Comparative LCA of Sustainable Aviation Fuel Pathways: Environmental Impacts from Cradle-to-Wake for WCO, Tallow, Camelina, and Biodiesel

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Abstract

The aviation industry, a significant contributor to global greenhouse gas (GHG) emissions, has increasingly sought sustainable alternatives to conventional jet fuel. Sustainable Aviation Fuels (SAFs) offer a promising pathway toward decarbonization. This study presents a comprehensive Life Cycle Assessment (LCA) comparing four SAF feedstocks—Waste Cooking Oil (WCO), Tallow, Camelina, and Biodiesel—across a cradle-to-wake boundary. Environmental impacts, including GHG emissions, energy consumption, land use, and water footprint, are evaluated using standardized LCA methodologies and databases. Results reveal key trade-offs among the feedstocks, providing actionable insights for policy makers and industry stakeholders. While all SAF pathways demonstrate reduced emissions relative to fossil jet fuel, significant differences exist in resource usage and scalability, underlining the importance of feedstock selection for long-term sustainability.

Keywords: Sustainable Aviation Fuel (SAF), Life Cycle Assessment (LCA), Waste Cooking Oil (WCO), Tallow, Camelina, Biodiesel, Environmental Impacts, Cradle-to-Wake

I. Introduction

The urgent need to reduce greenhouse gas emissions in the aviation sector has fueled interest in Sustainable Aviation Fuels (SAFs), which promise substantial environmental benefits over conventional fossil-derived jet fuels. SAFs are derived from renewable feedstocks such as biomass, waste oils, and non-food crops, and can be used in existing aircraft with minimal modifications. The International Air Transport Association (IATA) targets net-zero emissions by 2050, and SAF adoption is central to achieving this goal.

Among the various SAF production routes, hydroprocessed esters and fatty acids (HEFA) have gained popularity due to their compatibility with current infrastructure. However, the environmental impacts of different HEFA feedstocks vary considerably[1]. This paper focuses on a comparative Life Cycle Assessment (LCA) of four SAF feedstocks—WCO, Tallow, Camelina, and Biodiesel—examining their cradle-to-wake environmental performance.

This study aims to identify the most environmentally preferable feedstock for SAF production by evaluating impacts such as global warming potential (GWP), energy use, land occupation, and water consumption. By understanding these trade-offs, stakeholders can make informed decisions about feedstock prioritization and policy development.

II. Methodology

This LCA follows the ISO 14040/44 standards and employs a cradle-to-wake boundary, covering feedstock production/acquisition, transport, fuel conversion, distribution, and combustion in aircraft engines. The functional unit is defined as 1 MJ of energy delivered by SAF during flight. The study uses the Ecoinvent 3.8 database and SimaPro software for inventory analysis, with ReCiPe 2016 as the impact assessment method[2].

Data sources include published literature, national inventories, and industrial reports. For each pathway:

- **WCO** is assumed to be collected from urban restaurants.
- **Tallow** is derived from animal rendering processes.
- **Camelina** is cultivated in marginal lands with minimal irrigation.
- **Biodiesel** is derived from a mix of vegetable oils and used via transesterification.

Co-product allocation is performed based on energy content, and sensitivity analysis is conducted to test the robustness of assumptions. Emissions are modeled for various stages including fertilizer use (Camelina), methane from decomposition (Tallow), and avoided waste treatment (WCO)[3].

III. Feedstock Analysis

WCO is widely regarded as one of the most sustainable SAF feedstocks due to its waste-based origin. Since it is a by-product of the food industry, its collection prevents improper disposal and reduces landfill methane emissions. The energy required for collection and pretreatment is relatively low.

LCA results indicate that WCO-derived SAF exhibits the lowest GHG emissions among the four pathways—up to 85% lower than fossil jet fuel. However, its availability is constrained by regional collection systems and inconsistent quality. Scalability remains a major limitation, particularly in countries without organized waste management systems.

Despite these limitations, WCO’s performance in categories such as eutrophication and water use is superior, as it does not require agricultural inputs. From a circular economy perspective, WCO exemplifies an ideal closed-loop feedstock[4].

Tallow, a by-product of meat processing, offers another waste-based feedstock with moderate GHG reductions. Like WCO, its production requires minimal additional land or water resources. However, rendering and refining processes are energy-intensive, contributing to a higher fossil energy demand[5].

One major concern is ethical and environmental implications associated with livestock industries, such as methane emissions from cattle and land use for animal feed. While tallow itself is a by-product, indirect emissions complicate its sustainability profile.

LCA shows a 65–75% reduction in GHG emissions compared to fossil fuel, but the variability is high depending on animal source, rendering technology, and allocation assumptions. Additionally, concerns about zoonotic diseases and hygiene affect the regulatory acceptance of tallow-based SAF in some regions.

Camelina sativa, a non-edible oilseed crop, is well-suited for marginal lands and requires less fertilizer and irrigation than conventional oil crops. Its compatibility with existing crop rotation systems (especially with wheat) makes it attractive for sustainable agriculture and fuel production.

LCA results show that Camelina-derived SAF has a GHG reduction potential of about 60–70%, contingent on cultivation practices. However, Camelina cultivation still involves land use change, fertilizer input, and emissions from farming equipment. These factors increase acidification, eutrophication, and water use compared to waste-based feedstocks.

On the upside, Camelina offers scalability and rural economic benefits. Its agronomic flexibility and potential for carbon sequestration in soils make it a competitive candidate for long-term SAF production, provided sustainable land use practices are followed[6].

Biodiesel, produced mainly through transesterification of vegetable oils or animal fats, is often considered a transitional fuel. While not a direct SAF, it can serve as a feedstock for further hydroprocessing into jet fuel. Biodiesel's lifecycle emissions are heavily influenced by the source oil—palm oil, soybean, rapeseed, etc[7].

The environmental impact of biodiesel-based SAF is highly variable. GHG savings range from 40% to 65%, with palm oil-based pathways scoring lowest due to deforestation and peatland conversion. Additionally, biodiesel production involves considerable water and chemical use.

Compared to WCO or Tallow, biodiesel has higher land and energy footprints. However, it benefits from mature production technology and established supply chains. When derived from second-generation or waste oils, biodiesel can offer comparable sustainability to WCO-based SAF.

IV. Comparative Environmental Impacts

Using the ReCiPe method, we assessed the following impact categories: climate change, fossil depletion, land use, freshwater ecotoxicity, and human health. The cradle-to-wake results are normalized and presented per MJ of fuel energy[8].

- **Climate Change**: WCO shows the best performance, followed by Tallow, Camelina, and Biodiesel. Fossil fuel equivalents range from 10 g CO_2-eq/MJ (WCO) to 40 g CO_2-eq/MJ (Biodiesel).
- **Land Use**: Camelina and Biodiesel score higher due to dedicated crop cultivation. WCO and Tallow, being waste products, require negligible land[9].
- **Water Use**: Biodiesel (especially from irrigated crops) and Camelina consume more water than WCO and Tallow.
- **Fossil Energy Use**: WCO and Camelina exhibit the lowest fossil energy inputs, though processing WCO requires cleaning steps that contribute slightly.

- **Human Health**: All SAFs perform better than fossil fuels, but tallow scores lower due to emissions from rendering and handling of animal by-products[10].

Trade-offs are evident. While WCO excels in most categories, its availability is limited. Camelina offers scalability but at higher resource costs. Tallow sits in the middle ground, and biodiesel's performance depends heavily on feedstock origin.

V. Sensitivity and Uncertainty Analysis

Sensitivity analyses were conducted to test the robustness of assumptions, particularly regarding allocation methods, collection efficiency (WCO), yield variability (Camelina), and energy intensity (Tallow rendering). Monte Carlo simulations (n = 1000) were used to assess result uncertainty[11].

Results reveal that WCO's performance remains consistent even under less favorable scenarios. However, Camelina and Biodiesel outcomes vary significantly with land-use assumptions and agricultural practices[12]. Tallow's performance is highly sensitive to the rendering energy mix and co-product credit allocation[13].

Uncertainty analysis confirms that although all SAFs outperform fossil fuels, policymakers must consider local context, data quality, and infrastructure maturity when selecting feedstocks.

VI. Conclusion

This comparative cradle-to-wake LCA demonstrates that while all SAF pathways studied offer environmental advantages over fossil jet fuel, they are not created equal. Waste-based feedstocks—particularly WCO—emerge as the most sustainable option due to their low emissions, minimal land and water use, and circular economy alignment. Tallow also presents a viable alternative, albeit with ethical and processing concerns.

Camelina provides a scalable and moderately sustainable solution, especially in rotation systems, while biodiesel's sustainability is highly variable and feedstock-dependent. Policymakers should prioritize waste-based SAFs while investing in scalable, low-input crops like Camelina for long-term deployment. Further research into region-specific practices, co-product handling, and energy inputs is essential to refine SAF sustainability assessments.

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