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Analysis of the Potential for Sustainable Aviation Fuel (SAF) Production from Colombian Agro-Industrial Residues

Mauricio López^{a,e,*}, Sergio Leon^{b,c}, Sergio Rocha^e, Johan Saenz^c, Santiago Rincon^c, Vladimir Silva^b, John Posada^d, Oscar Alvarez^a.

^aLos Andes University, Bogotá, Colombia

^bECCI University, Bogotá, Colombia

^cUniversidad Nacional de Colombia, Bogotá, Colombia

^dDepartment of Biotechnology, Delft University of Technology (TU Delft), Delft, the Netherlands

^eColombian Aerospace Force, Bogotá, Colombia

m.lopezg23@uniandes.edu.co

This study assesses the economic and environmental implications of Sustainable Aviation Fuel (SAF) production using Alcohol-to-Jet (ATJ) and Gasification Fischer-Tropsch (GFT) technologies, focusing on Colombian lignocellulosic feedstocks and evaluating key performance indicators such as yield, minimum fuel selling price, and life cycle assessment. GFT demonstrates promising results, yielding a Minimum Fuel Selling Price (MFSP) of about 1.3 USD/L and a Life Cycle Assessment (LCA) of 3.2 to 7.7 gCO₂ eq/MJ. However, its scalability is constrained by the volumes it manages. On the other hand, ATJ has an MFSP between 1.9 and 2.4 USD/L. Aligned with aviation industry goals for carbon-neutral growth, this analysis provides valuable insights for policymakers and industry stakeholders, supporting informed decisions toward sustainable aviation fuel adoption in the Colombian context.

1. Introduction

The aviation sector aims to achieve carbon-neutral growth and using Sustainable Aviation Fuel (SAF) is essential in achieving this goal. While the aviation industry accounts for only 2% of anthropogenic Green House Gases (GHG) emissions, adopting sustainable fuels is vital for contributing to global emissions reduction (Cui et al., 2022). ASTM D7566 certification includes eight pathways for SAF production (American and Standard, 2020), although only three, Hydroprocessed Esters and Fatty Acids (HEFA), Alcohol to Jet (ATJ), and Gasification Fischer-Tropsch (GFT), are currently at a commercial scale (IRENA, 2021). SAF production faces challenges such as high costs, logistics and quality control, political uncertainty, and competition with fossil fuels (Kandaramath Hari et al., 2015). However, the aviation industry, driven by IATA and its 2050 waypoint, is working to overcome these barriers and gradually adopt sustainable fuels (IATA and ATAG, 2021). Additionally, using hydrogen in the fuel improvement process presents an opportunity to reduce the carbon intensity of the final product (Zandi Atashbar et al., 2018). Likewise, the Colombian Government will promote the development and use of sustainable aviation fuels SAF according to the National Development Plan 2022-2026 (National Planning Department of Colombia, 2023).

This study analyzes two distinct technologies for SAF production using Colombian feedstocks, mostly residues like lignocellulosic co-products and wastes, all of this with a primary focus on assessing their economic and environmental implications from initial factors, encompassing mass conversion or yield, costs, and CO₂ emissions across the entire production process. The key performance indicators include yield, minimum fuel selling price (MFSP), and life cycle assessment (LCA). Through some calculations and in-depth analysis, this study aims to discern the most suitable technology and feedstock for the region's SAF production. The investigation includes two production technologies that could use lignocellulosic feedstock: ATJ and GFT, each evaluated within the context of Colombian feedstocks, especially lignocellulosic residues as municipal solid waste (MSW), agro-industrial wastes and especially highlighting the by-products of sugar cane and panela

production, such as bagasse and heart leaves, also, residues of palm oil, corn, rice production among others of high production in the country. These findings from this study would provide the basis for developing an efficient and sustainable strategy for SAF production in Colombia, furthering the prospects of producing environmentally responsible aviation fuels in the region.

Regarding technology pathways, ATJ process initiates with the dehydration of alcohol feedstock to produce alkenes, utilizing zeolite and metal oxide catalysts. It focuses on converting commercially available alcohols such as methanol, ethanol, and butanol sourced from conventional fossil fuels and various biomass materials. In addition, GFT involves biomass gasification, synthesis gas cleaning and conditioning, and subsequent synthesis to produce liquid biofuels. While GFT-produced fuels offer high specific energy levels and enhanced payload capacity, they lack essential aromatics for elastomer seal swell in aircraft components. Advanced Fischer-Tropsch synthesis methodologies have been developed to incorporate additional aromatic compounds, maintaining their attractiveness for sustainable aviation fuel (SAF) production. Every operation unit involves costs and emissions, in which a factor was considered to represent all OPEX and CAPEX costs, like in this case for biorefinery, however, factors for every value step chain were calculated.

2. Methodology

The economic analysis methodology for evaluating various value chain scenarios in Sustainable Aviation Fuel (SAF) production involves data collection from reliable sources to compare different technologies and raw materials. This process utilizes an application based on the Huang-Zhang mathematical model, initially developed in collaboration with Stender Kwakernaak (Kwakernaak, 2022.). The authors of this article have subsequently reworked the foundational code. At *Figure 1*. Shows The model which commences with *i*-th regions, each assigned coordinates in ArcGIS® software, where biomass is produced. Biomass is assumed to be transported to *j*-th Centralised Storage Processing (CSP), serving as either accumulation points for biomass from various regions or intermediate processing centers. The intermediate raw material is then transported to *k*-th biorefineries, typically 1 for SAF in the Colombian context. Finally, SAF is transported to *m*-th international airports.

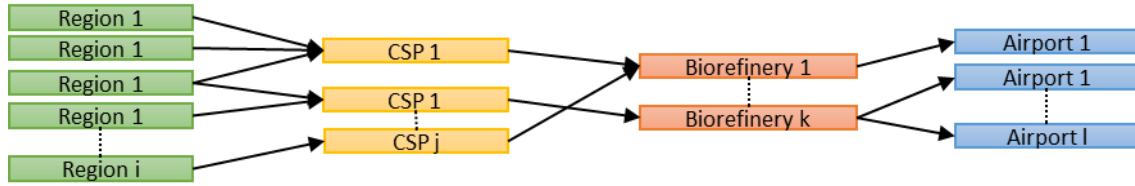


Figure 1: Diagram of the supply chain used in the analysis.

Each route incurs transportation costs, and CSP and biorefineries have associated CAPEX and OPEX. Biomass, process technology, and co-products have market prices, with the "economic allocation factor" representing income from co-products sales. The financial aspect involves modelling the initial investment as credit with returns to investors for biorefinery construction, represented by the "alpha" factor Technological. The equations of the optimization model working in the Python application are supported in equations 1 and 2.

$$OBJ_1 = Alloc_{Econom} \cdot (C_{Feed} + C_{CSP} + C_{Bioref}) + C_{Transport} = MFSP \cdot P \quad (1)$$

$$OBJ_2 = Alloc_{Environment} (E_{Feed} + E_{CSP} + E_{Bioref}) + E_{Transport} = LCA \cdot P \quad (2)$$

In the first equation the variables *C* refers to the costs, individually, the one that is specified in the index, either Feedstock, CSP, biorefinery and transport, also the allocation factor, that affect every cost but transport, because, in calculation of this costs this allocation is taken into account but in a complex way, similarly for the second equation where *E* means emissions, the result of these equations gives the total costs or emissions, which were optimized by the mentioned program.

This application can simulate any technology for SAF production; however, this article focuses on technologies such as ATJ and GFT.

The simulation of both pathways was conducted using conversion data sourced from literature, alongside mass balances specifically developed for calculating overall bio-jet conversion (Leon, 2023). This method additionally enables the determination of bio-naphtha and bio-diesel percentages, contingent upon the collected conversions and the composition of raw materials. Notably, despite being lignocellulosic materials, the composition of these feedstocks varies considerably based on the origin and species of the treated residue. Thus, a detailed analysis regarding the composition of different materials was also carried out.

This study collected data from multiple sources and converted it to a dry feedstock mass basis. Particularly for the CAPEX data it was conducted some regressions to approximate a curve from which the factors were derived for every technology. In other cases, some information from the Colombian context was adjusted to recalculate some economic factors, like allocations, in which were replicated calculation from Capaz et al. (2020). Likewise, the supply chain from the feedstock, CSP and biorefinery and the transportation added at each of the points to the end user at the airport.(Kwakernaak, 2022).

In addition, for transportation cost, a calculator were made for include taxes, devaluation, and mainly, Colombian prices, for trucks and fuel, and even emissions were added to the calculator. In Environmental LCA, the research emphasizes selecting impactful categories for GHG attribution. Examining feedstock procurement given by a data basis made by ANSCENT (ICAO, 2023). In this basis is included some Indirect Land Use Change (ILUC) and Land Use Change (LUC)(Han et al., 2013),those are crucial, however there is no data for Colombia, so data for near countries were taken, like Brazil. Identifying low-risk raw materials, such as waste and high-yield sources, is imperative (De Jong et al., 2017). The study scrutinizes GHG emissions at biorefineries, Centralized Storage Processing units, and transport, ensuring a comprehensive assessment (Capaz et al., 2020).

3. Results

Technology Results: The significance of moisture in the raw material is quite noticeable because the amount of feedstock currently used for SAF production decreases as moisture increases. However, another important factor is the amount of lignocellulose present, as it does not convert into fermentable sugar that can participate in the ATJ route. For this reason, FT yields tend to be higher. However, pretreatment may increase costs for very humid raw materials since the mandatory drying operation before gasification would require an amount of energy that would make the technology unfeasible(López Gómez et al., 2023). MSW is a broad concept and must be characterized or classified to ensure accurate results. For simulations, it was characterized in two: MSW Paper and cartons, and MSW sludge or household organic waste, which has a higher humidity than papers, also information for those materials is very complex, so for approximation in LCA and MFSP were considered materials with similar properties, like forest residues or wood for paper case and agricultural residues for sludge and also theoretical yields shown in Table 1, conversions calculated for ATJ and FT technologies by (Leon, 2023) from agro-industrial waste (AR), forest waste (FR), and MSW to distillate are presented. This includes SAF, along with other co-products commonly found in research articles, and a separate entry for conversion to SAF.

Table 1: Conversion to SAF from waste

Yields (Kg/Kg feedstock)		GFT		ATJ	
		wet	dry	wet	dry
AR	SAF	9.0%	13.8%	5.1%	8.5%
	Distillated	10.8%	16.6%	8.2%	13.7%
FR	SAF	5.2%	13.0%	4.6%	11.5%
	Distillated	6.2%	15.6%	7.4%	18.5%
MSW: sludge	SAF	3.3%	8.2%	2.1%	5.1%
	Distillated	3.9%	9.8%	3.3%	8.3%
MSW: paper	SAF	12.6%	14.0%	8.8%	9.8%
	Distillated	15.2%	16.8%	14.2%	15.7%

Production Capacity: Considering the various residues produced in Colombian agriculture, analyzing variables such as moisture and type of raw material, assuming that feedstock with moisture above 50% is better suited for ATJ, and those high in lignin should be treated with GFT, the potential is as follows in Table 2, where the selected yields depend on the humidity as described before and considering dry basis. where it relates the total production according to the database (Ministerio Agricultura, 2022). However, it must be kept in mind that according to the location, part of this material is used as energy material and others for land fertilizer. This total represents 1,760 million gallons of potential bio-jet with the previously mentioned waste supply, considering that the current demand in Colombia is approximately 600 million gallons per year(López Gómez et al., 2023), or 1.8 million tons per year. This ensures that the current production can meet this demand. However, it's important to note that these calculations are based on total production, and the actual availability of raw materials may vary due to multiple uses depending on regions and production chains, such as self-generation, among others.

Table 2. SAF production potential in Colombia

Crop Type	Residue Name	Humidity	Feedstock ton/Year	SAF potential ton/Year
Sugarcane	Bud	68%	14,935,746	406,899
	Bagasse	41%	12,220,156	994,760
Sugarcane (panela)	Bud	71%	50,131,714	1,237,715
	Bagasse	41%	28,199,089	2,295,496
Rice	Chaff	73%	1,054,554	39,285
	Husk	4%	909,099	113,301
	Shell	17%	258,875	27,895
Oil Palm	Fibers	35%	345,167	30,955
	Palm rachis	58%	1,121,793	65,006
	Stubble	32%	980,230	91,966
Corn	Cob	27%	382,124	38,487
	Basket	6%	299,053	38,785
	Pulp	80%	4,679	80
Coffee	Cisco	7%	453	55
	Stems	26%	8,377	805
			Total	5,381,489

Economic Results: The behaviors of the regressions comply with the economy of scale rule, where operating costs exhibit an inverse trend, and capital costs show an ascending trend. It is emphasized that the regressions contain a couple of counterintuitive data points, although the overall regression demonstrates the aforementioned behavior. This is because the collected data included versions of pioneering plants, so it is normal that these values may be higher than those indicated by the trend. Additionally, the allocation factor with information from (Capaz et al., 2020) allowed for an approximation of these values to be carried out. On the other hand, it is important to mention that the operation costs and transportation information are supported in the Colombian context, where the following data is related. The OPEX includes relations between inputs and feedstock taken from (Capaz, 2021), cost for power (196.07 USD/MWh) H2 grey (0.98 USD/kg), natural gas (17.6 USD/GJ) (Ministerio de Minas y Energia, 2021) the variable transport costs, in every phase of the value chain, for these costs a few suppositions took place like capacity and fuel performance in function of truck size, fuel cost (2.3 USD/gal), Toll prices and frequencies (0.0294 km-1), labor time and price (1.6 million COP/month, 172h/month (Martinez, 2022). For the different sizes, the main difference is the size of the truck for transportation and the density of the transported material. so C2 is lightweight, has a capacity of 5 tons or 21.5 m3 (Transcomercol S.A.S, 2017), for C3S2 which means three-axle truck with two-axle semitrailer, and which have a capacity of 35 tons or 72 m3 (Transcomercol S.A.S, 2017). In the fixed transport costs: price and capacity of the truck in the function of its size and its useful time (about 12 years), insurance (26,44 times SMDV minimum current diary wage), and the exchange rate (4100 COP/USD in November 2023). (Martinez, 2022). For the economic allocation factor was taken the information of mass relation shown in (Capaz, 2021) and using prices for jet fuel (1.31 USD/L) biodiesel (1.08 USD/L) bioethanol (0.98 USD/L) for Colombia (Fedebiocombustibles, 2022).

Minimum Fuel Selling Price (MFSP):

After carrying out the simulations focused on supplying the SAF in the 4 main airports (Bogota, Rionegro, Cartagena, and Cali), the following results were obtained from the economic point of view. Beforehand the current market prices according to ICAO. (2023) an ATJ 2.2 USD/L for an ethanol basis, and GFT 0.9, 1.7, 2.0 USD/L for MSW, FR and AR respectively. As expected, biorefinery costs are among the highest throughout the process. The allocation factor, especially for GFT, about 0.24, and for ATJ, 0.6, is crucial for cost reduction. Similarly, for this technology, it is observed in Figure 2, that biorefinery costs are the most significant, several times higher than the total of all other costs combined. In the case of ATJ, transportation also plays a significant role, as distances to distilleries were considerably high. This transportation value can be reduced by building

new points that connect the raw material generation points with the end users and in this way ATJ can be more competitive with respect to GFT.

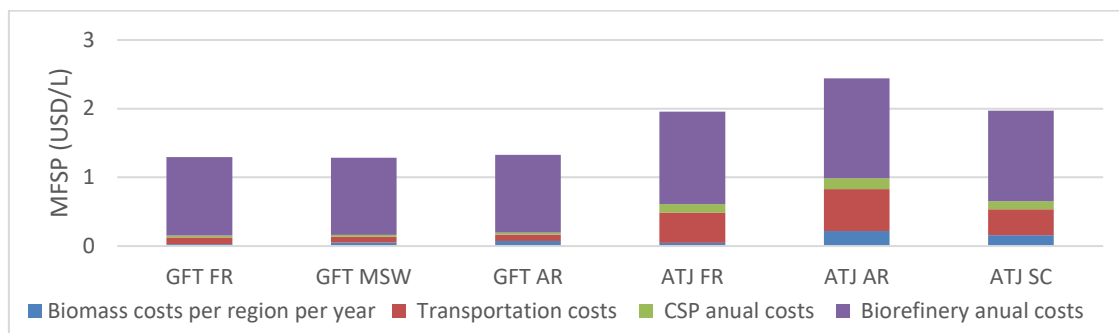


Figure 2: Minimum Fuel Selling Price (MFSP) by technology and raw material Environmental Results

Life Cycle Assessment LCA

The impact of the GFT route is lower than ATJ because in this route, synthesis gas residues can be utilized, and effluents can be treated in a more controlled manner. Conversely, for the ATJ route, once again, the biorefinery accounts for a significant portion of emissions due to the presence of more polluting effluents such as vinasse and biological residues, which have a higher environmental impact than GFT. It is also worth mentioning the effect of the Allocation factor, which again primarily influences the vast difference between both LCAs. Figure 3 shows the distribution of LCA by technology and raw material.

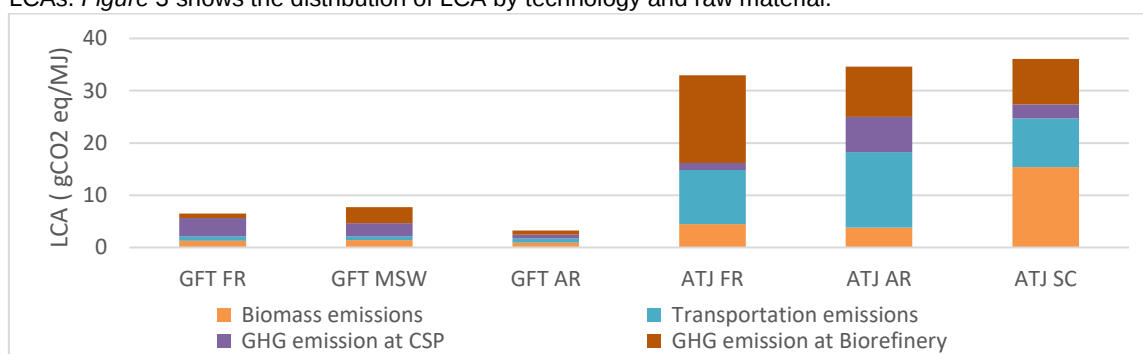


Figure 3: Life cycle analysis by technology and raw material

Regarding the economic and environmental aspects. The research findings reveal that the capacity to produce 5,381,489 tons of SAF per year from agro-industrial waste needs careful consideration of logistics optimization scenarios to mitigate impacts on the final price and LCA. Differentiating residue types from the same crop, based on moisture and raw material type variables, suggests that raw materials with moisture above 50% are better suited for ATJ. At the same time, those high in lignin should be treated with GFT. This allows for multiple logistic options from the same point. In the Colombian context, GFT demonstrates promising results, with a competitive MFSP of about 1.3 USD/L and an LCA of 3.2 to 7.7 gCO₂ eq/MJ. However, scalability is hindered by volume constraints, necessitating government policies, including credits and incentives, to maintain a favorable price for end users. On the other hand, ATJ, with an MFSP between 1.9 and 2.4 USD/L, presents a competitive global market price and lower capital investment costs compared to GFT. Despite its higher LCA of about 34 gCO₂ eq/MJ, ATJ may find traction in markets like the United States or through the book and claim mechanism.

4. Conclusions

Even though it has the capacity to produce 5,381,489 tons of SAF per year from agro-industrial waste. It is necessary to consider that a percentage of this is part of the real availability, which is why logistics optimization scenarios must be considered for subsequent work so that it does not affect the final price and the LCA.

The type of residue from the same crop means that considering variables such as moisture and type of raw material, assuming that raw materials with moisture above 50% are better suited for ATJ, and those high in lignin should be treated with GFT, so several options can be generated from the same logistic point.

In the Colombian context, GFT demonstrates promising results, yielding an MFSP of about 1.3 USD/L and an LCA ranging from 3.2 to 7.7 gCO₂ eq/MJ. However, its scalability is constrained by the volumes it manages,

hindering the achievement of a balance point. Additionally, government policies, such as credits, incentives, and exemptions, can play a crucial role in maintaining a favorable price that does not negatively impact the end user. On the other hand, although ATJ has an MFSP between 1.9 and 2.4 USD/L, it is a competitive price for what is currently managed worldwide and the capital investment costs are lower if compared with GFT. Likewise, it has an LCA about 34 gCO₂ eq/MJ, which can be striking for a market like the United States or through the book and claim model.

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