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Diagnosis of Challenges and Uncertainties for Implementation of Sustainable Aviation Fuel (SAF) in Colombia, and Recommendations to Move Forward

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Abstract: This article reviews the current scenario and the main uncertainties and challenges associated with implementing Sustainable Aviation Fuel (SAF) in Colombia, from which it determines the possible certified technologies under the ASTM D 7566 standard as well as co-processing technologies contemplated within the ASTM D 1655 standard, more suitable for the implementation of SAF production. Likewise, through the PESTEL tool (Political, Economic, Social, Technological, Environmental, and Legal), a diagnosis is made in order to obtain an updated overview of the implementation of SAF in Colombia. Based on the above, it provides recommendations to mitigate the uncertainties identified, and it is complemented by the ECOCANVAS tool, which applies to businesses related to the circular economy, and also include the net production potential of SAF in Colombia, considering the production of feedstock, in agricultural residue of sugarcane, oil palm, corn, and coffee. This study concludes with some policy recommendations that can make SAF implementation viable and allow responsible institutions to organize themselves for better strategic action and identify the fields of research and the need for investment in R + D + i to strengthen the supply chain.

Keywords: aeronautical biofuel; Sustainable Aviation Fuel (SAF); sustainability; Colombian PESTEL; ECOCANVAS; SAF policies

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1. Introduction

Air transport accounts for approximately 2.4% of global greenhouse gas (GHG) emissions [1], and the exponential growth of the sector may significantly increase this proportion [2]. In 2021, the International Civil Aviation Organization (ICAO) adopted the goal of achieving net zero emissions by 2050 [3]. In addition, in 2016, ICAO approved the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [4]. Regarding the issue of reducing emissions, Colombia initially committed, in the COP21 Paris Agreement, to reduce GHG emissions by 20% before the year 2030 and, subsequently, by 51% in year 2015, in its Colombia Carbon Neutral Plan, issued in 2021 by the Ministry of the Environment [5]. In Colombia, fossil fuel use in aviation generates around 4.45 million tons of CO_2 per year (with an average consumption of 500 million gallons of JET A-1 per year in Colombia, taking as reference the years 2019 and 2022). Sustainable Aviation Fuel (SAF) is one of the key alternative fuels that can help to reduce these emissions, and it has a level of strategic importance for Colombia because the country is seeking to achieve its implementation, just like some examples of other countries in the past, starting in 2008, see Table 1.

Table 1. Initial flights with SAF.

Year	Country	Company	Plane	Percentage of SAF Blend	Type of SAF	From	To	Ref
2008	United Kingdom	Virgin Atlantic Airlines	B746-400	20%	Coconut and babassu oil fuel	Seattle, Washington	Seattle, Washington	[6]
2009	United States	United Airlines	Boeing 737		Jatropha and algae derived fuel	Houston	Chicago	[7]
2011	Germany	Lufthansa	Airbus 321	50%	biofuel	Hamburg	Frankfurt	[8]
2011	Netherlands	KLM	Airbus	50%	Recycling Frying oil fuel	Amsterdam	Paris	[9]
2011	France	Air France	Airbus A321	50%	cooking oil	Toulouse	Paris	[10]
2012	Chile	LAN Airlines; COPEC	Airbus A320		cooking oil	Santiago	Concepcion	[11]
2013	Colombia	LAN Colombia; TERPEL	Airbus A320	33%	Camelina oil	Bogotá	Cali	[12]

By March 2023, more than 469,000 flights had been carried out, according to information from the ICAO [13]. However, SAF use under purchase agreements is 41.8 billion liters as of March 2023, and this only covers 2% of the total amount of fuel demand by 2025 [13] and remains negligible because they are considered to have little competitiveness with fossil fuels for jets and this [14].

According to the director of Boeing Commercial Airplanes, Richard Wynne, before generalizing the commercial use of biofuels in the aeronautical sector, it is necessary to overcome a series of obstacles [15], among which are the following: (i) biofuels will have to be chemically identical and perform the same as fossil fuels; (ii) there should be a large-enough source to make these new fuels available at an acceptable cost; (iii) the SAF has to be drop-in fuel because modifications must be made to the supply and logistical support programs so that airports can handle fuels without making significant changes in storage tanks, pipelines, and other infrastructure [16]; (iv) commercial production must have a comparatively favorable price concerning conventional fuels [16]; finally, (v) they have to be sustainable and not compete with food sources [14,17].

Regarding the technologies to produce SAF, there are nine ways to produce it, which are certified under the ASTM D4054 standard [18] and found within the annexes of ASTM D7566 [19] and ASTM D 1655 [20], related in Table 2. However, four are currently at or near commercial scale: (i) Hydroprocessing of Esters and Fatty Acids (HEFA); (ii) Fischer–Tropsch Gasification; (iii) Alcohol to Jet (ATJ); and (iv) co-hydroprocessing of esters and fatty acids in a conventional oil refinery [14,20].

With the creation of Law 693 of 2001, the development of biofuels in Colombia began. Currently, the country has six sugar mills (Incauca, Providencia, Riopaila Castilla, Mayagüez, Risaralda, and Manuelita Mill), and Bioenergy, located in the department of Meta, produces fuel alcohol based on sugar cane as raw material. Currently, the sector has an installed capacity of 2,154,000 L per day. On the other hand, the biodiesel production plants (Aceites Manuelita, BioD, Ecodiesel, BioSC, Bgreen, Inversiones la Paz, Alpo, among others) have an installed capacity close to 750 thousand tons per year, of which the largest is that of BioD. It should be noted that the production of biofuels is strategic for the country because this allows it to reduce its dependence on non-renewable fuels and contribute to maintaining the reserves of these energy sources, such as oil and gas. Currently, and as a renewable energy source, the fuel alcohol is mixed with regular and extra gasoline in a percentage between 2% and 10% of fuel alcohol, while the mixture of biodiesel with ACPM is 10% nationally by mandate. However, several cargo and package fleets use 20% mixes and belong to the Biotanking Club [21].

Table 2. Sustainable aeronautical fuel conversion pathways are certified under the ASTM 7566 standard.

ASTM Reference [1]	Conversion Process	Abbreviation	Possible Feedstock	Mix Ratio by Volume	Marketing Proposals/Projects
ASTM D7566 Annex 1	Fischer–Tropsch Hydroprocessed Synthesized Paraffinic Kerosene	FT	Coal, natural gas, biomass	50%	Fulcrum Bioenergy, Red Rock Biofuels, SG Preston, Kaidi, Sasol, Shell, Syntroleum
ASTM D7566 Annex 2	Paraffinic kerosene synthesized from hydroprocessed fatty acids and esters	HEFA	Bio-oils, animal fats, recycled oils	50%	World Energy, Honeywell UOP, Neste Oil, Dynamic Fuels, EERC
ASTM D7566 Annex 3	Isoparaffins synthesized from hydroprocessed fermented sugars	SIP	Biomass used for sugar production.	10%	Amyris, Total
ASTM D7566 Annex 4	Kerosene synthesized with aromatics derived from the alkylation of light aromatics from non-petroleum sources	FT-SKA	Coal, natural gas, biomass	50%	Sasol
ASTM D7566 Annex 5	Synthetic Paraffinic Kerosene Alcohol to Jet	ATJ-SPK	Biomass from the production of ethanol or isobutane	50%	Gevo, Cobalt, Honeywell UOP, Lanzatech, Swedish Biofuels, Byogy
ASTM D7566 Annex 6	Catalytic Hydrothermolysis Jet Fuel	CHJ	Triglycerides such as soybean oil, jatropha oil, camelina oil, carinated oil, and tung oil	50%	Applied Research Associates (ARA)
ASTM D7566 Annex 7	Paraffinic kerosene synthesized from hydrocarbon esters and fatty acids	HC-HEFA-SPK	Algae	10%	IHI Corporation
ASTM D1655 Annex A1	co-hydroprocessing of esters and fatty acids in a conventional oil refinery	Co-processed HEFA	Fats, oils, and fats (FOG) co-processed with petroleum	5%	
ASTM D1655 Annex A1	Fischer–Tropsch hydrocarbon co-hydroprocessing in a conventional oil company refinery	Co-processed FT	Fischer–Tropsch hydrocarbons co-processed with petroleum	5%	Fulcrum

[1] Sources: ASTM 7566-20c—Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons, ASTM 1655-21a, and adapted from https://www.caafi.org/focus_areas/fuel_qualification.html, accessed on 28 July 2022.

In the Colombian context, several initiatives have been formulated that support the legal framework, as shown in Table 3.

Table 3. Legal framework for biofuels in Colombia.

Year	Document	Theme	Observation	Reference
2008	CONPES 3510	Policy Guidelines to promote sustainable biofuel production in Colombia	Policy aimed at promoting the sustainable production of biofuels in Colombia, taking advantage of the opportunities ofeconomic and social development offered by emerging markets.	[22]
2008	Decree 2328	Promotion	Whereby the Intersectoral Commission for the Management of Biofuels is created	[21]
2010	Resolution 180,919	The Action Plan is adopted to develop the PROURE	PROURE: Program for the Rational and Efficient Use of Energy and other forms of Unconventional Energy	[17]
2021	LAW 336	To establish minimum measures to achieve carbon neutrality, climate resilience, and low-carbon development in the country	This commitment means progress in assigning responsibilities to key government actors to support the feasibility of an early phase of the SAF	[23]
2022	CONPES 4075 ENERGY TRANSITION POLICY	The Ministry of Mines and Energy, in 2023, will establish the sectoral roadmap for the consolidation of the use of first-generation biofuels	The definition, analysis, design, evaluation, and formulation of guidelines and regulations for the promotion of the alternative use of biofuels	[23]
2023	National Development Plan 2022–2026 (literal D)	More efficient modes of transport at the operational and energy level, Number 3; technological advancement of the transport sector and promotion of active mobility	The government will drive the development and use of SAF sustainable aviation fuels	[24]

However, a regulatory framework is required to implement the production and use of SAF based on a diagnosis adjusted to the economic, social, technological, and environmental context [25].

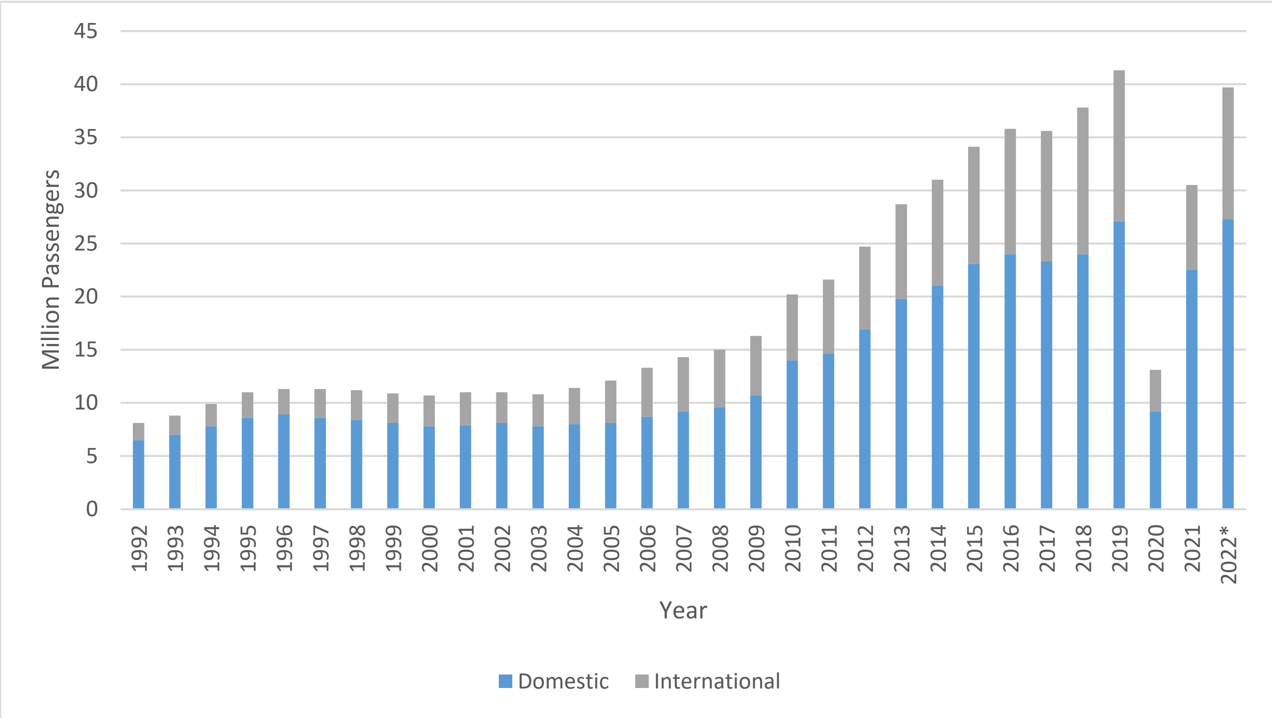
In Colombia, support experiences have been carried out between the ECCI University and the Colombian Air Force (COLAF) around the use of biofuels in two technologies of military-type aeronautical engines. These were developed using stationary test benches in order to be able to evaluate the behavior of local biofuel mixtures in the country on conventional aviation engines, their environmental impact, aeronautical logistics, operational safety, and aeronautical maintenance. Carried out within the framework of the calls, which were 852-2019 and 995-2017 of Minciencias [12,26]. For these studies, the adaptation of two test benches for turbojet and turboprop engines was carried out. Fossil fuel blends with biofuel from palm oil and palm kernel oil were tested using additives to improve the freezing point. As aeronautical engines, a Pratt and Whitney PT6A-60 engine [27] and a fully functional J69-T-25 engine were used [28,29]. These investigations are currently continuing to be able to carry out diagnostic tests [30] that allow for superior scientific support in the behavioral results before aviation tests in factual flights.

Colombia has 202 airports, among which are commercial, municipal, military, and private [31]. Figure 1, displaying the main commercial Colombian airports, illustrates the 14 international and 40 national airports with more than 48 million annual passengers, representing most of the Colombian commercial airflow. Military operations are centered in nine military airports.

Figure 1. Main commercial Colombian airports adapted from [32].

The air transport market of passengers in Colombia has kept a growing tendency over the past 30 years. Over recent years, an essential driver of air passenger demand has been the reduction of airfares, partially because of a substantial degree of competition between airlines [33]. In 2020, due to the COVID-19 pandemic, there was a 68.3% drop compared to 2019, with a slow rebound in 2021 (Figure 2). Domestic passengers lead the air transport market. In the last decade, around 68% of air passengers covers domestic routes, with the remaining 32% being international.

Bogotá has the airport with the largest number of international routes, passengers, and cargo traffic, followed by Medellin-Rionegro and Cartagena [32,34]. The main cities of origin and destination of domestic flights are Bogota, Medellin, Cartagena, Cali, and Santa Marta (Figure 3a); however, Colombia has almost 90 domestic connections. In 2022, the leading carriers for domestic flights were Avianca, Latam, and Easyfly (Figure 3b).



* January to October 2022

Figure 2. Air transport market in Colombia. Annual domestic and international passengers transported 1992–October 2022 [34].

From January to October 2022, Bogotá and the United States were the main destinations, with around 30% of the national and international passengers separately. Miami, New York, and Fort Lauderdale are the main destinations in the United States. Colombian emissions associated with international aviation are estimated at 11.4 million tCO_{2e} by 2030 if no mitigation action exists. It is equivalent to 6.7% of the maximum emissions (169.44 million tCO_{2e}) aimed by the country that year [35,36].

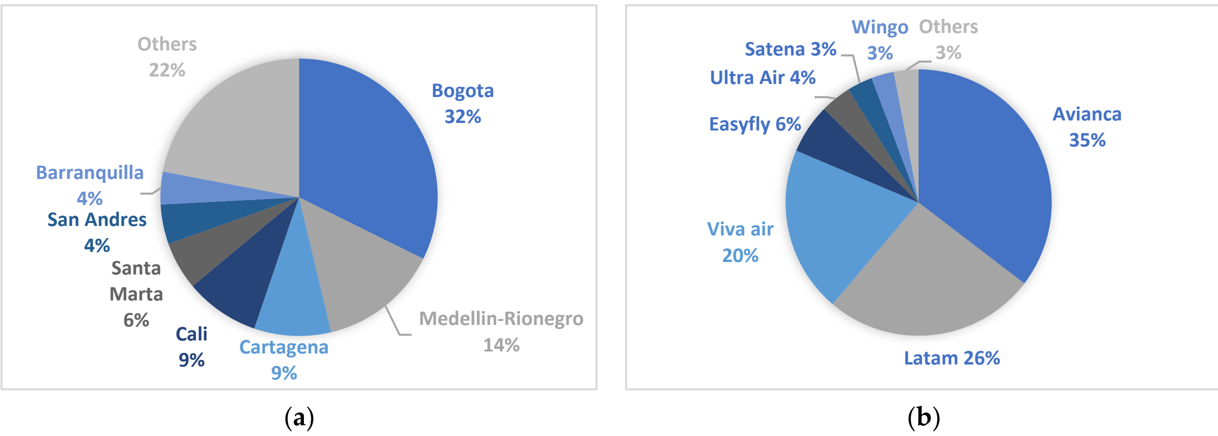


Figure 3. (**a**) Main domestic origin and destination flights. (**b**) Main carriers in domestic flights from January to October 2022 [36].

Liquid fuels are obtained by refining crude oil (petroleum). Crude oil is a blend of paraffin (straight-chain and branched-chain compounds), naphthenes (cyclo paraffins), and aromatics (benzene and its derivatives) [37]. In Colombia, crude oil refining is carried out principally in the refineries owned by ECOPETROL S.A. and located in Barrancabermeja and Cartagena. Nonetheless, there are three other auxiliary refineries—Apiay, Orito, and Hidrocasanare—which have limited processing capacity. Figure 4 shows the location of this complex throughout the country [38].

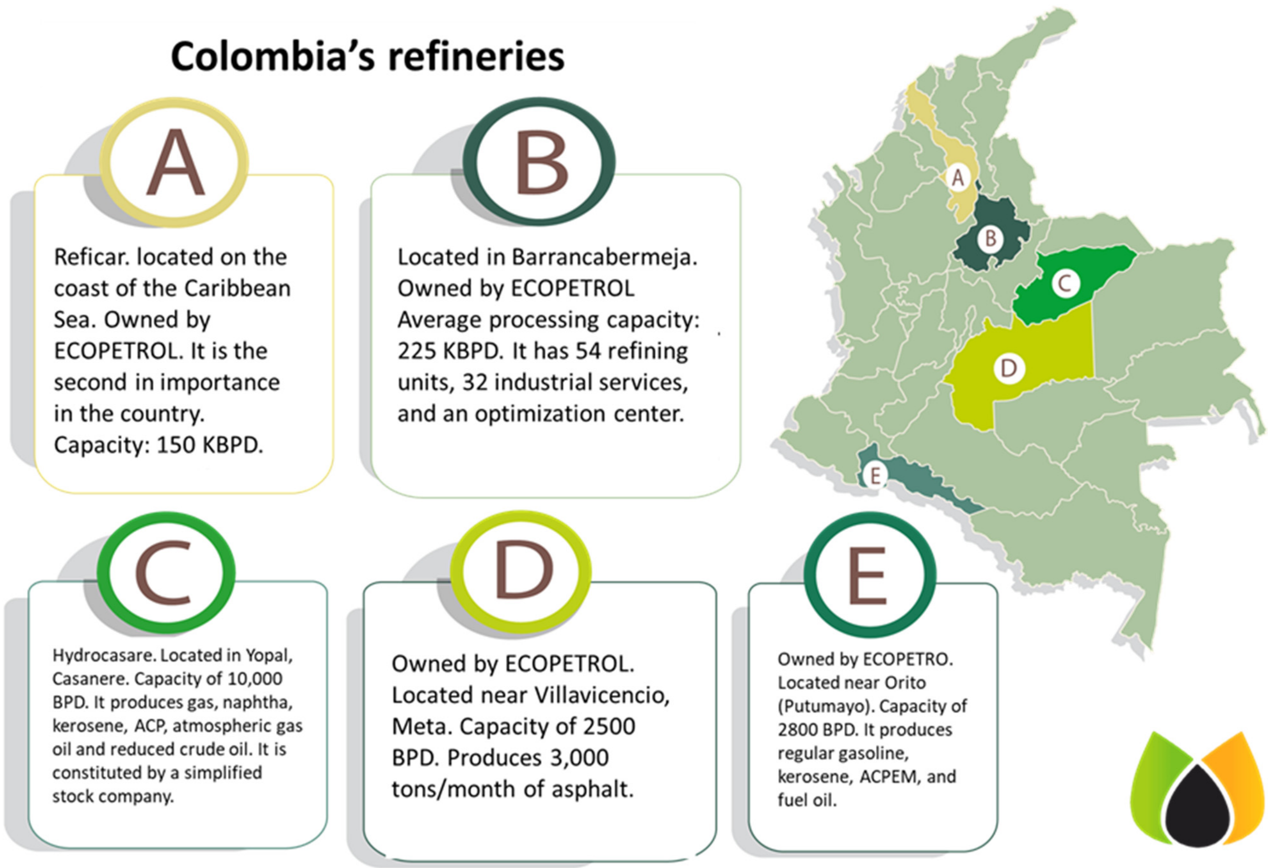


Figure 4. Refineries in Colombia [39].

Barrancabermeja refinery is located on the banks of the Magdalena River and has the highest capacity for transforming crude oil and petrochemistry [40]. The plant produces a nominal load volume of 250,000 barrels per day, supplying about 59.6% of national demand. Its configuration allows light crude processing with a medium conversion level, transforming 76% of the crude into light products and limiting the processing of heavy crudes (most of the Colombian production). Typical yields by mid-2021 were 1% for LPG, 24% for gasoline, 9% for jet, and 29% for diesel. This complex produces around 60.3% of gas, 57.8% of diesel, and 64% of jet required domestically [39].

Cartagena's refinery (REFICAR) is the second-largest refinery in the country, located on the Caribbean coast. It has a capacity of 165,000 BPD, a conversion yield of approximately 95%, and port infrastructure for loading and unloading products [38,39]. REFICAR can process heavy crudes with high sulfur content. Typical yields are 1% LPG, 19% gasoline, 7% Jet, and 52% for diesel. Cartagena refinery produces marine diesel, a fuel distributed exclusively for river and sea vessels on both coasts and for electricity generation in San Andres and Providencia [41]. One of the distributors of marine diesel is TERPEL, serving 15 ports with 23 marine terminals [42].

The article is structured as follows:

Materials and Methods: This section explains the PESTEL and ECOCANVAS tools, highlighting their significance in the analysis. Additionally, the existing technologies for the production of Sustainable Aviation Fuel (SAF) are presented, including their Technology Readiness Level (TRL). The section also includes an economic analysis and assessment of the production potential of SAF.

Results: This section presents the findings of the co-creation workshops and the application of the aforementioned tools. It showcases the collaborative work conducted in the workshops, which contributes to the development of the SAF implementation strategy. The results also include the net production potential of SAF in Colombia, considering the production of raw materials. HEFA, ATJ, and FT technologies with conversions and yields are reported in the bibliography, which were applied to mass balances.

Conclusions: The concluding section summarizes the most significant results and insights obtained from the study. It highlights the key findings and their implications for the article's main focus. These conclusions are derived from the evidence and arguments presented throughout the article, providing a cohesive and logical ending to the research.

In this context, and given its relevance, this article aims to make a diagnosis based on the PESTEL tool (which refers to the factors analyzed: Political, Economic, Social, Technological, Environmental, and Legal), supported by a review of the literature, for the implementation of the production of SAF [43]; thus, it is designed to have an updated overview of the execution of SAF in Colombia. Based on the above, it provides recommendations to mitigate the uncertainties identified and is complemented by the ECOCANVAS tool that applies to businesses related to the circular economy. It should be noted that previous studies have also investigated some of the main challenges of the SAF market in the world, which shows that the difficulties faced by emerging markets are not exclusive to Colombia [16,44]

The contribution of this article is to generate a diagnosis for future reference. This diagnosis will serve as an input for determining the value chain required for the implementation of Sustainable Aviation Fuel (SAF) production. The determination of this value chain will take into consideration the economic, social, and environmental context. The objective is to generate inputs that can meet the demand for SAF consistently in the future, while also reducing greenhouse gas (GHG) emissions in the medium term. Additionally, this work aims to contribute to local socioeconomic development through the establishment of new production chains. Furthermore, it seeks to optimize aeronautical logistics processes and position the biofuels sector at a regional level.

2. Materials and Methods

To deal with this methodology, the PESTEL framework is a strategic analysis tool, an acronym for the defined segments of the macro-environment: P for "political," E for "economical," S for "social," T for "technology," E for "environmental," and L for "legal". It begins with an analysis of technological surveillance; later, a verification of the most viable technologies is presented, supported by the previous investigation, and validated with the stakeholders, where proposals are made bearing in mind their limitations in order to obtain an understanding of how an option can be transformed into a real one. Subsequently, by its very nature, the project's sustainability is addressed as a mandatory point. For the strategy approach, the most relevant stakeholders are interacted with using the ECOCANVAS tool.

In the process of technological surveillance for the production of SAF, the stages are distributed by their level of development progress until commercialization worldwide (Figure 5), according to the Technology Readiness Level (TRL) classification [45], in which four initially feasible technologies are found due by the type of raw material used and availability in Colombia, as is the case of sugar cane, palm, banana, rice, cassava, corn, coffee, and soybeans, according to the Biomass Atlas [46] and updates from the Ministry of Agriculture: (i) hydroprocessing of esters and acids (HEFA); (ii) gasification with Fischer–Tropsch; (iii) Alcohol to Jet (ATJ); and (iv) co-hydroprocessing of esters and fatty acids in a conventional oil refinery [43]. However, a strategy is also required that involves private and governmental actors such as the Ministry of Mines and Energy, the Ministry of the Environment, the Ministry of Transportation, the Ministry of Finance and Public Credit, as well as Fedebiocombustible, ECOPETROL, IATA, and the Air Force.

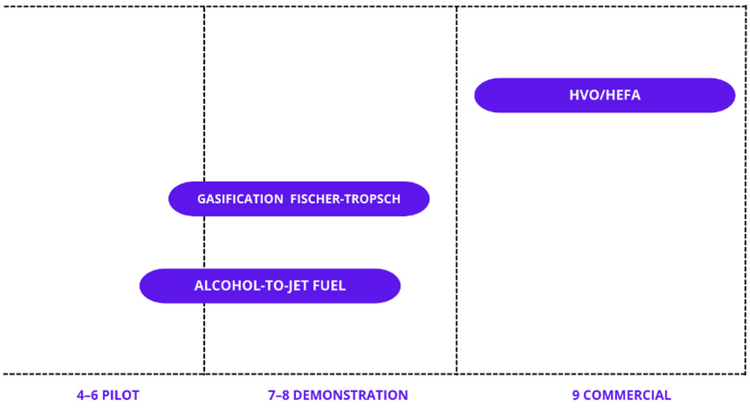


Figure 5. Sustainable Aviation Fuel (SAF) Technology Readiness Levels. Source: IRENA (2021) [45].

In the verification of the cost structure of the technologies, the CAPEX (Capital Expenditure), OPEX (Operational Expenditures), feedstock costs, and minimum fuel selling price are taken into account, according to Figure 6. With this, it can be concluded that the Fischer–Tropsch or Alcohol to Jet gasification technology, from garbage and organic waste, can develop in Colombia, despite being in a TRL 8, without reaching its complete commercialization phase, as indicated in (Figure 5) [45]. Following the above, under this technology, there is an opportunity to continue advancing in cost optimization. When evaluating this possibility with users of the COLAF as end users [47], in charge of controlling expenses in logistic support and meeting the goals at the sustainability level according to the strategic plan of 2042 [48], this technology is presented as one of the most optimal solutions to incorporate the final product into your logistics chain. On the other hand, generating added value to organic waste is part of the priorities within the National Circular Economy Strategy [49]. In this way, a double environmental impact is achieved, with a decrease in the carbon footprint and a reduction of the negative effect generated by organic waste.

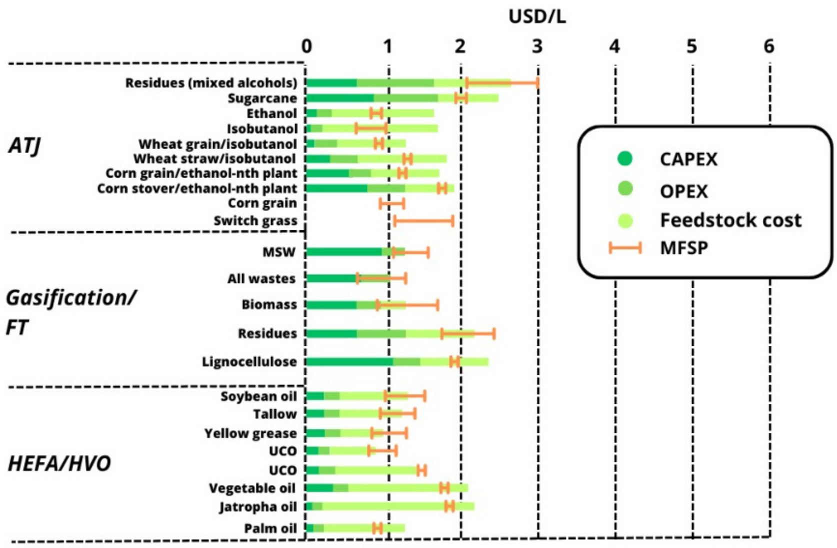


Figure 6. CAPEX/OPEX FEEDSTOCK analysis SAF technologies. Source: IRENA (2021) [45].

MFSP represents the break-even price at which fuel products must be sold to attain a zero NPV. It may include additional costs or benefits compared to the production cost, such as tax credits, additional infrastructure costs, environmental benefits, and by-product revenue [45].

Based on the above, sustainability is part of the conditions for implementing the SAF, making it transversal to all stages of project development from its approach, where Sustainable Aviation Fuel (SAF) must meet a set of sustainability indicators to ensure its viability in reducing greenhouse gas emissions in the aviation industry. These indicators are established by regulatory bodies and industry standards organizations, such as the International Air Transport Association (IATA) and ICAO [3]. SAF must reduce greenhouse gas emissions compared to conventional fossil fuels while avoiding causing land use change, significant water stress or depletion, harm to biodiversity, or negative impacts on human rights and local communities. It should also contribute to sustainable development and have traceability from the feedstock source to the end user to ensure compliance with sustainability criteria. By meeting these sustainability indicators, SAF production is environmentally, socially, and economically sustainable and helps promote a generally more sustainable aviation industry.

On the other hand, within CORSIA, the adopted baseline for Well to Wake (WTWa) emissions from conventional jet fuel production is 89.0 gCO_2e/MJ jet [50]. This value was agreed upon after considering a variety of refinery configurations worldwide for the production of fossil jet fuel and used for this work, where the SAF has to reduce at least 10% of LCA. Additionally, the raw material, the source of production of the SAF, must refrain from competing with food security or displacing another activity, which hinders the development of an economic sector. In this sense, the Roundtable on Sustainable Biomaterials (RSB) and ISCC International Sustainability Carbon Certification each, independently, [51] are responsible for verifying the accomplishment of mandatory selection guidelines for SAF feedstock generated by ICAO, within which are found land crops with a low carbon content that do not threaten food or water security. All of this favors the environment for the organic waste use in Colombia.

ECOCANVAS is a valuable sustainability tool for identifying and prioritizing the challenges and opportunities associated with implementing Sustainable Aviation Fuel (SAF) in Colombia's aviation industry. The framework can help stakeholders identify the sustainability indicators that SAF must meet and assess the potential impact of implementing SAF on reducing carbon emissions, improving local economic development, and reducing adverse effects on local communities and the environment. By identifying potential challenges and barriers, stakeholders can develop a strategy to overcome them and maximize the potential benefits of SAF implementation [52].

To land the strategies through the ECOCANVAS in the co-creation workshop [53], which was carried out at the facilities of the Colombian Air Force officers club, and to carry out an analysis of how to implement SAF in Colombia, among the guests were the following officials: Fedebiocombustible, BIOD, TERPEL, ECCI University, University National, IATA, and COLAF. The user stories were generated for workshop participants and validated with the following actors: government, clients, technical advisors, and industry. As a result, it was possible to show that the needs and challenges concerning the implementation of SAF in Colombia, which are exposed in the results of this article, are mutual.

The tests are supported by the reference [54], which concerns the formulation of scenarios supported by technological surveillance, interviews, discussion forums, field studies, and success stories, which had been validated and tested with relevant stakeholders. This will be conducted to find the strategy that manages to make the technology a real option by which to produce a SAF that meets international standards at a competitive price so that it can be incorporated into state and commercial aviation and achieve the interest of the different actors, thus positioning Colombia in the scenario of aeronautical sustainability from organic waste [47,55–58].

Within the diagnosis, in order to determine the gross SAF production potential, research of the production of different feedstocks was made, and a simulation also took place (this simulation was developed by [59]). For oils, especially palm oil production and Used Cooking Oil (UCO), a thesis was consulted; in it, an analysis of availability was carried out, in which the difference between production and demand was exposed for UCO [60].

Moreover, a compilation of information of lignocellulosic waste production in the country was made, see Table 4, taken from [61,62]. The information is separated into two groups, the waste that has more than 50% humidity; and the waste with lower than 50% humidity because of preference in technological conversion.

Table 4. Resume of lignocellulosic feedstock, adapted and supported in [61,62].

Crop Type	Production 2021	Residue Name	Residue Percentage	Residue/Year	Humidity
Sugarcane	27,155,902	Bud *	55.00%	14,935,746	68%
		Bagasse	45.00%	12,220,156	41%
Sugarcane (panela)	78,330,803	Bud *	64.00%	50,131,714	71%
		Bagasse	36.00%	28,199,089	41%
Rice	1,963,653	Chaff	53.70%	1,054,554	73%
		Husk	46.30%	909,099	4%
Oil Palm	1,725,835	Shell	15.00%	258,875	17%
		Fibers	20.00%	345,167	35%
		Palm rachis *	65.00%	1,121,793	58%
Corn	1,661,407	Stubble	59.00%	980,230	32%
		Cob	23.00%	382,124	27%
		Basket	18.00%	299,053	6%
Coffee	13,508	Pulp *	34.64%	4679	80%
		Cisco	3.35%	453	7%
		Stems	62.01%	8377	26%

* Humidity greater than 50%.

Furthermore, simulations were carried out to evaluate the potential of SAF generation in three technologies—HEFA, ATJ, and FT—which were made in three stages: conceptualization, implementation, and validation. The conceptualization was based on two parts: the search for information about the processes and feedstock, and the design of the simulation, the latter including the decision on which mathematical models to apply.

Regarding the mathematical model, mass balances were carried out to allow an approximation to the yields [59] using information collected from the literature mentioned in Table 5; since mass balances are primarily linear, is possible to derive efficiency factors (yields) based on feedstock characterization. The respective mass balances were made using the chemical reactions and their stoichiometry, or, failing that, elemental balances in more complex reactions such as oligomerization, hydrocracking and gasification, in which compositions were used in the products reported in Table 5.

Table 5. References of the simulation data [59].

Technology	Operation	References
HEFA	General	[63,64]
	Hydrolysis	[65]
	Deoxygenation	[66,67]
	Hydrocracking	[68–71]
ATJ	General	[6,44,72–74]
	Pretreatment y saccharification	[75]
	Fermentation	[76]
	dehydration	[77–80]
	oligomerization e hydrocracking	[81,82]
FT	General	[83]
	Gasification	[84–87]
	Fischer–Tropsch Reaction and Hydrocracking	[88,89]
General	Validation	[90–95]

The implementation of the simulations was developed according to the available information on the substances involved, such as the characterizations of feedstock similar to the Colombian ones. In the case of the oils for the HEFA route, it was necessary to know distribution of the fatty acids that compose the triglyceride on average [60]; and in the case of ATJ and FT, information on the type of lignocellulose, its cellulose, hemicellulose, and lignin content was necessary, including some calculations to obtain its carbon content and/or fermentable sugars [75]. Necessary information on the mass balances; information on the reactions, such as their stoichiometry or the already-mentioned distribution of the products; and the main design variables, such as conversion, selectivity, and operating conditions; in addition to other factors for the relationship between the currents of reagents and inputs and the main current regarding the feedstock, was also included. The lignocellulosic material with high humidity—since drying them would be inconvenient, they are destined for the ATJ process, and those with lower humidity are destined for the FT process—see Table 4.

Once the results were given, they were validated by comparing them with similar results reported by other authors (see validation in Table 5), and a sensitivity analysis of the design variables was also carried out in order to provide a verdict on the application of these technologies [59].

3. Results

This section shows, in detail, the analysis and results achieved for the phases established in the methodology, starting from the observation and understanding of actors, going through experimentation, and proceeding to the diagnosis of the proposal of a value chain for SAF implementation in Colombia. In the discovery phase, the map of actors was obtained in a co-creation workshop [53] to identify, in this way, the roles that each one of them plays, regardless of whether they belong to the government, the academy, or the state, as shown in (Figure 7). The above is intended to focus efforts on crucial actors (beneficiaries, users, and regulators) as part of the value chain proposal. On the other hand, the major technology providers of Sustainable Aviation Fuel (SAF) worldwide include Nestle, Honeywell UOP, World Energy, Gevo, Inc., and Velocys. These companies specialize in the production of SAF using various feedstocks, including waste oils and fats, renewable hydrocarbons, and biomass [96]. A line to connect users with beneficiaries is the Waypoint 2050, a vision for the future of aviation set forth by the International Air Transport Association (IATA) in 2019. It represents a long-term goal for the aviation industry to achieve net-zero carbon emissions by the year 2050. The initiative recognizes that aviation contributes significantly to global carbon emissions, and that urgent action is needed to reduce its environmental impact. It provides a framework for the industry to work towards carbon-neutral growth and ultimately achieve net-zero emissions. The initiative calls for implementing a range of measures, including Sustainable Aviation Fuel (SAF) development and use, improvements in operational efficiency, and investments in new technologies such as electric and hybrid aircraft [56].

Colombia has diverse potential feedstocks for producing Sustainable Aviation Fuel (SAF), including waste oils and fats, palm oil, agricultural residues [46], and municipal solid waste. However, the best feedstock for SAF production in Colombia may depend on several factors, including economic availability, sustainability, and viability. For this reason, the feedstock must be certified for RSB or ISCC. According to the above, to verify the accurate availability of raw materials, the Ministry of Agriculture plays an important role.

According to Figure 7, the difference between the end user and the beneficiary is that "end user" refers to those who use the SAF in their aircraft. However, according to the Colombia Carbon Neutral plan, the principal beneficiary is the government with the fulfillment of the decarbonization goals.

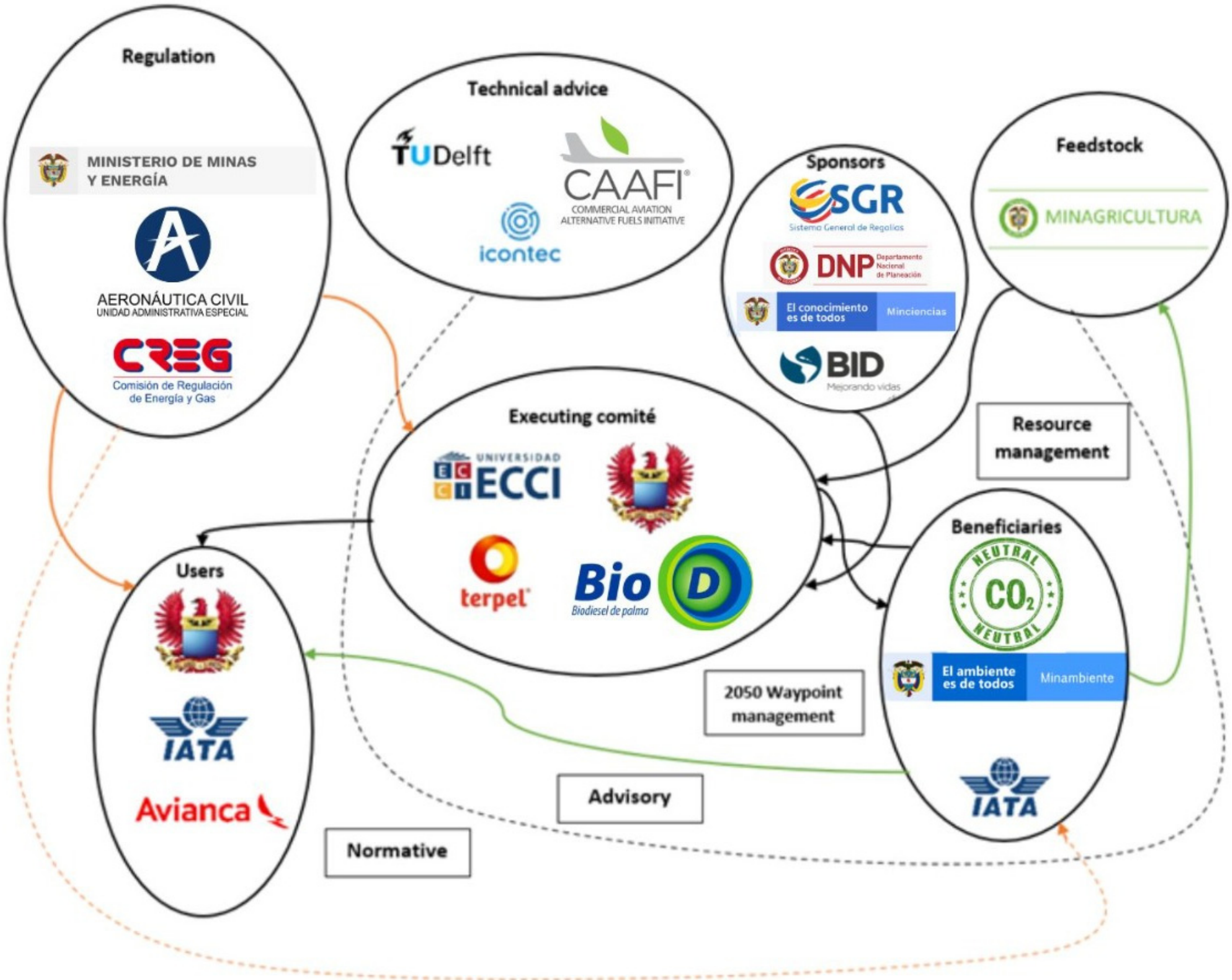


Figure 7. Map of SAF implementation actors Colombia 2021. Source: author.

After the identification of the actors, an analysis of the most relevant points within the environment is carried out, as well as the challenges that must be faced in order to implement SAF in Colombia using the ECOCANVAS tool within the co-creation workshop [52,53], the main characteristic of which is its triple perspective provided by the three additional blocks, which comprise the forces of environmental, legal, and social (Figure 8), resulting in this first iteration that the value proposition is the implementation of a SAF, sustainable at an environmental and economic level, where the flow of income to sustain the business also depends on the SAF, its by-products, and incentives directly related to the regulatory framework.

Thus, by anticipating the possibility of the society having a Fischer–Tropsch or ATJ gasification technology with which garbage and organic waste can be transformed into SAF, the generation of a positive impact is visualized with new productive chains and the adoption of a pattern of behavior that will favor the implementation of this project, where the regulatory framework is a significant resource for its viability.

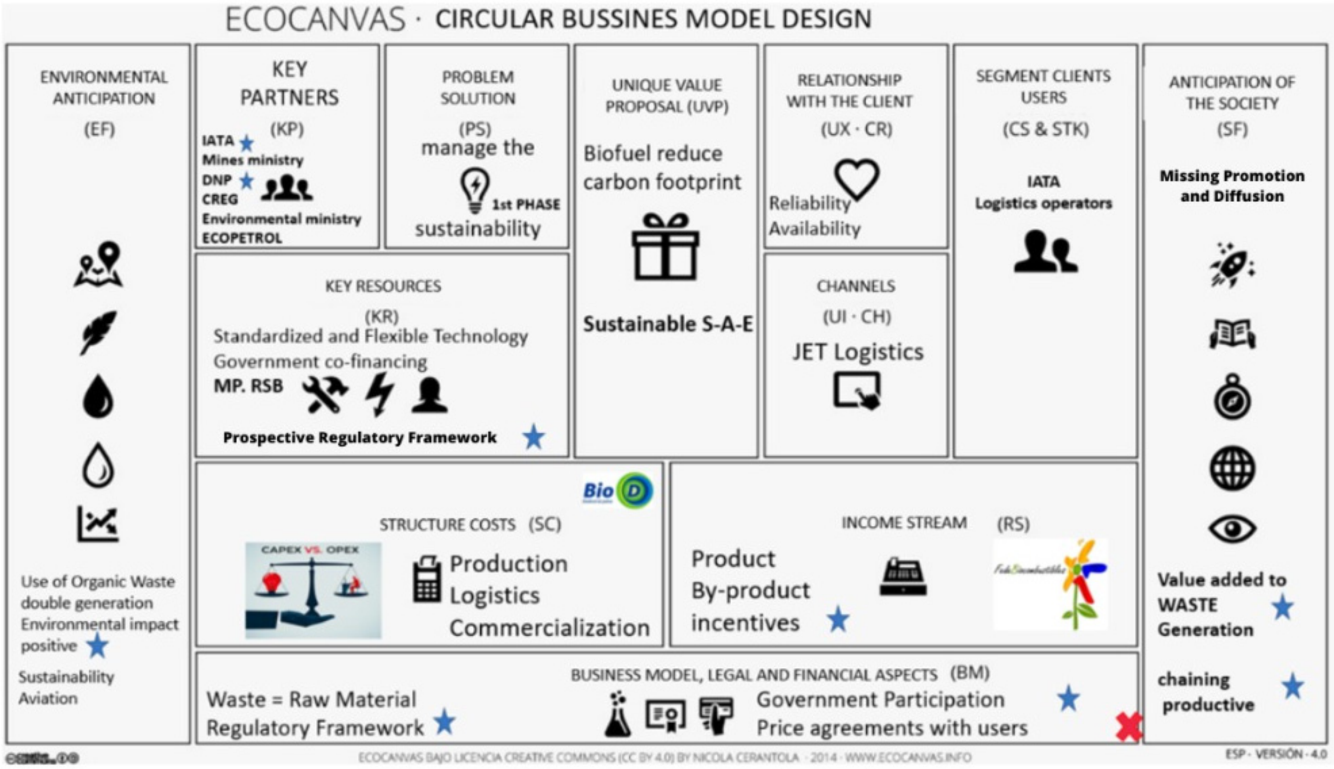


Figure 8. ECOCANVAS design of circular business models. Source: co-creation workshop [52,53].

As a result, it was possible to show that in order to achieve the implementation of SAF in Colombia, the mutual needs and challenges are as follows: (a) managing the technology capable of transforming organic waste; (b) having a competitive production cost; and (c) having a regulatory framework development that generates the appropriate ecosystem for its viability. The latter constitutes the basis for formulating a solid strategy that will bring the value chain proposal to a successful conclusion. This was validated through interviews with technical experts from CAAFI [96], TU DELFT [58], IATA [56], ECOPETROL [97], and FEDEBIOCOMBUSTIBLE [57]. Subsequently, by interrelating the challenges, it can be determined that the transaction cost to implement SAF in Colombia depends on (i) the cost and availability of raw material (CAAFI—Csonka Steve—Director Ejecutivo, 2021); (ii) the distribution and implementation logistics [57]; (iii) TRL of technology [58]; and (iv) a regulatory framework [56,58,96].

Based on technological surveillance, the verification of the cost structure of the technologies, CAPEX and OPEX, and the costs of raw materials indicated in Figure 6 was carried out [45], together with the type of raw material. Accounting for their use and sufficient availability in Colombia, according to the Biomass Atlas [46], the most viable technologies to implement are (i) Hydroprocessing of Esters and Fatty Acids (HEFA); (ii) gasification with Fischer–Tropsch; (iii) Alcohol to Jet (ATJ); and (iv) co-hydroprocessing of esters and fatty acids in a conventional oil refinery [14,17,20,22,23,43]. FT and ATJ have the highest added value due to their environmental component, an annual availability in Colombia that exceeds 10 million tons [46], and a cost below 1 USD per liter of SAF [45].

In consideration of the above, the choice of the gasification with Fischer–Tropsch and ATJ, despite being between a TRL 7 and 8 [45], because the components of the transaction cost, the ECOCANVAS analysis, the PESTEL, and user stories, is the one with the highest probability of becoming a real option. However, at the moment, it is an intermediate option, as the predictions of optimal strategies are made based on transaction costs. As for how to convert the production of SAF in Colombia into a factual possibility, the answer may involve adjusting the regulatory framework based on the current context; On the other hand, in the short term, co-processing will play an essential role on the international stage because ECOPETROL has sufficient infrastructure in the Cartagena refinery; hence, production can begin without making investments in infrastructure, which positions it as a viable option in the short term.

It will focus on the key actors and actions, adjusted to the Colombian context, where, in order of importance, the first is a regulatory framework, which will be in charge of regulating producers, quality, tax aspects, prices, mix ratio, promotion, and incentives [98] where the initial focus is regulation of, and incentives for, the entire logistics chain, including the end user, which will interact in the SAF price equation. Another point to take into account is that the price in an initial phase is not regulated, which will encourage the offer while the market consolidates.

It is worth noting that when analyzing the user stories, the majority agree that what is sought is to achieve the positioning of Colombia in the international scenario, reducing the carbon footprint and optimizing costs, together with the generation of new productive chains. For this reason, the Ministries of Mines and Energy, the Ministry of the Environment, the Ministry of Transportation, and the most important customers of aeronautical fuel at the state level, such as the Colombian Air Force (COLAF), and at the commercial grade, such IATA members, must be included in order for the value chain proposal to come close to a real option. Although the carbon tax in Colombia for aeronautical fuel is approximately 5 dollars per ton [25], it is below the 45 dollars paid in the Netherlands, where the book and claim system is a mechanism which allows for the certification and tracking of Sustainable Aviation Fuel production and enables airlines and other users of aviation fuel to support the development and use of SAF, even if they do not have direct access to a local producer. The above may be a strategy for Colombia to be competitive with respect to SAF implementation.

For the next iteration, work is being conducted with the District University to update the status of biomass (agricultural, organic, and urban waste) in Colombia (volumes, characterization, and location) so that the determination of production potential is adjusted to the Colombian context and reality, where, to date, there are 40 national airports, of which 14 are international, and two JET A-1 aeronautical fossil fuel production refineries. With this, the initial result of the study, supported by multivariate analysis, will show the volume and approximate locations of the four end user points, where 80% of national consumption is concentrated and where SAF can be produced for the end user at an affordable cost, guaranteeing sustainability throughout the chain, as shown in the example of Figure 9, where the Central, Atlantic Coast, Antioquia and Valle del Cauca areas with the Coffee Region are the starting points from which to continue with the iteration.

For the SAF implementation roadmap in Colombia, the study of biomass, technology, and logistics began to determine the potential production of SAF in Colombia, this being the input for the value chain proposal that will have a greater level of resolution because new actors related to the logistics chain were identified. It will be necessary to carry out a new iteration of the regulatory framework to have a proposal that serves as input for the acceleration phase. The generation of the regulatory framework contemplates policies for use, price, incentives, credits, and exemptions, which are significant actions that must be validated with end users and the government so that they adjust to the context.

On the other hand, PESTEL analysis is a tool with which to analyze the current and future environment in which it can manage the use, implementation, and production of SAF, as listed in Table 6.

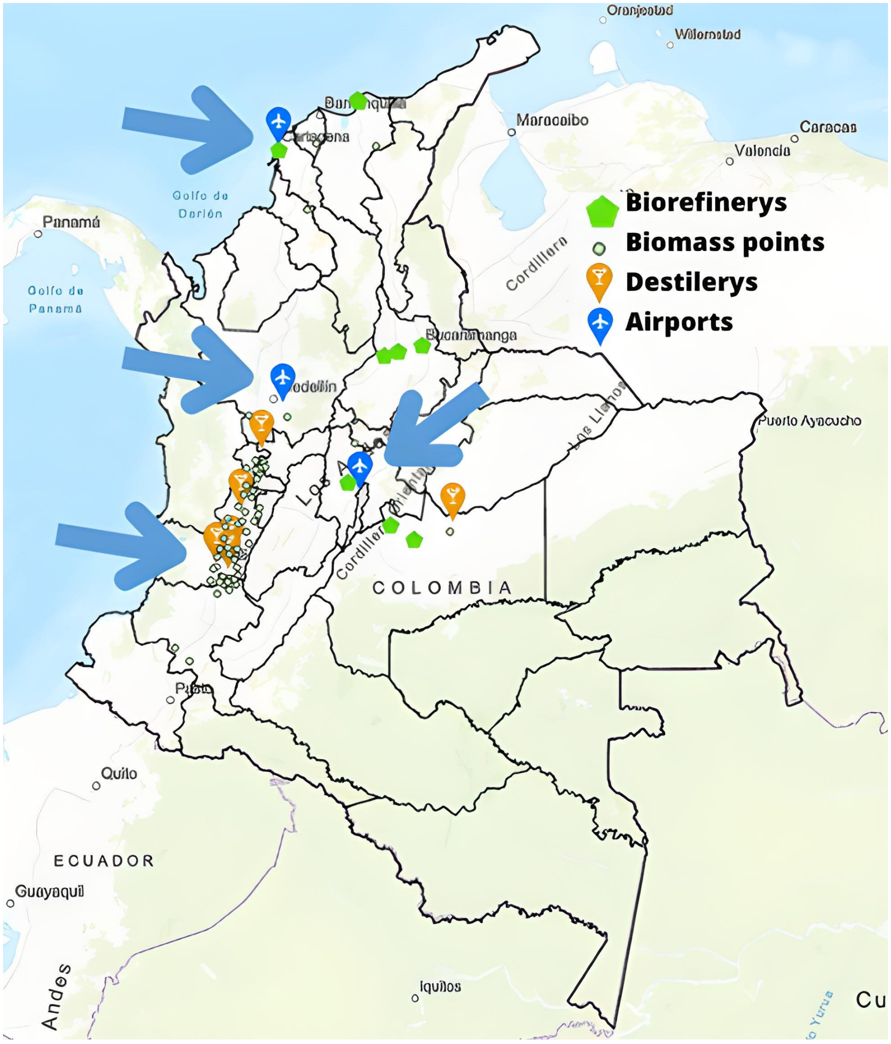


Figure 9. Potential example of SAF production in Colombia. Source: author supported, by RSB, AGROICONE PUBLISH STUDY TO SUPPORT SUSTAINABLE TRANSFORMATION IN BRAZIL WITH SAF [99].

Table 6. PESTEL diagnosis for SAF implementation in Colombia.

Factor	Analysis
Political	1. Government stability: Colombia has made significant strides towards stability in recent years, with the signing of a peace deal with the Revolutionary Armed Forces of Colombia (FARC) in 2016; 2. Guidelines: the government has established environmental guidelines and laws which could support the implementation of Sustainable Aviation Fuel in the country; 3. Corruption: corruption has been a long-standing issue in Colombia; it could pose a challenge to implementing sustainable aviation fuel if it impacts the government's ability to provide adequate support and incentives; 4. The assurance of the National Government to reduce the carbon footprint with its Colombia Carbono Neutral plan, which is proposed to reduce 51% by 2030 and reach carbon neutrality by 2050 [5]; 5. Inclusion of the issue of sustainability within the political agenda of the President, embodied in the National Development Plan 2022–2026, where the government will drive the development and use of SAF sustainable aviation fuel [24].

Table 6. *Cont.*

Factor	Analysis
Economic	1. GDP: Colombia has a growing economy, with a GDP of USD 323.7 billion in 2020; 2. Market demand: with the growth of air travel in the region, there is an increasing demand for aviation fuel; 3. Cost: Sustainable Aviation Fuel is currently more expensive than traditional fossil fuels, which could pose a challenge for implementation; 4. Non-oil country dependent on the royalties generated [97]; 5. Need for the economic viability of the SAF concerning fossil fuels by the Government; 6. Need for subsidies and support for the production of SAF [57]; 7. International commitments of WAYPOINT 2050 Net ZERO [56].
Social	1. Attitudes towards the environment: there is growing concern about climate change in Colombia, which could support the implementation of sustainable aviation fuel; 2. Public awareness: the general public's awareness of sustainable aviation fuel and its benefits may need to be improved, impacting adoption [100]; 3. Education and skill development: there is a need to educate and train stakeholders about sustainable aviation fuel and how it could be implemented in the country—the feedstock used in the SAF must guarantee food safety; 4. The implementation must seek the generation of new productive chains [101]; 5. Possible generation of a negative impact if agricultural activities are displaced by others that require less labor; 6. The difficulty in working on joint initiatives in the government.
Technology	1. Availability of technology: technology for producing sustainable aviation fuel is available, but it may not be widely adopted in Colombia. 2. Infrastructure: adequate infrastructure, such as refineries, may be required to produce sustainable aviation fuel in Colombia; 3. Innovation: there is potential for innovation in developing sustainable aviation fuel technology; 4. Technological certification under the standards of ASTM D7566 and ASTMD 1655 [19]; 5. Advancement of technologies between TRL 8 and TRL 9, such as HEFA and coprocessing, Fischer–Tropsch, and GT [45]; however, it is necessary to update the economic factors of Colombia; 6. There are ongoing studies on the inclusion of certified Colombian raw materials for the production of SAF, sponsored by the World Bank.
Environmental	1. Climate: Colombia is home to diverse ecosystems, and climate change could impact these ecosystems and the country's natural resources; 2. Air pollution: the aviation industry is a significant culprit to air pollution, and implementing sustainable aviation fuel could help reduce emissions; 3. Deforestation: the country has faced challenges with deforestation, which could impact the availability of sustainable feedstocks for producing aviation fuel; 4. The need to implement a sustainable aeronautical biofuel SAF [5]; 5. The controversy of increasing oil reserves by exploitation with non-traditional means [97]; 6. Comply with the ICAO International Civil Aviation Organization guidelines for sustainability in aviation [51]; 7. The feedstock must comply with the guidelines of ICAO, with the certification of RSB Roundtable Sustainable Biomaterials guidelines or International Sustainability Carbon Certification (ISCC).

Table 6. *Cont.*

Factor	Analysis
Legal	1. Environmental regulations: Colombia has established environmental standards and laws that could support the implementation of sustainable aviation fuel; 2. Intellectual property rights: the legal framework for intellectual property rights could impact sustainable aviation fuel technology development and adoption; 3. Tax incentives: the government could provide tax incentives for producing and using sustainable aviation fuel; 4. Law 336 of 2021 on climate change, Draft CONPES ENERGY TRANSITION POLICY; this commitment means progress in assigning responsibilities to key government actors to support the feasibility of an early phase of the SAF; 5. CONPES 3510 of 2008 Biofuel, a policy aimed at promoting the sustainable production of biofuels in Colombia, taking advantage of the economic and social development opportunities offered by emerging markets; 6. Law 1819 of 2016 Carbon tax requires companies to pay a tax on their greenhouse gas emissions—the carbon tax provides a financial incentive for companies to reduce their emissions and invest in sustainable practices, including using Sustainable Aviation Fuel (SAF); 7. CONPES 4075 Energy Transition Policy 4: pending laws for the implementation in production and use of SAF based on a diagnosis adjusted to the economic, social, technological, and environmental context.

On the other hand, concerning the approximation of the potential of SAF production, the feedstock was separated into lignocellulosic and oils, because for oils, see Table 7, the amount of feedstock taken to calculate the potential of SAF was a percentage of the total production of palm oil (5%), or the availability of UCO according to [60], while for lignocellulosic materials, see Table 8, the information of the net production is found in ref. [61].

Table 7. Simulation results of oil feedstock.

Feedstock	Production Ton/Year	SAF/Feedstock	SAF Production Potential Ton/Year	SAF Production Potential Gal/Year
Production of UCO	8866.00	44.30%	3927.64	1,284,372.89
Production of palm oil	87,604.79	43.70%	38,283.30	12,518,981.36
			TOTAL	13,803,354.26
			Demand Contribution	2.76%

Table 8. Simulation results of lignocellulosic feedstock.

Technology	Feedstock Ton/Year	SAF/Feedstock	Production Potential of SAF Ton/Year	Production Potential Gal/Year
FT	43,602,622.01	11.00%	4,796,288.42	1,568,429,382.94
ATJ	67,248,486.04	7.60%	5,110,884.94	1,671,305,269.15
			TOTAL	3,239,734,652.09
			Demand Contribution	647.95%

4. Analysis

Starting with the map of actors based on the roles they play around the implementation of SAF in Colombia, it was possible to show that it was more accurate when compared with the triple helix model (government, state, and academy) because, thanks to these, we were able to identify the functions, customer needs, and limitations accurately. Despite there being a clear goal of achieving sustainability by the primary users at the state and private level in Colombia, such as the COLAF and members of IATA, this will only be achieved if its cost center is not affected.

By including society within the map of actors and incorporating it with the Quadruple Helix model, it is possible that the proposal should not displace other economic models that start from the raw material that is going to be used, and this, in turn, tends to the generation of new productive chains, as proposed by the gasification technology with Fischer–Tropsch or ATJ. It should be noted that HEFA from palm oil requires a validation process by RSB or ISCC in order to be admitted as raw material, and the World Bank sponsored a project under development as of March 2023.

Subsequently, supported by user stories and based on analysis of the literature, it was identified that this transaction cost is viable if the liter of SAF is below 1 USD [45], which is mainly composed of the following: (i) cost and availability of raw material [96]; (ii) logistics of distribution and implementation [57]; (iii) technology TRL [58]; and (iv) regulatory framework [56,58,96], the last being one of those responsible for the feasibility and generation of the appropriate ecosystem for its implementation [96]. It should be noted that, when comparing with the literature in the Colombian case, typology, procedures, and times must be taken into account in the management of a document of the regulatory framework; thus, the way in which it will materialize must be accompanied by a strategy; the Ministry of Mines and Energy must lead it, initially, together with the end users (COLAF and IATA) [56].

Based on the above, an iteration with higher resolution must be carried out, supported by the determination of the production potential of SAF in Colombia, where the biorefineries must be concentrated at a point close to the airport so as not to impact the carbon footprint negatively. Likewise, the regulatory framework must generate incentives for organic waste generators, maintaining a balance in the formulation of the price, considering the unforeseen events generated with the incorporation of palm biodiesel in the ACPM in Colombia [98].

Despite obtaining, as a result, four plants located in the Central, Atlantic Coast, Antioquia, and Valle del Cauca with *Eje Cafetero* zones, it is necessary to identify if, with the change in the type of organic waste and environmental conditions typical of each of these points, Fischer–Tropsch gasification technology can maintain or improve efficiencies and obtain a standardized product that meets the specifications of ASTM D 1655 and ASTMD 7566 [19].

Within the roadmap in the regulatory framework, the use of policies, prices, incentives, credits, and exemptions were identified as crucial actions. However, by having a higher level of accuracy in determining the production potential of SAF, strategies can be generated for the use and consolidation of raw materials or research in the standardization of processes to achieve a lower SAF transaction cost.

The implementation of an adequate ecosystem is required for the management of technology transfer, so the field tests must be complemented with the available raw materials that simulate the levels of efficiency and quality of the final product as support for future work.

To conclude, debating and educating are among the stages of system dynamics [102] which will lead to the incorporation of new actors and the adjustment of the proposal to the Colombian context, where the Government must be the leading actor from the initial approach to its development [96]. We have identified, so far, the Ministry of Mines and Energy, the Ministry of the Environment, the Ministry of Transport, and the Ministry of

Finance, whose involvement must be accompanied by a strategy due to how the initiatives materialize in the Latin American countries [56].

The simulation results are in similar order to those reported by bibliographies, with small differences attributed to differences in feedstock and more specificity in the different stages. It can also be observed that lignocellulose in the Fischer–Tropsch route is more efficient; however, it is also known that this route has quite important requirements in energy matters; in any case, the approximation that was made.

Taking into account a demand of 500 million gallons of aeronautical fuel for oil feedstock, is it noted that 2.76% of said demand could be covered, which, although it may seem small, is an important contribution of about 13 million gallons per year; moreover, for lignocellulosic feedstock, the demand contribution is about 6 times the actual demand; however, it must not be forgotten that production is not equivalent to availability, which must be analyzed in the future, along with its economic and environmental factors.

5. Conclusions

- With the fieldwork, 25 actors, four technologies, and the components of the transaction cost were identified, reaching the point of having the bases to define the regulatory framework as the most relevant component for viability. Moreover, as it is iterated and interacts with the key actors, the form and strategy to generate a value chain proposal is identified, which adjusts to the Colombian context.
- Among the challenges for the implementation of SAF in Colombia are guaranteeing sustainability from the selection of the feedstock, transformation, transportation, and final use, where the amount of energy involved and the impact of the carbon footprint throughout the life cycle and having indicators that align with the requirements of ICAO and certified by RSB Roundtable on Sustainable Biomaterials or ISCC, and failing that, possible integration with chains supply of foreign airlines.
- The leading choice made in the optimal strategy predictions based on transaction costs was technology because, at the moment, in Colombia, neither HEFA with a TRL 9 nor Fischer–Tropsch with a TRL8 are a real option. However, the latter, together with Alcohol to Jet, generates a double environmental impact and is aligned with the National Circular Economy Strategy and the Colombia Carbon Neutral Strategy of the Ministry of the Environment because its raw material is organic waste and integrates sustainably into the aeronautical sector.
- The transaction cost is the decisive factor in Colombia by which to integrate SAF by clients, both at the state and private level (COLAF and IATA), where the regulatory framework plays a decisive role in the transformation of this factor, for which the policies of use, price, incentives, credits, and exemptions are part of the roadmap to turn SAF production technology in Colombia into a real option.
- An important aspect is that feedstock, even though they can be used within the research, must be certified by competent entities such as ISCC or RSB in order to be used on a large scale in such a large and demanding industry to ensure the quality and security of its inputs, especially palm oil.
- At the moment, the gross production potential for lignocellulosic feedstock was calculated based on production. However, it is necessary to submit it to some economic and environmental evaluation filters to find the availability of this material to be used in SAF production, which will be the subject of the following article, and it is necessary to do fieldwork to determine the real availability of the types of biomasses mentioned in this article.
- The viability of the SAF implementation in Colombia, according to the ECOCANVAS tool, cannot be analyzed only from the economic point of view; it must also be analyzed under the environmental, legal, and social components, where the government is the leading actor with the management of framework regulation so that the flow of income that sustains the business generates the incentives, credits, and exemptions. On the social side, having gasification Fischer–Tropsch technology that transforms

garbage and organic waste into SAF will have a positive impact, with new productive chains and the adoption of behavior patterns that will favor the implementation of this project.

- The book and claim system is a mechanism that allows for the certification and tracking of Sustainable Aviation Fuel production, enabling airlines and other aviation fuel users to support the development and use of SAF, even if they do not have direct access to a local producer. The above may be a strategy by which to make Colombia competitive in SAF implementation.

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