

Life Cycle Assessment (LCA) of the Production of Sustainable Aviation Fuels (SAF) in Colombia

Miguel A. Romero^{a*}, Manuel A. Mayorga^b, Zully E. Gómez^a, Felipe Correa-Mahecha^c, Luz A. Suarez^d

^aFacultad de Ciencias Ambientales, Universidad Santo Tomás. Bogotá, Colombia. Cra 9 # 51-11.

^bGrupo de Investigación en Tecnologías para el Desarrollo Sostenible – GITDES, Universidad Libre, Bogotá, Colombia. Av. 70 # 53-40.

^cGrupo de Procesos Sostenibles GPS, Universidad de América. Bogotá, Colombia. Av. Circunvalar # 20-53.

^dFacultad de Ingeniería Ambiental, Fundación Universitaria Agraria de Colombia. Bogotá, Colombia. Cll 170 #54A-10. miguelromerom@usantotomas.edu.co

Globally, aviation operations contribute significantly to greenhouse gas (GHG) emissions, primarily due to Jet A-1 fuel, creating sustainability challenges. This is highlighted by an 80% increase in GHG emissions following the economic recovery post-COVID-19. Colombia has the potential to produce approximately 250 million gallons of Sustainable Aviation Fuel (SAF) annually. A life cycle assessment (LCA) was developed for SAF production in Colombia using SimaPro® software. Three types of residual biomass were selected via a multi-criteria analysis of energy indicators: *Pinus Patula* (PP), Empty Fruit Bunches of Palm Oil (EFBPO), and Used Cooking Oil (UCO), corresponding to the production routes of Alcohol to Jet (ATJ), gasification with Fischer-Tropsch synthesis (FT), and Hydro-processed Esters and Fatty Acids (HEFA). Life cycle inventory (LCI) data were consolidated to quantify potential environmental impacts, identifying critical points in each route using the Environmental Product Declaration (EPD) methodology. The use of hydrogen in the ATJ route accounted for 99.7% of impacts in the Global Warming (GW) category, while heat requirements for HEFA contributed 77.13% to Water Scarcity (WS). In the FT route, 99.97% of impacts were associated with Acidification (AC) due to hydrogen supply. The LCA illustrates that despite efforts to reduce GHG emissions, strategies to enhance sustainability in SAF production processes in Colombia are imperative.

1. Introduction

The extensive operation of air fleets presents a range of negative implications, including the generation of greenhouse gases (GHG) and significant consumption of fossil fuels, (mostly Jet A-1), thereby exacerbating the detrimental effects of climate change (Okolie A. J et al., 2023 and Z. Gao, et al., 2022). The recovery of the aviation sector in the aftermath of the COVID-19 pandemic resulted in an 80% increase in GHG emissions relative to previously documented levels, equating to 800 Mt of CO₂ released into the atmosphere, according to the International Energy Agency (IEA, 2023). In recent years, there has been an increasing focus on mitigating these emissions through the production of Sustainable Aviation Fuels (SAF), which have the potential to facilitate the decarbonization of the sector and achieve long-term sustainability targets; The International Air Transport Association (IATA) anticipates that by 2050, the sector will aim for net-zero carbon emissions, with 65% of the fuels utilized in aircraft derived from sustainable production processes (IATA, 2022).

Production pathways for SAF that utilize residual biomass as feedstock for biofuel generation are regarded as one of the most promising for synthesizing these energy carriers (Bhatt, A. H et al., 2023). Organic matter rich in sugars, lipids, and lignocellulosic residues holds significant potential for advanced biofuel production, consequently promoting the closure of organic matter generation cycles through principles of circular economy and biorefinery processes (Puschnigg, S. et al., 2023). However, improper disposal of this biomass can result in undesirable environmental impacts affecting various biotic and abiotic resources, as well as diverse ecosystems.

Assessing the sustainability of these energy carriers' production processes is essential, particularly in light of the GHG reduction policies being advanced in the aviation sector. It is crucial that biofuels undergo certification under established standards, including those set forth by the American Society for Testing and Materials (ASTM), as the utilization of SAF is governed by a stringent regulatory framework that mandates adherence to necessary standards prior to implementation in various aviation systems (Su-ungkavatin P. et al., 2023). Furthermore, for SAF production to meet sustainability criteria, it is imperative to integrate life cycle assessment (LCA) principles as a tool for identifying critical points and potential environmental impacts across production routes, thereby enabling the formulation of engineering-based solutions (Rojas-Michaga et al., 2023). A widely adopted methodology in LCA for quantifying environmental impacts is the Environmental Product Declaration (EPD), which categorizes and allows for the percentage distribution of the negative environmental implications associated with the inputs and outputs of production processes (Heidari-Maleni, A., et al, 2024).

Colombia possesses significant potential for SAF production through diverse pathways, as the biomass generated can be processed through various biochemical and thermochemical methods (Sagastume Gutiérrez, A et al., 2020). The scenarios of residual biomass generation, which include agricultural, forestry, food, and urban waste, offer an abundant and diverse source of raw material for SAF production in Colombia (López, M. et al, 2024). Similarly, with the publication of the Eighth Circular Economy Report by the National Administrative Department of Statistics (DANE), material and waste flows for 2023 in Colombia were reported, where the biomass category exceeds 11 million tons of waste (DANE, 2023). Regarding the generation of used cooking oil, the volume corresponds to 330.000 tons/year (Casas L.C, et al., 2024). This research examined three specific routes in Colombia for SAF production: Alcohol to Jet (ATJ), gasification with Fischer-Tropsch (FT), and Hydroprocessed Esters and Fatty Acids (HEFA). These processes have been progressively scaled up in recent years, with pilot and commercial productions implemented (IRENA, 2021). The study employed LCA to evaluate the sustainability of these routes, assessing the potential production of SAF alongside associated environmental impacts, thus providing critical insights for the enhancement of these processes.

2. Methodology

The developed LCA is a gate-to-gate analysis, meaning it focuses on the stages of the production routes for SAF, from the input of the biomass selected to the synthesis of the biofuel. This assessment is oriented toward analyzing the environmental impacts specific to each process (Gheewala, S. H., 2023). The functional unit, following the mass allocation in SimaPro®, corresponds to a standard of 10 tons of SAF produced per route (ATJ, FT and HEFA). The selection of biomass was based on the use of the Macbeth multicriteria analysis method, which facilitates decision-making through the evaluation of various scenarios or alternatives to identify the most suitable type of biomass for the research, linked to sustainability indicators for biomass in general, reported by the Global Energy Partnership and additional research (FAO, 2011 and Martínez-Hernández, E., et al, 2021). This tool enables the integration of numerous factors that may influence environmental, economic, technical, and other studies, ranging from the definition of specific criteria and their weighting to the classification of alternatives and the final selection of the option that aligns with the desired model (Juanpera, M. et al., 2022). The Macbeth method is grounded in a numerical scale derived from semantic evaluations of the perceived differences in desirability among elements within a set. This scale provides a cardinal measure that enables precise and quantitative assessment of desirability in an objective manner (Suárez Palacios, O, 2011), as modeled by Eq. (1).

$$U_i = \sum_{j=1}^n [w_j f_j(C_j)] \quad (1)$$

U_i corresponds to the utility value of option or alternative i , w_j fulfills the weight of n criteria j considered in the multicriteria analysis. The function $f_j(C_j)$ estimates the preference for each criterion j . A difference scale, ranging from "insignificant" (valued at 2) to "very extreme" (valued at 20), is employed to quantify the criteria (w_j), as shown in Eq. (2). The sustainability of the SAF production routes examined in this research was assessed using SimaPro®, following the Environmental Product Declaration (EPD) methodology. Table 1 presents the impact categories and their corresponding units. As a result of the SimaPro® assessment, an environmental profile was generated for each SAF production pathway, reflecting the distribution of environmental impacts by category. Consequently, a detailed analysis of the information was conducted, highlighting the diverse implications of each pathway through a comparison of the three evaluated routes. Additionally, recommendations were formulated to improve the sustainability of the production processes for this type of biofuel.

$$w_j = \frac{\frac{\sum_{j=1}^n a_{jk} - \sum_{j=0}^k a_{jk}}{\sum_{j=1}^n a_{jk}}}{\frac{\sum_{j=1}^n \frac{\sum_{j=1}^n a_{jk} - \sum_{j=0}^k a_{jk}}{\sum_{j=1}^n a_{jk}}}} \quad (2)$$

Table 1: Consolidation of environmental impact measurement categories (EIMC) of the EPD methodology.

EIMC	Unit of measurement
Acidification	kg SO ₂ eq
Abiotic depletion, fossil fuels	MJ
Eutrophication	kg PO ₄
Global warming	kg CO ₂ eq
Water scarcity	m ³ eq

The LCI was calculated based on the reactions reported by Wyman, C.E. et al, (2019), Speight, J, (2020), Mayorga Betancourt, M., (2023) and Su-ungkavatin, P. et al., (2023), for the three SAF production pathways evaluated in the Colombian context. In SAF production, specifically in the FT and HEFA routes, operations such as hydroprocessing, hydrocracking, isomerization, and hydrogenation, and in the ATJ route, oligomerization, play crucial roles by offering various pathways to optimize the quality, yield, and compatibility of biofuels with the specifications of the aviation industry (Brooks, K. P, et al 2016). The aforementioned operations were included in the sustainability assessment of SAF production.

3. Results and Discussion

The multicriteria analysis using the Macbeth method was developed to assess the production of SAF in Colombia, considering various relevant criteria in this process. The factors evaluated included biomass cost and availability, productivity in the synthesis of bioenergetics (PSB), greenhouse gas emissions throughout the fuel's life cycle, among other key aspects. Table 2 shows the results of the method, calculating the difference between criteria, which allowed for the identification of the most important indicator for selecting residual biomass.

Table 2: Estimation of the criterion differences.

Indicator	C1	C2	C3	C4	C5	Total	Difference	Correlative	% w _j
C1. Biomass availability	-	14	11	11	2	38	8	1	40
C2. Biomass cost	-	-	11	11	8	30	11	0.8	31.6
C3. GHG emissions	-	-	-	11	8	19	11	0.5	20
C4. PSB	-	-	-	-	8	8	8	0.2	8.4
C5. Others	-	-	-	-	-	-	-	-	-
Total	-	-	-	-	-	-	38	2.5	100

Table 3 consolidates the information related to the calculation of the global profitability for the selection of biomass, based on the following alternatives: bioethanol from sugarcane (BSC), energy crops (EC), empty fruit bunches of palm oil (EFBPO), forest lignocellulosic biomass with the species *Pinus Patula* (PP), palm oil (PO), organic fraction of solid waste (OFSW), and used cooking oil (UCO). The weighting of the alternatives according to the sustainability indicators in bioenergy production, calculated in the multicriteria analysis, led to the selection of EFBPO, PP and UCO as the raw materials for SAF production through ATJ, FT, and HEFA, respectively.

Table 3: Final utility of the Macbeth method.

Alternatives of biomass (i)	C1	C2	C3	C4	Utility (U _i)
UCO	5	5	3	5	4.600
EFBOP	5	5	3	3	4.432
PP	5	4	3	5	4.284
OFSW	5	3	3	3	3.800
PO	4	3	3	3	3.400
BSC	4	3	2	3	3.200
EC	3	3	2	3	2.800

Assuming 100 tonnes of SAF as the reference for calculation, the synthesis heat and the obtained SAF are the critical points of the HEFA route. The former has the greatest impact on the categories of GW and WS, at 79.6% and 77.13%, respectively, while the potential impacts of the bioenergetic process are more significantly distributed across the AC (83.67%), ADFF (79.13%), and ET (72.28%) categories. Within the SAF synthesis via

ATJ, three critical points were identified, which include hydrogenation, the final product, and the synthesis heat. Hydrogenation is the stage with the largest potential distribution across the five categories evaluated in the LCA, ranging from 87.5% to 99.97%. In contrast, in the synthesis of SAF via FT, there is a notable percentage distribution with a significant contribution from the synthesis heat and final product in the ADFE and GW categories, with values of 36.62% and 26.28%, as well as 3.98% and 18.03%.

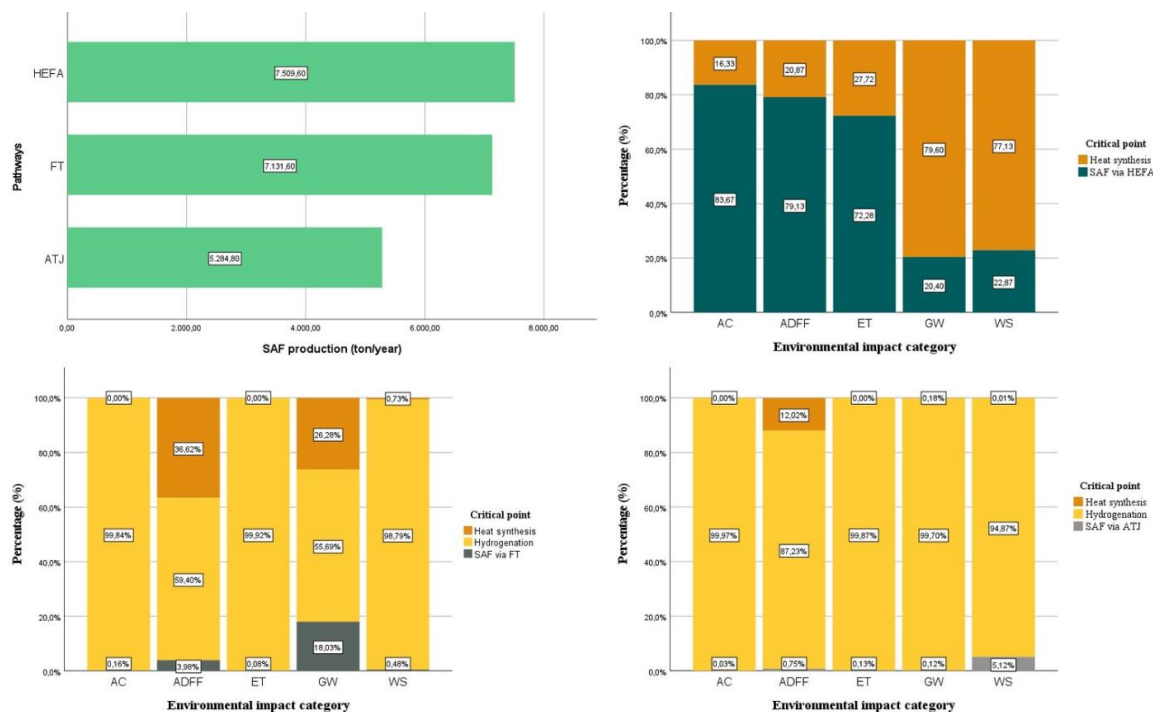


Figure 1: SAF potential production and critical points per route.

Based on the assumed data from the calculation framework for inventory estimation, Figure 1 shows the SAF production and the critical points per route, in accordance with the estimates for the LCA developed in this study. It can be observed that the HEFA route presents the highest production value among the evaluated routes. Similarly, it displays the percentage distribution of the environmental impact categories assessed for each of the SAF production routes. For the development of the calculations, a target SAF was selected corresponding to the molecular structure of $C_{13}H_{28}$. However, in the HEFA production process, due to the nature of the decarboxylation reactions (Mayorga Betancourt, M., 2023), a considerable fraction of SAF with a different molecular structure, corresponding to $C_{15}H_{32}$, was obtained, which is relevant to the research.

The heat requirement not only exerts significant pressure on natural resources, as considerable amounts of water and fuel (mainly natural gas) are needed, within the context of the LCA and the research developed, but also, as an environmental impact, it contributes to the depletion of natural and energy resources. Its release into the environment can modify microclimates and disrupt a wide variety of ecosystems (Mahmoud, M, et al., 2020). Hydrogenation, which is used in all three routes, is another critical point identified by the LCA. Specifically, in the ATJ and FT routes, weightings for certain categories of potential environmental impacts were found to approach 100%, and it is imperative to discuss this aspect, first, as hydrogen is essential to reduce the oxygen content in biomass and subsequently improve the SAF (Sinha, A.K. et al., 2016). Therefore, the supply of this compound is crucial for SAF synthesis, and within the Colombian context, it could become one of the drivers for developing a hydrogen market that can be incorporated into various production processes (Rodríguez-Fontalvo, D. et al, 2023). In the SimaPro® evaluation, hydrogen produced via conventional methods, specifically from fossil fuels, was considered, as the hydrogen market in Colombia remains limited and insufficient to meet the demand for SAF production, nor can it support large-scale renewable production pathways such as water electrolysis (Ministerio de Minas y Energía, 2021). Given its fossil fuel origin, the evaluated categories recognize this stage as critical in SAF production. Therefore, an alternative to meet hydrogen demand could involve the use of in-situ hydrogen generation catalysts, which facilitate the production of hydrocarbons in the (C_9 - C_{15}) range, applicable not only to SAF but also to renewable diesel (Pipitone, G. et al, 2023). To complete the discussion on the critical aspects of the routes, HEFA-derived SAF is not only associated with significant

implications regarding synthesis heat, but it may also generate potential environmental impacts, particularly in the AC, ADFF, and ET categories, as wastewater is produced during the process and energy derived from fossil fuels is utilized (Therasme, O. and Kumar, D., 2024). A pivotal aspect of the ATJ route is advancing research on microbial strains capable of fermenting pentoses, as conventional yeast strains exhibit limitations in incorporating such sugars into their metabolic pathways (Wyman, C. et al., 2019).

In general, for all three processes, criteria can be considered to enhance the sustainability of a potential SAF production in the Colombian context. These include the appropriate selection of renewable-origin catalysts or those with a reduced environmental impact (Pipitone, G. et al, 2023), the evaluation of raw material sustainability, and the selection of geographic regions within the country where production processes can be established under a biorefinery framework (López Gómez, M. et al., 2023). Additionally, it is important to follow the recommendations from one of the first reports on SAF production potential in Colombia, developed by Washington State University, an outstanding tool that provides a comprehensive diagnosis for the decarbonization of the sector (Martinez-Valencia, L., & Valderrama-Rios, C., 2024).

4. Conclusions

The LCA conducted for SAF production in Colombia facilitated the identification of the potential environmental ramifications associated with the unit operations of the three evaluated production routes. SAF production via the HEFA pathway exhibits the most extensive distribution of environmental impacts across the assessed categories within the SimaPro® software, with values that approach the total percentage distribution in certain categories. This is primarily attributable to the thermal demands and the final SAF synthesis, which are the critical points determined in the study, with a predominant association to the GW and WS categories. For the ATJ and FT routes, the category with the highest weightings is ET, with calculated values of 74.1% and 70.9%, respectively, suggesting that the emissions associated with these processes may have significant impacts on water resources. A pivotal aspect of the research is ensuring that the hydrogen utilized in these processes is derived from renewable sources, thereby mitigating adverse environmental impacts. Additionally, optimizing heat recovery in the process operations is crucial, ensuring that any thermal emissions to the environment are captured and repurposed for preheating the feedwater in the processes.

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