil producing country worldwide [45]. The magnitude of this waste highlights a significant chance for sustainable fuel production if effective conversion strategies are utilized.

Potential of POME as a Low-Emission Fuel for Aviation

Evidence indicates that biofuels derived from POME may achieve a 60% to 85% reduction in lifecycle greenhouse gas emissions compared to conventional Jet-A fuel. [46, 47]. This is attributed to the waste nature of POME, which avoids land-use change emissions commonly associated with dedicated energy crops. The net energy ratio of POME-based biofuel is estimated at 3.5 to 4.2, indicating a favorable energy return on energy invested (EROEI) [48].

Furthermore, hydroprocessing of residual oils in POME yields a hydrocarbon product with an energy density of approximately 43 MJ/kg, comparable to fossil jet fuel standards [49]. Fuel stability tests under ASTM D7566 certification parameters confirm that POME-derived synthetic paraffinic kerosene meets key jet fuel requirements, including freezing point (-47°C), flash point (above 38°C), and sulfur content (below 15 ppm) [50].

Technological Pathways for POME Conversion

From the literature, three primary technological pathways for converting POME to sustainable aviation fuel (SAF) emerge: anaerobic digestion for biogas production, transesterification of residual oils into biodiesel, and thermochemical conversion to hydrocarbons suitable for jet fuel [51].

Anaerobic digestion of POME yields biogas with methane content between 60% and 70%, with biogas production rates ranging from 20 to 30 m³ per ton of POME [52]. Biogas is mostly applied for heat and power generation, but enhancing it to biomethane and then transforming it into synthetic fuels via Fischer-Tropsch synthesis is an emerging and promising pathway [53].

Transesterification of residual oil fractions can produce biodiesel with cetane numbers of 48 to 55 and oxidative stability exceeding 8 hours, making it a viable blendstock for jet fuel after further hydroprocessing [54]. However, the oil content in POME is relatively low, often less than 1%, limiting the biodiesel yield unless integrated with other feedstocks.

Techniques such as HTL and gasification coupled with Fischer-Tropsch synthesis are highlighted as effective routes for creating drop-in jet fuels adhering to international quality benchmarks [55]. Yields of liquid hydrocarbons from HTL of POME are reported between 25% to 35% by weight, with energy recovery efficiencies up to 65% [56].

Environmental Impact and Emission Reductions

Studies consistently report significant environmental benefits from POME-derived aviation fuels. According to lifecycle assessments, GHG emissions may be lowered by approximately 70% when compared to conventional fossil jet fuels, primarily due to avoided methane emissions from untreated POME discharge [57]. Methane emissions from conventional POME treatment ponds are estimated at 0.25 to 0.35 kg CH_4 per m^3 of untreated effluent, contributing to potent global warming potential [58].

Moreover, the utilization of POME for fuel production supports circular economy principles by transforming waste into value-added products, thus reducing environmental pollution and eutrophication risks associated with POME discharge [59]. The net water footprint of POME-based biofuel is also lower than that of other biofuel feedstocks, given that POME is an industrial waste rather than a water-intensive crop [60].

Economic Feasibility and Scalability

Economic analyses in the reviewed literature suggest that POME-based aviation fuel production can achieve competitive costs, ranging from USD 0.8 to 1.2 per liter, depending on scale and technology used [61]. Integration with existing palm oil mill infrastructure reduces feedstock transportation and processing costs significantly.

Barriers continue to exist because of capital-intensive upgrading processes, regulatory complexities, and a shortage of large-scale pilot plants. Making these fuels financially viable compared to standard jet fuel requires policy support through mechanisms like carbon pricing, renewable fuel mandates, and subsidy programs [62].

Overall, the comprehensive assessment of 80 studies confirms POME's strong potential as an eco-friendly, low-emission feedstock for aviation fuels. The high organic content and large volume of POME generate ample raw material for biofuel production with significant GHG reduction potential. Technological advances in hydroprocessing and thermochemical conversion provide pathways for producing jet fuels that meet international standards. While environmental and economic benefits are promising, scaling up production requires supportive policies and further technological optimization.

Discussion

The findings from the comprehensive qualitative literature review clearly indicate that Palm Oil Mill Effluent (POME) holds significant promise as a sustainable and low-emission feedstock for aviation fuel production. Consistent with the research objectives, this section discusses the technological feasibility, environmental benefits, and economic implications of utilizing POME, integrating relevant data extracted from the literature.

Firstly, the chemical composition and high organic content of POME make it an excellent substrate for biofuel generation through various biochemical and thermochemical processes [63]. The presence of substantial residual oil fractions and elevated Chemical Oxygen Demand (COD) levels provides the necessary raw materials for effective bioconversion into hydrocarbons that satisfy jet fuel quality standards [63]. The technological pathways identified, anaerobic digestion, transesterification, and hydrothermal liquefaction, each demonstrate unique advantages. Anaerobic digestion contributes to biogas production with methane concentrations ranging from 60 to 70%, which could be further upgraded for fuel use [64]. Meanwhile, hydrothermal liquefaction has shown liquid hydrocarbon yields of up to 35% by weight, indicating considerable efficiency in converting POME into drop-in aviation fuel [65].

Secondly, environmental analyses from multiple lifecycle studies support that POME-based aviation fuels can lower greenhouse gas emissions by roughly 70%

when compared to conventional jet fuels [66]. This substantial reduction stems from mitigating methane emissions otherwise released from untreated effluent ponds, as well as utilizing a waste by-product rather than dedicated crops, which avoids land-use change impacts [67]. The data also reveal that POME biofuels possess favorable properties such as low sulfur content and high energy density, ensuring compliance with ASTM standards and supporting clean combustion [68].

Economically, although the initial investment for conversion technologies remains high, the integration of POME valorization within existing palm oil mill infrastructure presents a cost-effective approach. Studies indicate production costs ranging between USD 0.8 and 1.2 per liter, which is competitive under supportive policy frameworks like carbon pricing and renewable fuel incentives [69]. The findings underscore the feasibility of POME-based fuels within the expanding sustainable aviation fuel sector [70].

Despite these promising outcomes, challenges remain in scaling up technologies from laboratory and pilot stages to commercial operation. Barriers include the variability of POME composition across mills, technological complexity of upgrading processes, and regulatory hurdles in certifying alternative aviation fuels [71]. Furthermore, comprehensive assessments of the long-term sustainability, including water footprint and social acceptance, require further investigation [72]. From a strategic standpoint, repurposing POME as a biofuel source supports circular economy goals by turning a waste product with significant pollution potential into useful energy and mitigating the palm oil industry’s environmental footprint [73]. By addressing both waste disposal challenges and climate goals, this approach supports the aviation sector’s ongoing efforts to find effective decarbonization pathways [74].

The synthesis of findings underscores the importance of multidisciplinary approaches combining engineering innovations, environmental assessments, and policy frameworks to maximize the benefits of POME utilization. For instance, coupling anaerobic digestion with downstream upgrading technologies can enhance fuel yield and quality while ensuring environmental compliance [75]. Additionally, strengthening cooperation between industry stakeholders, government bodies, and academic institutions is vital for accelerating the adoption of technologies and increasing market penetration [76].

In conclusion, this literature review demonstrates that POME represents a valuable and largely untapped resource for producing low-emission aviation fuels. The comprehensive data analysis supports the potential for significant greenhouse gas reductions and economic feasibility under appropriate technological and policy conditions. Future research should focus on pilot-scale demonstrations, life cycle impact assessments incorporating broader sustainability indicators, and exploring hybrid conversion technologies to improve fuel yields and reduce costs [77], [78]. Additionally, the investigation into regional adaptation strategies considering local palm oil industry characteristics could enhance the scalability and acceptance of POME-derived aviation fuels [79].

Implications of this study are profound, suggesting that integrating POME valorization into palm oil mills can transform an environmental liability into an economic and environmental asset, contributing directly to sustainable aviation objectives. It also emphasizes the need for supportive regulatory environments and investment in R&D to bridge the gap between research findings and commercial reality [80]. Policymakers and industry leaders should prioritize facilitating technology transfer, establishing fuel certification pathways, and providing incentives for renewable fuel manufacturing to maximize POME’s role as a strategic resource in reducing aviation emissions [81].

Conclusion

Due to its vast availability and rich organic composition, Palm Oil Mill Effluent (POME) is emerging as a highly attractive feedstock for generating low-emission aviation fuels. Reviewed studies repeatedly emphasize that technologies such as anaerobic digestion, hydrothermal liquefaction, and transesterification can efficiently transform POME into biofuels meeting rigorous aviation fuel standards, optimizing fuel output and substantially cutting greenhouse gas emissions compared to fossil-derived jet fuels.

Environmental assessments demonstrate that utilizing POME as a biofuel source contributes to substantial mitigation of methane emissions typically generated from untreated effluent. Such an approach encourages environmentally responsible waste handling within the palm oil industry, turning an environmental liability into a valuable resource. Moreover, the integration of POME valorization within existing palm oil mill infrastructures enhances the economic feasibility of biofuel production, especially under supportive policy frameworks.

Despite these advantages, several challenges must be addressed to realize large-scale implementation. Variability in POME characteristics, technological complexities, and regulatory certification processes requires continued research and development. Additionally, fully understanding the environmental, economic, and social implications is crucial for ensuring enduring sustainability and acceptance in the market.

Collectively, the research supports the idea that POME-derived aviation fuels can meaningfully contribute to lowering carbon footprints in aviation, consistent with global environmental and climate commitments. Strengthening interdisciplinary collaboration and policy support will be essential to advance technological maturity and facilitate the transition from pilot studies to commercial-scale applications.

References

1. LL Jensen, PA Bonnefoy, JI Hileman, JT Fitzgerald (2023) The carbon dioxide challenge facing US aviation and paths to achieve net zero emissions by 2050 Prog. Aerosp Sci 141: 100921.
2. P Friedlingstein, Michael OS, Matthew WJ, Robbie MA, Dorothee CEB, et al. (2023) Global carbon budget 2023 Earth Syst. Sci Data 15: 5301-5369.
3. D Chiaramonti, G Talluri, G Vourliotakis, L Testa, M Prussi, et al. (2021) Can lower carbon aviation fuels (LCAF) really complement sustainable aviation fuel (SAF) towards EU aviation Decarbonization?. Energies 14: 6430.
4. E Yoo, U Lee, M Wang (2022) Life-cycle greenhouse gas emissions of sustainable aviation fuel through a net-zero carbon biofuel plant design. ACS Sustain Chem Eng 10: 8725-8732.
5. R Khalifa, M Alherbawi, Y Bicer, T Al Ansari (2024) Fueling circularity: A thorough review of circular practices in the aviation sector with sustainable fuel solutions. Resour Conserv Recycl Adv 200223.
6. BHH Goh, Cheng TC, Yuqi G, Hwai CO, Jo-Han N, et al. (2020) Progress in utilisation of waste cooking oil for sustainable biodiesel and biojet fuel production. Energy Convers Manag 223: 113296.
7. Ayob S, Othman N, Hamood Altowayti WA, Khalid FS, Bakar NA, et al. (2021) A review on adsorption of heavy metals from wood-industrial wastewater by oil palm waste. J Ecol Eng 22: 249-265.
8. MA Nasution, DS Wibawa, T Ahamed, R Noguchi (2018) Comparative environmental impact evaluation of palm oil mill effluent treatment using a life cycle assessment approach: A case study based on composting and a combination for biogas technologies in North Sumatera of Indonesia. J Clean Prod 184: 1028-1040.
9. A Rishanty, MT Sambodo, M Silalahi, E Hambali (2024) Zero-waste bioenergy to lower energy transition risks in Indonesia-a circular economy practice on methane capture in biogas production from POME. BioEnergy Res 17:1930-1942.
10. Awogbemi, DV Von Kallon (2022) Valorization of agricultural wastes for biofuel applications, Heliyon 8: e11117.
11. S Chinwetkitvanich, H Jaikawna, Volatile fatty acids (VFAs) production from palm oil mill effluent (POME) fermentation, in Environmental Science and Information Application Technology, London: CRC Press 151-156.
12. N VelaGarcía, D Bolonio, MJ García-Martínez, MF Ortega, L Canoira. Thermochemical conversion of agricultural waste to biojet fuel, in Sustainable alternatives for aviation fuels. Elsevier 27-48.
13. NFB Jamaludin (2020) Integrated sustainability assessment framework with mitigation strategy for palm oil mill, Universiti Teknologi Malaysia https://eprints.utm.my/92510/1/NabilaFarhanaPMChE2020.pdf.pdf.
14. RA Kristanti, T Hadibarata, A Yuniarto, A Muslim (2021) Palm oil industries in Malaysia and possible treatment technologies for palm oil mill effluent: A review. Environ Res.Eng Manag 77: 50-65.
15. AM Gómez Mateus, L Grimm, R Waldhardt (2021) Conversion of pastures to oil palm plantations in Colombia generates lower greenhouse gas

emissions than cattle ranching: a literature research https://jlupub.ub.uni-giessen.de/server/api/core/bitstreams/a22c7ccf-c714-4946-8b47-d74a74b6ca43/content.

16. ML Yeoh, CS Goh (2022) Hydrotreated vegetable oil production from palm oil mill effluents: Status, opportunities and challenges. Biofuels Bioprod Biorefining 16: 1153-1158.
17. RS Capaz, E Guida, JE Seabra, P Osseweijer, JA Posada (2021) Mitigating carbon emissions through sustainable aviation fuels: costs and potential. Biofuels Bioprod Biorefining 15: 502-524.
18. MF Ortegab, L Canoirab (2022) Agricultural waste to biojet fuel, in Sustainable Alternatives for Aviation Fuels 27.
19. L Arousell (2025) Will Sustainable Aviation Fuel (SAF) be able to meet future demand for sustainable air travel, and if so, at what cost?, Signature.
20. Theo WL, Lim JS, Ho WS, Hashim H, Lee CT, et al. (2017) Optimisation of Oil Palm Biomass and Palm Oil Mill Effluent (POME) Utilisation Pathway for 1 Palm Oil Mill Cluster with Consideration of BioCNG Distribution Network. Energy 121: 865-883.
21. S Cairns (2023) The Non-CO2 Impacts of Planes Are a Key Reason to Reduce Aviation Demand. https://www.creds.ac.uk/publications/the-non-co2-impacts-of-planes-are-a-key-reason-to-reduce-aviation-demand/.
22. R Malina, M Abate, C Schlumberger, F N Pineda (2022) The role of sustainable aviation fuels in decarbonizing air transport. https://documents1.worldbank.org/curated/en/099845010172249006/pdf/P17486308a996a08b098a10d078d421c6a3.pdf.
23. RC Boehm, LC Scholla, JS Heyne (2021) Sustainable alternative fuel effects on energy consumption of jet engines. Fuel 304: 121378.
24. MF Shahriar, A Khanal (2022) The current techno-economic, environmental, policy status and perspectives of sustainable aviation fuel (SAF). Fuel 325: 124905
25. Rosales Calderon O, Tao L, Abdullah Z, Talmadge M, Milbrandt A, et al. (2024) Sustainable aviation fuel state-of-industry report: hydroprocessed esters and fatty acids pathway https://doi.org/10.2172/2426563.
26. NA Sasongko, R Noguchi, T Ahamed (2018) Environmental load assessment for an integrated design of microalgae system of palm oil mill in Indonesia. Energy 159: 1148-1160.
27. SE Hosseini, M Abdul Wahid (2015) Pollutant in palm oil production process. J Air Waste Manage Assoc 65: 773-781.
28. JD Bala, J Lalung, N Ismail (2015) Studies on the reduction of organic load from palm oil mill effluent (POME) by bacterial strains. Int J Recycl Org Waste Agric 4: 1-10.
29. MI Anggamulia, M Syafila, M Handajani, A Gumilar (2020) The potential bio-conversion of Palm Oil Mill Effluent (POME) as Bioethanol by steady-state anaerobic processes. E3S Web of Conferences EDP Sciences 2001.
30. PL Soo, MJ Bashir, LP Wong (2022) Recent advancements in the treatment of palm oil mill effluent (POME) using anaerobic biofilm reactors: Challenges and future perspectives. J Environ Manage 320: 115750.
31. YY Choong, KW Chou, I Norli (2018) Strategies for improving biogas production of palm oil mill effluent (POME) anaerobic digestion: A critical review. Renew Sustain Energy Rev 82: 2993-3006.
32. T Rakkan, S Suwanno, N Paichid, T Yunu, S Klomklao, et al. (2017) Optimized synthesis method for transesterification of residual oil from palm oil mill effluent and lipase from Pacific white shrimp (Litopenaeus vannamei) hepatopancreas to environmentally friendly biodiesel. Fuel 209: 309-314.
33. MMA Nur, AG Buma (2019) Opportunities and challenges of microalgal cultivation on wastewater, with special focus on palm oil mill effluent and the production of high value compounds. Waste and Biomass Valorization 10: 2079-2097.
34. L Sani (2018) Pathways for a Sustainable Treatment of Biomass Residue at Palm Oil Mills: The Case of Indonesia.
35. RR Monteiro, IA dos Santos, MRA Arcanjo, FMT de Luna, RS Vieira, et al. (2022) Production of jet biofuels by catalytic hydroprocessing of esters and fatty acids: a review. Catalysts 12: 237.
36. JA Okolie, D Awotoye, ME Tabat, PU Okoye, EI Epelle, et al. (2023) multi-criteria decision analysis for the evaluation and screening of sustainable aviation fuel production pathways. Science 26: 106944.
37. IBTask (2021) Progress in commercialization of biojet/Sustainable Aviation Fuels (SAF): Technologies,

potential and challenges, Biomass and Bioenergy https://www.ieabioenergy.com/wp-content/uploads/2021/06/IEA-Bioenergy-Task-39-Progress-in-the-commercialisation-of-biojet-fuels-May-2021-1.pdf.

38. O Meijerink (2015) Investments in renewable jet fuels: Barriers and opportunities for investors.
39. N Pavlenko (2021) An assessment of the policy options for driving sustainable aviation fuels in the European Union.
40. SS Imam, S Sani, M Mujahid, R Adnan (2024) Valuable resources recovery from palm oil mill effluent (POME): a short review on sustainable wealth reclamation. Waste Manag Bull 3: 1-16.
41. T Jia, D Wang, BK Szymanski (2017) Quantifying patterns of research-interest evolution. Nat Hum Behav 1: 78.
42. S Hajkowicz, C Sanderson, S Karimi, A Bratanova, C Naughtin (2023) Artificial intelligence adoption in the physical sciences, natural sciences, life sciences, social sciences and the arts and humanities: A bibliometric analysis of research publications from 1960-2021, Technol. Soc 74: 102260.
43. WSSA Wan Sharifudin, A Sulaiman, N Mokhtar, A Samsu baharuddin, M Tabatabaei, et al. (2015) Presence of Residual Oil in Relation to Solid Particle Distribution in Palm Oil Mill Effluent. BioResources 10: 7591-7603.
44. L Yong (2019) Production of Aerobic Granular Sludge in Sequencing Batch Reactor for the Treatment of Palm Oil Mill Effluent.
45. H Kamyab, S Chelliapan, MFM Din, S Rezania, T Khademi, et al. (2018) Palm oil mill effluent as an environmental pollutant, in Palm oil. Intech Open 13-28.
46. P Muanruksa, J Winterburn, P Kaewkannetra (2021) Biojet fuel production from waste of palm oil mill effluent through enzymatic hydrolysis and decarboxylation, Catalysts 11: 78.
47. AK Paminto, M Karuniasa, E Frimawaty (2024) Optimization of palm oil biodiesel production: Environmental impact analysis and POME waste utilization. Appl Environ Sci 2: 15-30.
48. S Papagianni, I Capellán Perez, A Adam, A Pastor (2024) Review and meta-analysis of Energy Return on Investment and environmental indicators of biofuels. Renew Sustain Energy Rev 203: 114737.
49. AAV Julio, EAO Batlle, CJC Rodriguez, JCE Palacio (2021) Exergoeconomic and environmental analysis of a palm oil biorefinery for the production of bio-jet fuel. Waste and Biomass Valorization 1-27.
50. MA Rumizen (2021) Qualification of alternative jet fuels, Front. Energy Res 9: 760713.
51. A Vasileiadou (2024) From Organic wastes to Bioenergy, Biofuels, and value-added products for urban sustainability and circular economy: a review. Urban Sci 8: 121.
52. D Apriangga, D Tambubolon, E Sihombing, EP Siregar, S Aryza (2024) A Utilization of Solid and Liquid Waste from Palm Oil as A Power Plant. J Sci 13: 2040-2048.
53. JF Gonzalez, CM Alvez Medina, S Nogales Delgado (2023) Biogas steam reforming in wastewater treatment plants: opportunities and challenges. Energies 16: 6343.
54. OO Isaiah, AG Blessing (2020) Environmental Pollutant of Palm Oil Effluent and Its Management in Okitipupa Area of Ondo State, Nigeria. J Environ Prot Sustain Dev 6: 72-81.
55. M Alherbawi, G McKay, T Al Ansari (2023) Development of a hybrid biorefinery for jet biofuel production. Energy Convers Manag 276: 116569.
56. V Volli, ARK Gollakota, MK Purkait, CM Shu (2020) Conversion of waste biomass to bio-oils and upgradation by hydrothermal liquefaction, gasification, and hydrodeoxygenation, in Biorefinery of Alternative Resources: Targeting Green Fuels and Platform Chemicals. Elsevier 285-315.
57. SR Sharvini, ZZ Noor, CS Chong, LC Stringer, D Glew (2020) Energy generation from palm oil mill effluent: A life cycle assessment of two biogas technologies. Energy 191: 116513.
58. A Sodri, FE Septriana (2022) Biogas Power Generation from Palm oil mill effluent (POME): Techno-economic and environmental impact evaluation. Energies 15: 7265.
59. UWR Siagian, IG Wenten, K Khoiruddin (2024) Circular economy approaches in the palm oil industry: Enhancing profitability through waste reduction and product diversification. J Eng Technol Sci 56: 25-49.
60. A Akhbari, S Ibrahim (2024) Comparative Life Cycle Assessment and Carbon Footprint Analysis of Waste Treatment Facilities, in Material and Energy Recovery from Solid Waste for a Circular

Economy. CRC Press 277-291.

61. M Gozan, L Y Phang (2022) Technical and Economic Aspects of Oil Producing Plants. Biorefinery of Oil Producing Plants for Value-Added Products 2: 673-698.
62. D Timmons, R Terwel (2022) Economics of aviation fuel decarbonization: A preliminary assessment. J Clean Prod 369: 133097.
63. A Ahmad, A Buang, A H Bhat (2016) Renewable and sustainable bioenergy production from microalgal co-cultivation with palm oil mill effluent (POME): a review. Renew Sustain Energy Rev 65: 214-234.
64. N A N B Maarof, N Hindryawati, S N M Khazaai, P Bhuyar, M H A Rahim, et al. (2021) Biodiesel (Methyl Esters). Maejo Int J Energy Environ Commun 3: 30-43.
65. Zulqarnain, Mohd Hizami Mohd Yusoff, Muhammad Ayoub, Muhammad Hamza Nazir, Imtisal Zahid, et al. (2021) Comprehensive review on biodiesel production from palm oil mill effluent. Chem Bio Eng Rev 8: 439-462.
66. N B A Bakar (2024) Techno-Economic Assessment and Environmental Analysis of Bio-Compressed Natural Gas Production from Palm Oil Mill Effluent. University of Malaya (Malaysia), 2024.
67. Abu Bakar Nasrin, Abdul Aziz Abdul Raman, Nurul Adela Bukhari, Mohamad Azri Sukiran, Archina Buthiyappan, et al. (2022) A critical analysis on biogas production and utilisation potential from palm oil mill effluent. J Clean Prod 361: 132040.
68. A T Giduthuri, B K Ahring (2022) Current status and prospects of valorizing organic waste via arrested anaerobic digestion: production and separation of volatile fatty acids. Fermentation 9: 13.
69. K L Brandt, L Martinez-Valencia, M P Wolcott (2022) Cumulative impact of federal and state policy on minimum selling Price of sustainable aviation fuel. Front Energy Res 10: 828789.
70. A Tiwari, K Nakamura (2024) Closing the loop on biohydrogen production: A critical eview on the post-fermentation broth management techniques. Int J Hydrogen Energy 81: 595-614.
71. L Martinez-Valencia, C Valderrama-Rios (2024) Sustainable Aviation Fuel Production in Colombia: Opportunities and Challenges.
72. https://rex.libraries.wsu.edu/esploro/outputs/report/Sustainable-Aviation-Fuel-Production-in-Colombia/99901091341401842.
73. E Semmling (2021) EGU General Assembly Conference Abstracts EGU21-15434.
74. W Y Cheah, R P Siti-Dina, S T K Leng, A C Er, P L Show (2023) Circular bioeconomy in palm oil industry: Current practices and future perspectives. Environ Technol Innov 30: 103050.
75. T A Kurniawan (2025) Uncovering the Potential of Biomass from Agricultural Waste as Sustainable Biofuel in Aviation Industry to Promote Net Zero Emissions: A Critical Review. BioResources 20: 2.
76. B S Zainal, M A Ahmad, M Danaee, N Jamadon, N S Mohd, S Ibrahim (2020) Integrated system technology of pome treatment for biohydrogen and biomethane production in Malaysia. Appl Sci 10: 951.
77. S F Salleh, M E Mohd Roslan, A Abd Rahman, A H Shamsuddin, T A R Tuan Abdullah, et al. (2020) Transitioning to a sustainable development framework for bioenergy in Malaysia: policy suggestions to catalyse the utilisation of palm oil mill residues. Energy Sustain Soc 10: 1-20.
78. M N Uddin, F Wang (2024) A Review on the Production of Sustainable Aviation Fuels from Biomass and Wastes using Pyrolysis Technologies.
79. A F Dashti, M O Fatehah, M A Zahed (2021) Waste management of the palm oil industry: present status and future perspective. J Environ Eng Sci 17: 75-088.
80. I Abbas, A Shaar, R El Osta (2024) The pathway for achieving sustainable aviation fuel production in the Middle East and North Africa region. Environ Prog Sustain Energy 43: e14395.
81. A L Johnson (2024) Overcoming Barriers to R\&D Investment: A Case Study on US Small and Medium-Sized Enterprises," University of Arizona Global Campus, 2024.