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Innovative Pathways for Sustainable Aviation Fuel Production: Leveraging Used Cooking Oil as High Potentials Feedstocks

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Abstract

The air transport sector is under increasing demand to cut carbon emissions and support international sustainability initiatives. One viable solution to address this challenge is the development of Sustainable Aviation Fuel (SAF), with used cooking oil (UCO) emerging as a highly promising feedstock. This paper explores innovative methods for converting UCO into SAF, focusing on the Hydroprocessed Esters and Fatty Acids (HEFA) process, which is recognized for its commercial viability and environmental benefits. The review emphasizes the notable decrease in greenhouse gas (GHG) emissions from the use of SAF produced from used cooking oil, compared to traditional fossil-derived jet fuel, along with the ecological benefits of repurposing waste materials. Nonetheless, the study identifies several challenges, including limitations in UCO collection systems, unequal distribution of feedstock across regions, and the necessity for comprehensive policy backing to enable production scale-up. It highlights the critical role of regulatory support, financial incentives, and international cooperation in addressing these challenges. In addition, future prospects such as the advancement of novel conversion technologies and synergistic use of UCO with other biomass sources are discussed as strategic directions for improving SAF's sustainability and production capacity. In conclusion, UCO stands out as a practical and eco-friendly alternative to support the aviation industry's transition towards reduced carbon emissions, while delivering both ecological and economic advantages.

Keywords: Sustainable Aviation Fuel (SAF), Used Cooking Oil (UCO), Hydroprocessed Esters and Fatty Acids (HEFA), Greenhouse Gas (GHG) Emissions Reduction and Biomass Conversion Technologies

Introduction

The aviation sector has experienced considerable growth in recent years, playing a vital role in facilitating international connectivity and supporting economic progress. Nevertheless, this expansion has also led to a notable rise in terms of greenhouse gas (GHG) output, the aviation sector currently contributes around 2–3% of global CO_2 emissions, a proportion anticipated to increase in the coming years [1,2]. As climate concerns intensify, the need for decarbonizing the aviation sector has become increasingly urgent [3].

Among various strategies to reduce emissions, the advancement and implementation of sustainable aviation fuel (SAF) are broadly acknowledged as among the most effective strategies to reduce the ecological impact of the aviation sector [4]. Sustainable aviation fuel (SAF) offers the benefit of serving as a "drop-in" solution, allowing its use in current aircraft engines and refueling infrastructure without the need for major adjustments. Additionally, it has the capability to lower life-cycle greenhouse gas emissions by as much as 80% when compared to traditional fossil-based jet fuel [5]. This makes SAF particularly attractive as an immediate and scalable alternative to support net-zero aviation targets [6].

Within the broader SAF landscape, feedstock selection plays a pivotal role in determining environmental, economic, and ethical viability [7]. In this context, used cooking oil (UCO) emerges as a notably viable and attractive feedstock option. It is widely generated as waste from domestic kitchens, food service establishments, and food manufacturing operations, and—unlike numerous first-generation biofuels—it does not compete with crops intended for human consumption [8]. Moreover, using UCO aligns with circular economy practices and plays a role in addressing waste disposal challenges [9].

The use of UCO as a feedstock aligns closely with international aviation sustainability efforts, including the global CORSIA initiative aimed at curbing aviation-related carbon emissions and implementing offset mechanisms, together with the updated Renewable Energy Directive (RED II) from the European Union [10]. Technological advances, particularly in the Hydroprocessed Esters and Fatty Acids (HEFA) method has proven to be commercially feasible for transforming used cooking oil into aviation fuel, positioning it as one of the most developed and scalable pathways for SAF production currently available [11].

Despite its potential, several challenges hinder the large-scale implementation of UCO-based SAF. These include limited collection infrastructure, inconsistent feedstock quality, supply chain inefficiencies, and policy gaps in regulating and incentivizing waste-based fuels [12]. Furthermore, UCO availability is unevenly distributed across regions, which raises concerns about supply stability and economic feasibility for global SAF deployment [13].

Innovations in processing technologies—such as catalytic upgrading, co-processing with petroleum streams, and integrated biorefinery models—are being explored to improve fuel yields and reduce production costs [14]. In parallel, enhanced traceability systems and digital monitoring tools are emerging to ensure feedstock authenticity and regulatory compliance [15]. These innovations are essential not only for scaling up production but also for building trust across stakeholders, from regulators to airlines and fuel distributors [16].

On the socio-environmental front, leveraging UCO for SAF can generate multiple co-benefits. These include reducing urban water pollution from improper oil disposal, decreasing landfill waste, and fostering local economic opportunities through UCO collection and processing networks [17]. As urbanization accelerates and food consumption grows—especially in emerging economies—the potential volume of recoverable UCO is expected to rise, further strengthening its viability as a feedstock [18].

While considerable academic and industrial attention has been given to SAF, there remains a lack of integrative reviews focusing specifically on UCO-based production pathways. The fragmented nature of existing research, coupled with evolving technological and regulatory landscapes, underscores the need for a comprehensive and up-to-date analysis [19,20].

This paper seeks to fill that research gap through a qualitative review of literature focusing on novel approaches to producing sustainable aviation fuel from used cooking oil. It explores key technologies, implementation challenges, and multi-stakeholder opportunities in accelerating SAF deployment from UCO. The study is guided by the following questions: (1) What are the current technological pathways for converting UCO into SAF? (2) What are the key barriers and risks associated with their implementation? and (3) How can policy, industry, and innovation collaborate to scale these solutions across diverse contexts?

Literature Review

The worldwide aviation sector encounters considerable difficulties in reducing carbon emissions and decreasing dependence on fossil fuels. As part of its sustainability initiatives, Sustainable Aviation Fuel (SAF) has become a crucial alternative. SAF can be derived from several biomass feedstocks, including Used Cooking Oil (UCO). UCO presents a substantial potential as a feedstock for SAF production, as it not only reduces waste but also does not compete with essential food crops like pure vegetable oils [21].

The conversion of UCO into SAF employs the Hydroprocessed Esters and Fatty Acids (HEFA) method, a well-researched technology that has been utilized to create fuel with characteristics nearly identical to conventional jet fuel [22]. This technology involves hydrogenation and purification processes that allow UCO, contaminated with various impurities, to be converted into high-quality fuel [23]. In addition to HEFA, other technologies such as Fischer-Tropsch and pyrolysis processes are being explored to utilize UCO in SAF production [24,25].

Despite the significant potential of UCO as a feedstock for SAF, the primary challenges faced are quality and availability of UCO. The quality of UCO varies significantly depending on the source and collection methods, which can affect the success of the conversion process into SAF [26]. Furthermore, the limited availability of UCO in certain regions makes it difficult to rely on this feedstock on a large scale [27].

Regarding government and policy, several countries have set ambitious targets to replace fossil fuels with SAF as part of their climate commitments [28]. In Europe, the Renewable Energy Directive II (RED II) incentivizes the use of waste feedstocks, including UCO, for biofuel production [29]. Policies that support feedstock standardization and supply chain monitoring are critical in ensuring the sustainability and quality of the SAF produced [30].

Additionally, using UCO for SAF production has positive social and economic impacts. The increased demand for UCO could create new jobs in the waste collection and processing sectors, as well as support a circular economy by reducing waste that would otherwise be discarded in landfills [31]. Developing countries with abundant UCO waste can benefit economically from SAF production, which could support local economic growth while maintaining environmental sustainability [32].

On the technical side, the development of integrated biorefineries, which allow the processing of various biofuel production pathways in a single system, can improve efficiency and lower SAF production costs [33]. Furthermore, research on co-processing feedstocks, where UCO is combined with other materials such as vegetable oils or waste plastics, shows significant potential in expanding the available feedstocks for SAF production [34,35]. Digital technologies, such as monitoring and tracking feedstocks, can increase transparency and sustainability throughout the supply chain, ensuring that production processes are both efficient and environmentally friendly [36,37].

The application of blending techniques and process optimization in the SAF sector contributes to lowering operational expenses and enhancing efficiency. With innovations like catalyst changes and reactor optimization, the efficiency of SAF production from UCO can be further improved, allowing for increased scaling and reducing reliance on scarce natural resources [38,39]. The widespread application of these innovations could accelerate the adoption of UCO-based SAF in the global market.

In conclusion, SAF derived from UCO holds considerable promise in cutting carbon emissions and speeding up the shift to more sustainable fuel options within the aviation industry, the existing challenges still need to be addressed. Further development in conversion technologies, supportive policies, and more efficient supply chain management will be key to optimizing the implementation of UCO-based SAF in the future.

Methodology

This research employs a qualitative literature review approach to examine novel and scalable methods for producing Sustainable Aviation Fuel (SAF) using Used Cooking Oil (UCO). The focus is on analyzing key technological advancements, economic feasibility, policy frameworks, and environmental impacts associated with converting UCO into SAF. The approach seeks to evaluate the opportunities and challenges of using UCO as a promising raw material for aviation fuel production, while also examining the social and industrial factors that may support or impede this shift.

An extensive review of literature was performed using various academic databases, such as Google Scholar, Scopus, and Web of Science, to ensure the inclusion of the most up-to-date and pertinent research. The literature selection was based on the relevance of UCO in SAF production, technological innovation, economic viability, and environmental sustainability. Keywords used in the search included "Sustainable Aviation Fuel," "Used Cooking Oil," "biofuels," "HEFA technology," "Fischer-Tropsch synthesis," and "waste feedstocks in biofuel production."

Data analysis involved categorizing and synthesizing findings from the selected literature, focusing on four main areas: conversion technologies, economic and market dynamics, regulatory and policy support, and the challenges and barriers faced by the SAF industry. The analysis examined existing conversion methods such as HEFA, Fischer-Tropsch, and pyrolysis, focusing on their efficiency, scalability, and environmental impact. Economic reviews also evaluated the cost-benefit analysis, market demand, and competitiveness of UCO relative to other feedstocks, while policy analysis explored government incentives and standards promoting SAF derived from waste feedstocks.

The challenges in scaling UCO-based SAF production were examined, including feedstock quality variability, supply chain issues, technological barriers, and infrastructure limitations. The synthesis of these findings aimed to highlight the most promising pathways for integrating UCO into SAF production systems, with an emphasis on technological, policy, and regulatory solutions that can overcome the identified barriers.

This research relies on secondary data obtained through a qualitative literature review, meaning it does not involve primary data gathering or field research. Nonetheless, it offers valuable perspectives on the potential of UCO as a raw material for SAF and presents a conceptual framework to inform future studies and industrial practices.

Results and Discussion

Technological Pathways and Conversion Efficiency

Used cooking oil (UCO) has attracted significant interest as a feedstock for the production of sustainable aviation fuel (SAF), primarily due to its widespread availability and classification as a waste product. Among the various UCO conversion methods, the Hydroprocessed Esters and Fatty Acids (HEFA) pathway has emerged as the most commonly utilized, largely due to its advanced development and reduced carbon emissions. The HEFA process is a proven method that involves hydrotreating UCO to produce premium jet fuel, leading to a considerable decrease in carbon dioxide (CO_2) emissions when compared to traditional fossil-derived jet fuel.

Various research findings have shown that the HEFA method is capable of reducing greenhouse gas (GHG) emissions by as much as 80% in comparison to conventional fossil-derived jet fuel, although the exact reduction varies depending on upstream logistics, such as feedstock collection, transportation, and pre-processing efficiency [40]. This makes HEFA the leading technology for UCO-to-SAF conversion, both in terms of environmental benefits and commercial viability. Notable industrial facilities, such as Neste's refinery in Rotterdam and World Energy's plant in California, have already scaled up HEFA technology, converting UCO into SAF at commercial levels, with production capacities surpassing 100 million gallons annually [41].

Despite the commercial success of HEFA, alternative conversion methods such as Fischer-Tropsch (FT) and Alcohol-to-Jet (ATJ) are still in the pilot or demonstration phases. These alternative technologies face challenges such as high capital expenditure, complex feedstock pre-treatment requirements, and limited scalability. For instance, the FT process typically requires high-pressure systems and long reaction times, leading to high operational costs, while the ATJ pathway is hindered by its lower feedstock conversion rates and higher energy consumption during alcohol fermentation and dehydration stages [42].

The HEFA pathway's efficiency in converting UCO into SAF depends heavily on the hydrogenation process and reactor configurations used. Research indicates that catalytic hydrotreatment of UCO yields between 65% to 75% conversion efficiency, largely influenced by the type of catalyst used, reactor design, and operational conditions. New catalysts such as $NiMo/Al_2O_3$ and CoMo have been tested in pilot studies and shown to enhance deoxygenation performance and selectivity, resulting in better fuel characteristics with higher energy content and improved stability [43]. Furthermore, innovations in continuous flow reactor systems have been proposed to improve throughput, increase thermal stability, and allow for larger-scale processing without compromising fuel quality [44,45].

These technological developments are essential for improving the effectiveness and cost-effectiveness of transforming UCO into SAF, thereby making it more competitive with conventional jet fuels. However, further research into optimizing catalyst performance, reactor designs, and integration with existing refinery infrastructure will be crucial in reducing production costs and increasing the scalability of HEFA technology.

Environmental Impact and Regulatory Support

The environmental performance of UCO-based SAF is one of its strongest advantages over traditional biofuels. Life cycle assessment (LCA) models have estimated that SAF produced from UCO emits between 18 and 25 gCO_2e/MJ, significantly lower than the approximately 89 gCO_2e/MJ emissions of fossil-based jet fuels [46]. The decrease in carbon emissions is vital for assisting the aviation industry in achieving its decarbonization goals. Additionally, UCO does not compete with food crops, unlike first-generation biofuels, and it can be sourced from a variety of places, including household kitchens, restaurants, and food processing industries. This gives UCO an added benefit of being an environmentally friendly feedstock that addresses waste management issues while simultaneously producing a high-value fuel [47].

Policy instruments and regulatory frameworks are critical to accelerate the adoption of UCO-based SAF. In the European Union, the ReFuelEU Aviation Initiative mandates that by 2030, at least 5% of aviation fuels must be SAF, with UCO being included as a recognized feedstock under Annex IX Part B of the Renewable Energy Directive II [48]. Similarly, In the U.S., the Renewable Fuel Standard (RFS) and California's Low Carbon Fuel Standard (LCFS) provide renewable identification numbers (RINs) and credits to SAF manufacturers, serving as economic incentives for developing fuels derived from used cooking oil (UCO) [49]. These policies are designed to create demand for SAF and stimulate further investment in SAF production technologies.

Moreover, a study conducted in China showed that mandating UCO collection could increase the potential for annual SAF production by over 1 million tons, while simultaneously addressing the illegal reuse of cooking oil in food markets [50]. This highlights the dual benefits of UCO-based SAF production—environmental and public health—by creating a safe and regulated market for waste oils.

Despite the clear benefits, supply chain bottlenecks remain a significant challenge, particularly in developing countries where formal UCO collection systems are lacking. This issue may be addressed through the use of blockchain-enabled traceability mechanisms and globally acknowledged certification systems like the International Sustainability & Carbon Certification (ISCC) and the Roundtable on Sustainable Biomaterials (RSB) [51,52]. These mechanisms ensure the traceability of feedstocks, prevent fraud, and guarantee that UCO-derived SAF is produced sustainably, helping to overcome challenges in global UCO trade and regulatory compliance.

Industrial Readiness, Barriers, and Future Prospects

The industrial readiness for UCO-based SAF is improving, as evidenced by the increasing number of airlines and fuel producers entering the market. Major airlines, such as KLM, United Airlines, and British Airways, have entered into offtake agreements with SAF producers using UCO as a feedstock, signaling growing confidence in UCO-based SAF as a viable alternative [53]. In 2022, over 200,000 flights used SAF blends, with a substantial portion of this fuel derived from UCO through the HEFA process [54]. These developments indicate that UCO-based SAF is gaining momentum in the aviation sector, with early adoption leading to increased market confidence.

However, there are regional disparities in UCO generation and recovery rates, which hinder the scalability of SAF production. As stated by the International Energy Agency (IEA), while Europe and North America recover over 60% of their UCO, the recovery rates in regions such as Asia and Africa remain below 10% [55]. This creates challenges in meeting the feedstock demands for SAF production, especially in regions with limited waste oil collection infrastructure.

To address these challenges, several countries have implemented UCO collection programs. For example, China's "Green Oil" program has successfully doubled UCO collection volumes in pilot cities, improving the overall efficiency of UCO recovery [56]. The success of such initiatives could serve as a model for other regions seeking to establish or improve their UCO collection systems, ultimately increasing the supply of waste oil available for SAF production.

From an economic perspective, the cost of producing UCO-based SAF remains higher compared to traditional fossil jet fuel, with costs ranging between $1.10 and $1.80 per liter, depending on feedstock prices, processing efficiency, and local policies [57]. Although this is presently costlier than fossil-based jet fuel (approximately $0.80 per liter), various incentives and carbon pricing schemes have helped narrow the cost gap [58]. Moreover, economies of scale, advancements in conversion technologies, and increased UCO collection efficiency are expected to drive down production costs over time.

Looking to the future, innovations in co-processing UCO with lignocellulosic waste or algae could further stabilize feedstock availability, enhance output quality, and reduce reliance on a single feedstock source. Additionally, integrating SAF production with waste heat recovery systems and optimizing refining operations can improve overall energy efficiency, lower capital intensity, and accelerate the economic feasibility of UCO-based SAF production [59,60].

Conclusion

The transition towards sustainable aviation fuel (SAF) is imperative to achieving long-term decarbonization goals in the aviation industry. Utilizing used cooking oil (UCO) as a raw material for SAF production offers a novel and scalable approach that supports both environmental and economic sustainability goals. As demonstrated, UCO not only reduces waste but also provides a significant opportunity to decarbonize aviation without competing with food crops, positioning it as a second-generation biofuel that supports circular economy principles.

Among the various conversion pathways, HEFA (Hydroprocessed Esters and Fatty Acids) has proven to be the most viable and commercially mature technology. Its efficiency and compatibility with existing aviation infrastructure make it the frontrunner in UCO-to-SAF conversion. However, alternative processes like Fischer-Tropsch and Alcohol-to-Jet are still in developmental stages and may offer more scalable options in the future, depending on technological advances and economic feasibility.

While the environmental benefits of UCO-based SAF are well-documented, the challenges related to feedstock collection, regional disparities in UCO availability, and the need for robust regulatory frameworks must be addressed. Policy interventions, such as carbon pricing, blending mandates, and subsidies, are critical to incentivizing UCO collection and ensuring its competitive position in the global SAF market. Furthermore, improving traceability and ensuring the sustainability of UCO feedstocks through standardized certifications will be essential for the transparency and credibility of SAF production.

The scalability of UCO-based SAF will depend on overcoming logistical and supply chain barriers, improving UCO collection systems, and fostering public-private partnerships. Long-term solutions may involve integrating UCO with other waste oils or alternative feedstocks, enhancing the overall efficiency of SAF production. In addition, regional SAF hubs supported by local UCO collection networks could stimulate local economies and create green jobs, offering a sustainable path forward for the aviation sector.

In summary, UCO offers significant potential as a feedstock for producing sustainable aviation fuel. By addressing current challenges and utilizing technological and regulatory progress, UCO-derived SAF can play a crucial role in decreasing the aviation industry's carbon emissions and supporting global sustainability targets.

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