

TOWARDS A SYSTEM-OF-SYSTEMS ENGINEERING ROADMAP FOR INTEGRATING SUSTAINABLE AVIATION FUEL INTO MEXICO'S AIRPORT FUEL INFRASTRUCTURE

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Abstract

Sustainable Aviation Fuel (SAF) pathways require costly conversion, conditioning, hydrogen, certification and infrastructure activities; therefore, feedstock screening is needed before committing to long-term engineering or investment. A reduced-order Modelica model implemented in Wolfram System Modeler was first configured around agave bagasse from the tequila industry in Jalisco and later re-parameterized for barley straw and pelagic sargassum seaweed to test how contrasting biomass properties change preliminary SAF potential. Guadalajara International Airport is used as the demand reference, with 2% of the airport's total fuel demand used as a screening benchmark. A relative sensitivity analysis identifies available biomass as the strongest model driver, followed by moisture, alcohol/intermediate yield, and other variables. Under nominal production conditions, the barley straw waste from beer yields the highest potential for SAF with 6.52% of demand coverage, followed by partially conditioned agave bagasse covering 0.85% of the airport demand and finally sargassum with only 0.2% coverage. Barley straw performs best under the selected assumptions, but agave remains strategically relevant because its residue generation is concentrated in Jalisco and close to the selected airport. The model is positioned as the first quantitative decision gate of a broader System-of-Systems roadmap that can later incorporate logistics, conversion validation, certification, blending, storage and airport operations.

Keywords: Sustainable Aviation Fuel (SAF), agave production, sargassum, feedstock, system-of-systems

1. Introduction

Aviation decarbonization requires fuels that can be deployed within the existing fleet while longer-term propulsion alternatives continue to mature. SAF is attractive because qualified synthetic blending components can enter conventional aviation-fuel systems after the applicable technical, sustainability and blending requirements are satisfied [1–4]. However, conversion to SAF remains capital, energy and time consuming. Feedstock conditioning, hydrolysis or gasification, fermentation or intermediate production, upgrading, hydrogen supply, product fractionation, fuel qualification, logistics and airport integration can all require substantial investment [5–7]. Committing to those stages before confirming that a regional biomass resource is sufficiently available and convertible creates a risk of investing in a technically elegant pathway with an inadequate feedstock base.

Mexico provides a particularly relevant setting for early biomass screening. The state of Jalisco combines one of the world's most concentrated tequila-agave agroindustrial systems in close vicinity to the Guadalajara International Airport (GDL), while the national agricultural and beer economy also includes a substantial barley supply chain. At the opposite moisture extreme, recurrent pelagic sargassum arrivals in the Mexican Caribbean represent an environmental management challenge and a potential, although technologically difficult, carbon resource. These conditions make Mexico useful for comparing a locally concentrated wet residue, a relatively dry agricultural residue and a very wet marine biomass within the same decision framework [8]. The central research problem is

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therefore to determine therefore not only whether a biomass can theoretically be converted to SAF, but whether its available mass, moisture content and conversion performance are sufficient to justify the next and more expensive development stages. A transparent dynamic simulation can connect these upstream variables to potential SAF output and to a defined airport demand benchmark before laboratory campaigns, pilot facilities, long-term supply contracts or infrastructure modifications are initiated.

A reduced-order Modelica model can provide a practical preliminary feasibility filter by quantifying how biomass availability, moisture and conversion assumptions propagate into annual SAF output. The model was initially built around agave bagasse because of its regional relevance to Jalisco. Once the governing mass-balance structure was established, the same architecture was re-parameterized for barley straw (by-product of beer production) and sargassum seaweed, allowing the analysis to test whether the model can distinguish feedstocks that occupy very different moisture and availability regimes. The resulting screening layer is not a substitute for route-specific experimentation, techno-economic analysis, life-cycle assessment or fuel qualification. Its significance lies in reducing uncertainty before those investments are made. In the broader roadmap, this quantitative layer functions as an upstream decision gate that can later be connected to a System-of-Systems architecture covering feedstock suppliers, conversion facilities, certification, transport, blending, storage, airport fuel operations and airline demand [9, 10].

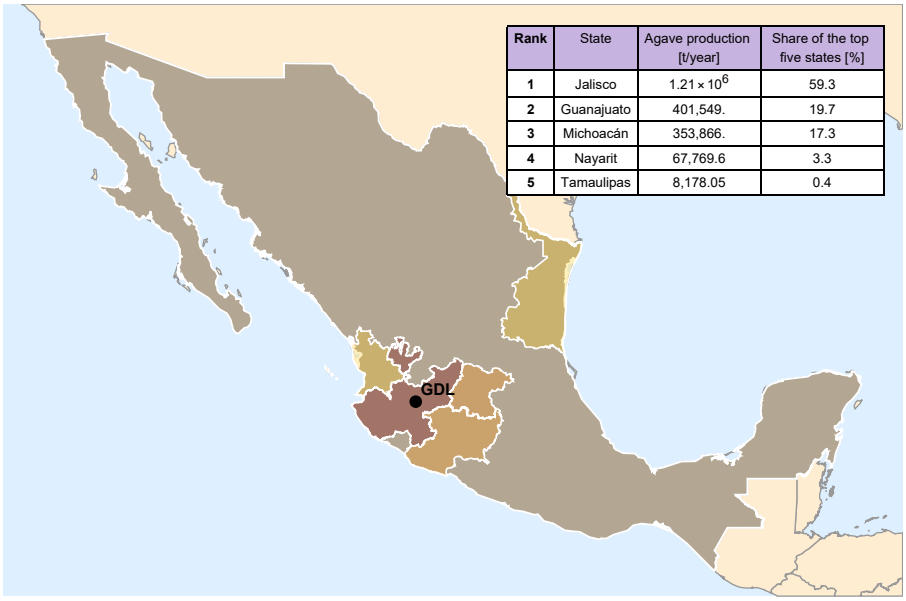
This work originates from a bachelor's project conducted by the first two authors under the supervision of the third author.

2. Background

This section provides a brief overview of the tequila and agave industries in Mexico, the generation of agave bagasse as a by-product of tequila production, and its potential conversion into SAF.

2.1 Tequila and agave scale in Mexico

Mexico's tequila industry provides a significant regional source of lignocellulosic residues for preliminary SAF assessment. In 2024, the industry produced 495.8 million L of tequila, exported 400.3 million liters (L) and processed approximately 1.8 million metric tons (t) of agave [8]. The geographic concentration of agave production is located mainly in western Mexico, as Fig. 1 shows. This strengthens the relevance of Guadalajara as a regional case because it combines a large agro-industrial base with proximity to Guadalajara International Airport (GDL).



Rank	State	Agave production [t/year]	Share of the top five states [%]
1	Jalisco	1.21×10^6	59.3
2	Guanajuato	401,549.	19.7
3	Michoacán	353,866.	17.3
4	Nayarit	67,769.6	3.3
5	Tamaulipas	8,178.05	0.4

Figure 1 – Geographic distribution and ranking of agave production among the five leading producing states in Mexico. Information from [8].

Published factors estimate approximately 694-720 kt/year of wet agave bagasse from the 2024 tequila industry [11]. Because fresh bagasse can retain high moisture, only part of this mass corresponds to dry convertible solids. This distinction between gross wet residue and useful dry resource is central to the screening problem and motivates the explicit treatment of moisture in the model.

2.2 Agave bagasse as a residue

A simplified diagram of the tequila production chain is shown in Fig. 2. Agave bagasse is generated inside the process after the piña (the agave cactus without its leaves) has been cooked, mechanically shredded or milled, and the soluble sugar-rich juice has been separated. The remaining fibrous solid contains cellulose, hemicellulose, lignin, residual sugars and water. Because the residue is already concentrated at tequila-processing facilities, it offers a more defined collection point than dispersed field residues, although its high moisture can increase handling and conditioning requirements [11–13].

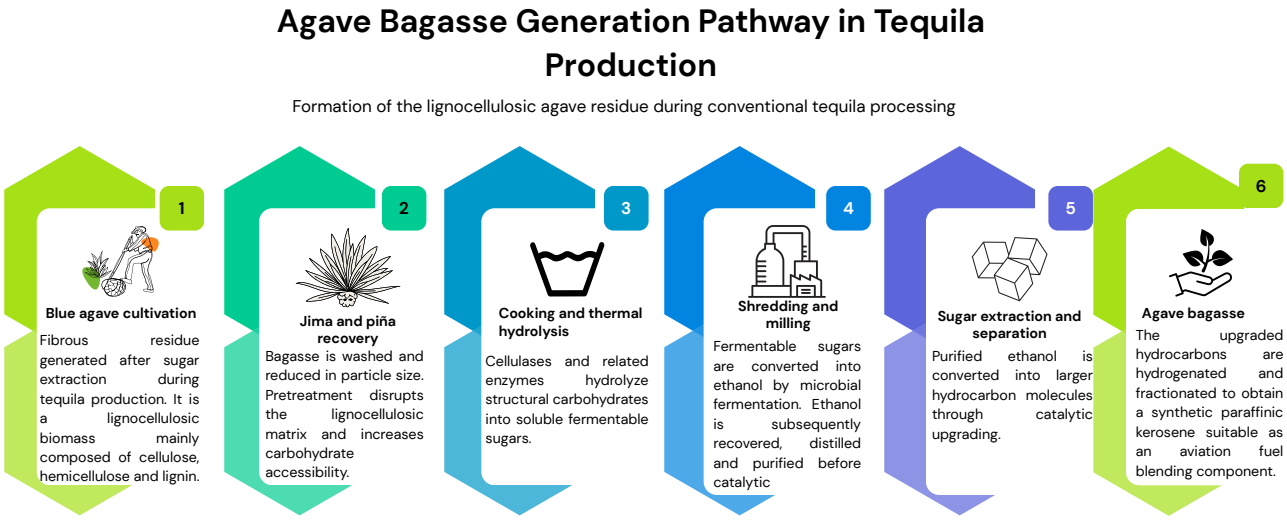


Figure 2 – Simplified tequila-processing sequence showing the point at which fibrous agave bagasse is generated after cooking, size reduction and sugar extraction.

For the Guadalajara case, this process location is relevant to the supply question since it is not the total amount of agave grown in Mexico, but the fraction of bagasse that can be obtained, recovered and transported from tequila facilities within a practical logistics radius. The 71 kt/year agave case used later is therefore treated as a local recoverable screening scenario.

2.3 From agave bagasse to SAF

The agave pathway considered for screening follows a lignocellulosic-to-alcohol route shown in Fig. 3. The bagasse is conditioned and pretreated, structural carbohydrates are hydrolyzed to fermentable sugars, a second-generation alcohol/intermediate is produced, and catalytic upgrading generates a jet-range hydrocarbon fraction. Alcohol-to-Jet (ATJ) provides the conceptual reference for this sequence, while the reduced-order model intentionally omits detailed kinetics and reactor design [3, 4, 13].

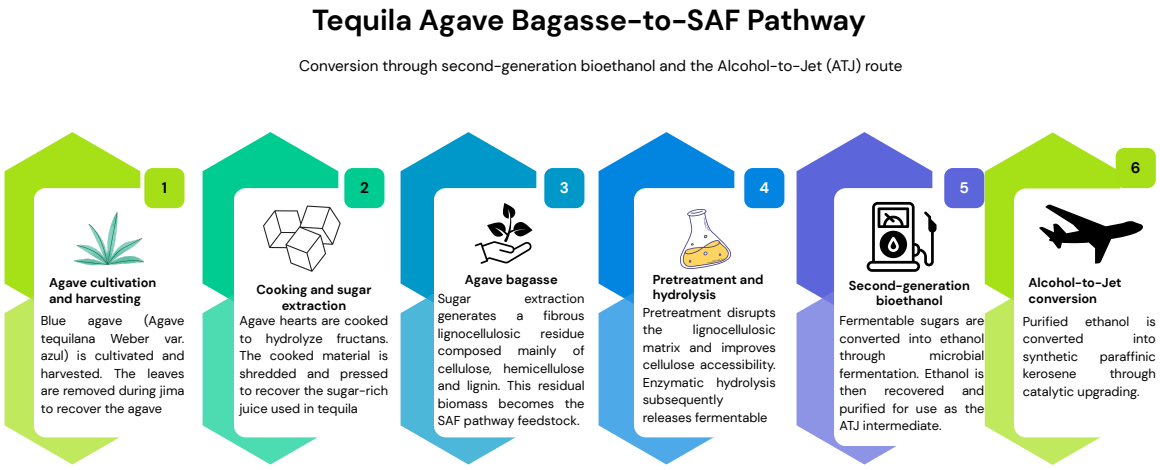


Figure 3 – Conceptual agave bagasse-to-SAF pathway through pretreatment, hydrolysis, second-generation alcohol production and Alcohol-to-Jet upgrading.

Two additional feedstocks were introduced to test the transferability of the screening logic. Mexico produced 832,299 t of barley grain in 2023; using a straw-to-grain ratio near 1.2 gives a gross straw order of magnitude close to 999 kt/year, although only a fraction can be removed without affecting soil protection, forage or existing uses [14, 15]. Barley straw is comparatively dry, with representative moisture values of roughly 6.5–11.4%, and therefore provides a useful low-moisture benchmark. The 300 kt/year model case corresponds approximately to a conservative 30% mobilization scenario rather than guaranteed supply. Pelagic sargassum provides the opposite boundary condition. Fresh material is commonly reported near 82–87% moisture and can also contain high ash, salts and trace metals; its carbohydrate composition differs from lignocellulosic straw and may require washing, demineralization and specialized biological conversion [16,17]. The 100 kt/year sargassum case is an illustrative screening quantity, not an estimate of dependable supply to Guadalajara. Its role is to test how the model responds to a highly wet, conversion-constrained feedstock that is environmentally relevant in the Mexican Caribbean.

3. Methodology

This section presents the methodology used to implement the Modelica model, define the input parameters, and estimate the resulting SAF production potential.

3.1 Model development and extension across biomass types

The quantitative model was implemented in Modelica using Wolfram System Modeler [18] and is shown in Fig. 4. The first configuration was created for agave bagasse and follows the sequence biomass input $\rightarrow$ conditioning $\rightarrow$ alcohol/intermediate production $\rightarrow$ fuel upgrading $\rightarrow$ SAF output $\rightarrow$ airport-demand coverage. Cost and simple profitability blocks were retained in the architecture for future extension, but the present results only use the physical screening outputs.

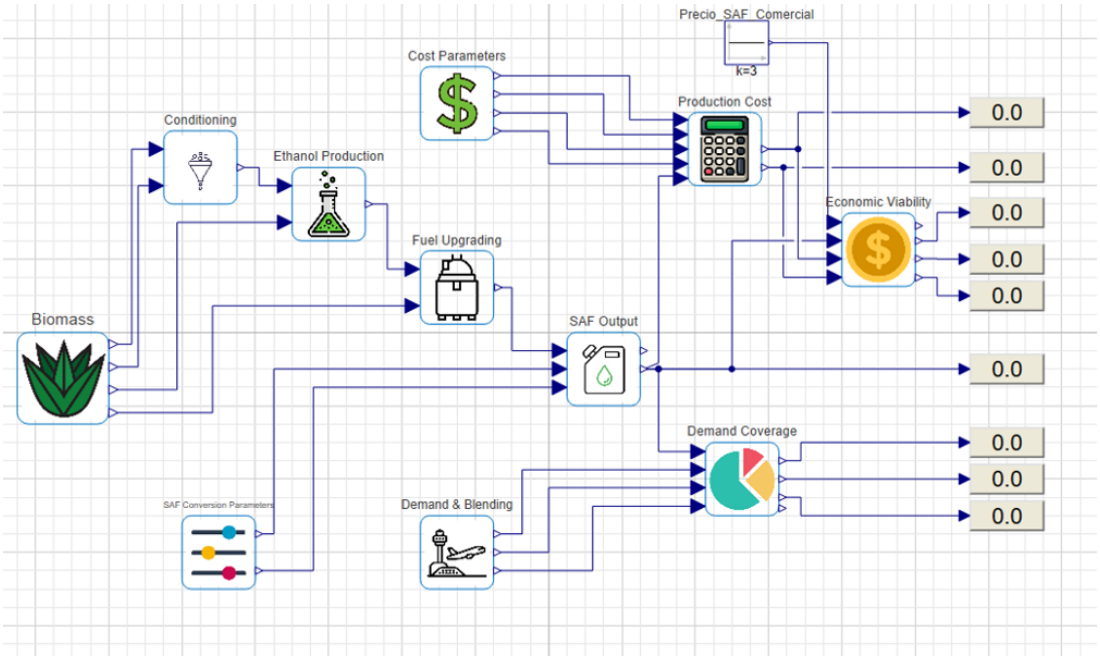


Figure 4 – Modelica model used for feedstock conditioning, SAF conversion screening, demand coverage and optional economic indicators, programmed in Wolfram System Modeler [18].

The architecture is intentionally modular. After the agave configuration was operating, only feedstock-dependent inputs needed to be re-parameterized to explore barley straw and sargassum at screening level. This does not imply that all three materials share the same physical pretreatment or fermentation route, but that the same mass-balance interface can be used to compare how moisture, available mass and an equivalent conversion yield influence the downstream SAF indicator. The blocks and outputs of the model are described in Table 1.

Table 1 – Functional description of the Modelica blocks and displayed outputs.

Model block / output	**Function in the simulation**
Biomass Scenario	Defines feedstock inputs such as available wet biomass, moisture content and conversion yield.
Feedstock Conditioning	Calculates the available dry biomass after accounting for wet-basis moisture.
Ethanol Production	Estimates the alcohol/intermediate mass produced from dry biomass using the selected yield.
Fuel Upgrading	Converts the alcohol/intermediate stream into total upgraded liquid fuel.
SAF Output	Applies the jet-range fraction and fuel density to calculate potential SAF volume.
SAF Conversion Parameters	Provides SAF-related constants, including jet fraction and fuel density.
Demand & Blending Parameters	Provides airport fuel demand and the selected SAF contribution target.
Demand Coverage Analysis	Calculates required SAF volume, target coverage and remaining deficit.
Cost Parameters	Provides screening economic inputs such as CAPEX, OPEX, feedstock cost and incentives.
Production Cost Analysis	Calculates total cost, net cost and estimated production cost per liter.

Model block / output	Function in the simulation
SAF Market Price	Defines the assumed SAF selling price used by the economic screening layer.
Economic Viability Analysis	Estimates revenue, margin per liter, total margin and simple profitability.
SAF Produced	Displays the calculated liters of SAF produced by the scenario.
Demand Coverage	Displays the contribution of the calculated SAF output relative to the selected demand reference.
SAF Deficit	Displays the remaining SAF volume needed to reach the selected target.
Cost per Liter	Displays the screening estimate of SAF production cost per liter.
Profitability Indicator	Displays whether the scenario is favorable under the selected price and cost assumptions.

3.2 Reduced-order mass-balance equations and nomenclature

The equations represent transparent screening balances assembled from the main biomass-to-SAF stages described in the literature [3, 4, 13]. Detailed chemical reactions and processes are not captured at this level of fidelity and are considered out of scope for this initial pre-screening study. The same equations are used for each feedstock, while feedstock-specific parameters are changed to represent different nominal conditions.

$$m_{\text{dry}} = m_{\text{wet}}\,(1 - x_{\text{moisture}}) \tag{1}$$

$$m_{\text{intermediate}} = m_{\text{dry}} Y_{\text{EtOH}} \tag{2}$$

$$m_{\text{fuel}} = m_{\text{intermediate}} y_{\text{upgrading}} \tag{3}$$

$$m_{\text{jet}} = m_{\text{fuel}} F_{\text{jet}} \tag{4}$$

$$L_{\text{SAF}} = \frac{m_{\text{jet}}}{\rho_{\text{jet}}} \tag{5}$$

$$L_{\text{required}} = D_{\text{airport}} Z_{\text{target}} \tag{6}$$

$$\text{Coverage} = \frac{L_{\text{SAF}}}{L_{\text{required}}} \tag{7}$$

$$\text{Deficit} = L_{\text{required}} - L_{\text{SAF}} \tag{8}$$

$$L_{\text{SAF}} = \frac{m_{\text{wet}}\,(1 - x_{\text{moisture}})\, Y_{\text{EtOH}} y_{\text{upgrading}} F_{\text{jet}}}{\rho_{\text{jet}}} \tag{9}$$

The nomenclature, symbol meaning and units used in Eqns. 1–9 are presented in Table 2.

Table 2 – Nomenclature used in Equations 1–9.

Variable	Symbol	Meaning	Units
Wet biomass mass	m_{wet}	Available wet biomass mass.	kg
Moisture fraction	x_{moisture}	Wet-basis moisture fraction.	–
Dry biomass mass	m_{dry}	Available dry biomass mass.	kg

Variable	Symbol	Meaning	Units
Ethanol yield	Y_{EtOH}	Dry-biomass-to-alcohol/intermediate yield.	–
Intermediate mass	$m_{\mathrm{intermediate}}$	Produced alcohol/intermediate mass.	kg
Upgrading yield	$y_{\mathrm{upgrading}}$	Upgrading mass yield.	–
Fuel mass	m_{fuel}	Total upgraded fuel mass.	kg
Jet fraction	F_{jet}	Fraction of upgraded fuel in the jet-range cut.	–
Jet fuel mass	m_{jet}	Jet-range fuel mass.	kg
Jet fuel density	ρ_{jet}	Jet-range fuel density.	kg/L
SAF volume	L_{SAF}	Potential SAF volume.	L
Airport demand	D_{airport}	Annual aviation-fuel demand at the reference airport.	L/yr
Target fraction	Z_{target}	Selected SAF contribution fraction.	–
Required SAF volume	L_{required}	SAF volume required to satisfy the selected target.	L/yr
Coverage	$\mathrm{Coverage}$	Ratio between potential SAF output and the selected target.	–
Deficit	$\mathrm{Deficit}$	Difference between required and potential SAF volume.	L/yr

3.3 Feedstock parameterization and sensitivity study

A sensitivity study was conducted where the relative influences of five model inputs on annual SAF production were compared. Parameter sweeps of reasonable ranges were applied to biomass availability, moisture, alcohol/intermediate yield, upgrading yield, and F_{jet}, and the resulting influence values were normalized to the largest response. The index is therefore a scenario-dependent comparative sensitivity indicator whose purpose is to identify which variables deserve the strongest data-quality effort before detailed engineering.

The values used for the feedstock evaluation are presented in Table 3. A common upgrading yield of 0.65 and jet fraction of 0.70 were retained so that differences in the comparison are driven primarily by feedstock availability, moisture, and conversion yield. Guadalajara International Airport's (GDL) annual aviation-fuel demand was determined to be 418 million L/year for 2023 [19].

Table 3 – Nominal input parameters for the selected feedstocks.

Feedstock	Dry biomass [kt/year]	Nominal humidity [-]	Wet biomass [kt/year]	Humidity range [-]	EtOH yield [-]
Barley straw	265.8	0.114	300.0	0.065–0.114	0.18
Sargassum	15.0	0.850	100.0	0.820–0.870	0.10
Agave	24.9	0.650	71.0	0.650–0.800	0.25

4. Results

This section outlines the results of the sensitivity analysis and the nominal evaluation for barley straw, sargassum, and agave.

4.1 Relative sensitivity of annual SAF production

The sensitivity study results shown in Figure 5 identify available biomass as the strongest driver of annual SAF production, with a normalized relative influence of 1.00. Moisture is the second most influential parameter, with a relative influence of 0.73. Its importance is physically intuitive because water increases handled mass while reducing the dry fraction that can enter conversion. The effect is especially important for wet residues such as agave bagasse and for very wet resources such as sargassum. Ethanol/intermediate yield follows with 0.48, showing that pretreatment and biological

conversion performance remain a major technical lever after the resource itself has been secured. F_{jet} has a relative influence of 0.35, while upgrading yield is lower in this selected screening at 0.21. These values do not imply that downstream upgrading is unimportant; rather, under the perturbations used here, uncertainty in the upstream feedstock condition dominates the preliminary output more strongly.

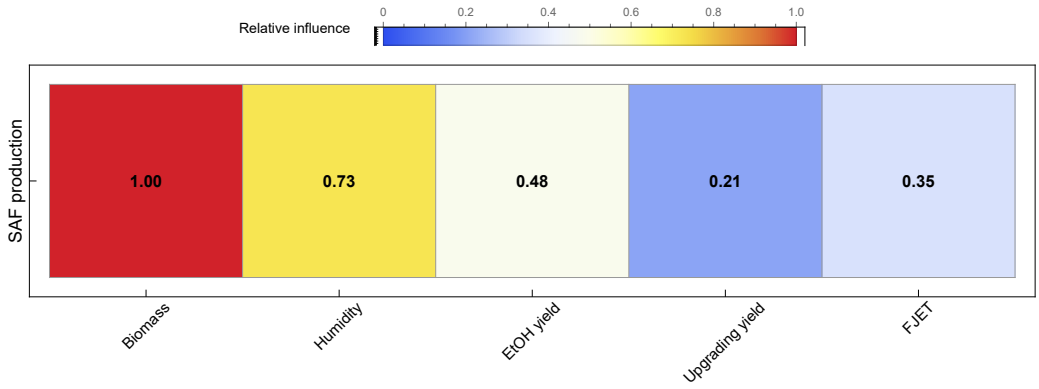


Figure 5 – Relative sensitivity of annual SAF production to the principal screening inputs. Influence values are normalized to the largest response in the selected sensitivity test.

The ranking therefore establishes a practical data-priority sequence: first quantify recoverable biomass, then characterize moisture, and then reduce uncertainty in conversion yield. Those three parameters should be measured or validated before committing to expensive pilot campaigns, hydrogen systems, refining equipment or airport-side infrastructure. The result supports the central role of early simulation as a way to direct limited engineering resources toward the scenarios with the strongest preliminary basis.

4.2 Comparative screening of agave bagasse, barley straw and sargassum

Table 4 shows the results of the model with the nominal values discussed in Sec. 3.3. Figure 6 compares the estimated SAF production from agave (green), sargassum (orange), and barley straw (blue). The x-axis shows the available wet biomass, while the left and right y-axes show SAF production and GDL airport demand coverage, respectively. The solid lines represent the nominal humidity values, while the shaded areas indicate the expected humidity ranges. The markers indicate the estimated SAF production at the nominally available wet biomass for each feedstock. The 2% screening benchmark for the Guadalajara airport is highlighted in red on the left y-axis.

Table 4 – Nominal SAF production results for the selected feedstocks.

Feedstock	**Dry biomass [kt/year]**	**Overall conversion [%]**	**SAF production [kt/year]**	**SAF production $[10^6$ L/year]**	**Demand coverage [%]**
Barley straw	265.8	7.26	21.77	27.21	6.51
Sargassum	15.0	0.68	0.68	0.85	0.20
Agave	24.9	3.98	2.83	3.53	0.85

Barley straw produces the highest output under the selected assumptions. At 300 kt/year and 11.4% nominal moisture, approximately 265.8 kt/year remain as dry biomass. With $Y_{\mathrm{EtOH}} = 0.18$, $Y_{\mathrm{upgrading}} = 0.65$, and $F_{\mathrm{jet}} = 0.70$, the model calculates 21.77 kt/year of SAF, equivalent to 27.21 million L/year or approximately 6.51% of total GDL annual fuel demand. Because the 2% benchmark is 8.36 million L/year, this nominal barley scenario exceeds the benchmark by more than a factor of three. This highlights the strong advantage of a low-moisture biomass when sufficient sustainable supply is available.

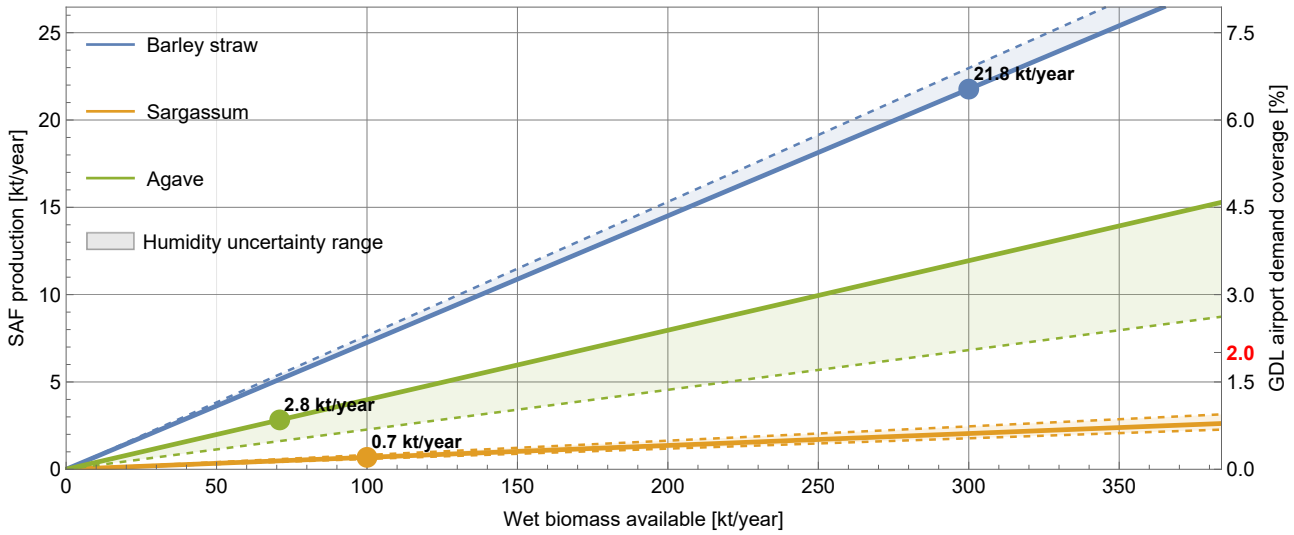


Figure 6 – Comparative feedstock screening for barley straw, sargassum and agave bagasse. The upper panel summarizes nominal inputs and calculated outputs; the lower panel shows SAF production versus wet biomass availability and the 2% GDL screening benchmark.

Agave bagasse occupies an intermediate position. The nominal 71 kt/year case at 65% moisture contains about 24.9 kt/year of dry biomass. Its higher alcohol/intermediate yield of 0.25 partially compensates for the smaller dry fraction, producing approximately 2.83 kt/year or 3.53 million L/year of potential SAF. This equals roughly 0.85% of total GDL demand and about 42% of the selected 2% benchmark.

Sargassum represents the high-moisture extreme of the feedstocks analysed. At 100 kt/year and 85% moisture, only about 15 kt/year remain as dry matter. Combined with the lower screening yield of 0.10, the model produces approximately 0.68 kt/year or 0.85 million L/year of potential SAF, equivalent to about 0.20% of total GDL demand. The result illustrates the combined penalty of high humidity and uncertain conversion performance. Sargassum can still be relevant as a waste-management and research feedstock, but its seasonal supply, salt and ash content, metals, and route-specific biology require a dedicated system boundary before it can be treated as a dependable SAF resource [16,17].

Results show that the approximate wet-biomass amounts needed to reach the same 8.36 million L/year benchmark are about 92 kt/year for barley straw, 168 kt/year for the agave scenario, and close to 984 kt/year for the sargassum scenario.

5. Discussion

The following sections provide a discussion of the results and their applicability to Mexico, method limitations and future work.

5.1 Biomass selection in Mexico

The comparison expands the interpretation beyond a single residue without displacing the original agave case. Mexico's tequila industry creates a concentrated lignocellulosic stream in Jalisco, while national barley production provides a much drier agricultural residue class associated with a large beverage and malting economy. At the other extreme, recurrent sargassum influxes in the Caribbean create an environmental management problem characterized by very high moisture and challenging composition. Using all three scenarios makes it possible to compare a relatively dry feedstock, an intermediate wet agroindustrial residue, and a very wet marine biomass within the same screening framework. Barley straw performs best in the nominal model, but feedstock selection could depend on many other factors. Sustainable straw removal, geographic dispersion, competing soil and forage functions, collection seasonality and transport still need to be verified. Agave bagasse produces less SAF per nominal scenario, yet its concentration at tequila facilities and proximity to GDL can improve the practical supply architecture. Sargassum performs poorly as a direct GDL feedstock under the

selected assumptions, but the result is useful because it shows how quickly humidity can surpass gross mass availability.

5.2 From feedstock screening to a System-of-Systems roadmap

The screening model represents a possible first quantitative layer of a broader System-of-Systems (SoS) simulation of the region. A deployable SAF chain would require autonomous stakeholders and subsystems for feedstock ownership, collection, conditioning, conversion, fuel qualification, sustainability certification, transport, blending, storage, airport fuel operations and airline demand. The present model does not yet simulate those subsystems explicitly; instead, it provides an upstream gate that can prevent resources from being committed to a complex integration program before the feedstock case is credible [9, 10]. Future model development can progressively convert the currently conceptual interfaces into computational blocks for dewatering energy, transport distance, monthly feedstock availability, tank inventory, blending schedules, batch traceability and airport dispatch. This stepwise expansion is particularly important because the preferred supply architecture may differ by feedstock: agave could favor a Jalisco-centered collection hub, barley straw may require a dispersed agricultural logistics network, and sargassum would require a coastal preprocessing system before any inland fuel pathway is considered. In this sense, the present screening is a first sketch of the SoS roadmap rather than a complete airport-integration model.

5.3 Limitations and next steps

The results are preliminary screening outputs and depend on scenario values not intended to be a complete supply chain analysis. The 71 kt/year agave case must be replaced by verified plant-level availability; the 300 kt/year barley straw availability case requires assessment by region; and the 100 kt/year sargassum case is illustrative and does not represent dependable annual delivery to Guadalajara. Likewise, Y_{EtOH} is used as an equivalent conversion parameter and does not imply that the three feedstocks can use identical pretreatment or fermentation systems. The next research stage should couple feedstock-specific characterization with a deeper System-of-Systems analysis for a complete techno-economic analysis. This could include geographiocally dispersed supplier inventories, seasonal moisture distributions, preprocessing energy, route-specific laboratory yields, transport and storage models, and explicit airport blending and storage interfaces. These additions would allow the current screening layer to evolve into the full roadmap implied by the title while retaining the same auditable decision logic.

6. Conclusions

Early SAF planning benefits from supporting feedstock selection through modelling and simulation before committing to expensive conversion and airport-integration activities. Results show that recoverable biomass quantity is the dominant screening variable, followed by moisture and conversion yield. This ranking explains the results for the nominal case of Guadalajara in the Jalisco region: low-moisture barley straw produces the strongest output, very wet sargassum is heavily penalized, and agave bagasse lies in an intermediate position. For the Guadalajara case, agave remains important even though it is not the highest-output feedstock in the comparison. Its value lies in the concentration of tequila production and residue generation in Jalisco, proximity to GDL, and the possibility of building a regional collection and conversion architecture around an existing industrial cluster. The comparison with barley straw and sargassum demonstrates that the same screening model can expose trade-offs among quantity, moisture and yield before more costly studies begin. These results form the first quantitative gate of a future System-of-Systems roadmap for SAF integration in Mexico.

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