Potential of Agave Sisalana in the Brazilian Semi-Arid Region for Ethanol and Biogas Production

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Abstract:

This study aims to conduct a bibliographic assessment of the potential of agave as a raw material for biofuel production in the Brazilian semi-arid region, considering agronomic, technological, and environmental aspects. Agave, a plant native to arid and semi-arid regions, stands out for its high biomass productivity and ability to adapt to conditions of low water availability. These characteristics make it a promising alternative for the sustainable production of biofuels, especially in areas less suitable for conventional agriculture. Unlike traditional crops such as sugarcane, agave cultivation does not compete directly with food production, which contributes to food security. Studies show that agave species can achieve ethanol yields of between 7,400 and 10,000 liters per hectare, which is competitive with or higher than the yields obtained from sugarcane in dry regions. In addition to ethanol, the bagasse and residual juice from the leaves can be used to generate biogas and biomethane, expanding energy utilization routes and assisting in the management of agro-industrial waste. Thus, agave has strategic potential to strengthen the renewable energy matrix, generate socioeconomic and environmental benefits, and contribute to climate change mitigation goals.

Keywords: *Biofuels. Sustainability. Efficiency. Energy.*

1. Introduction

Recent studies have shown that Agave species have a high potential for conversion into biofuels, reaching ethanol productivities comparable to or even higher than sugarcane in semiarid regions, in addition to significant methane yields from leaf juice [1]. Strategic initiatives, such as the Brazilian Agave Development Program (BRAVE), have fostered research and the development of technologies aimed at harnessing agave as a renewable energy source, reinforcing its importance in the national energy matrix [2].

The growing demand for energy and concern about climate change have led to a search for renewable and sustainable energy sources. In this regard, biofuels present themselves as an alternative to fossil fuels, since they offer the chance to reduce greenhouse gas emissions, in addition to promoting rural development [3]. Brazil, with its large area and diversity of biomes, has enormous potential to produce biofuels from various raw materials. Sugarcane and corn have traditionally been the main sources for producing ethanol, while agro-industrial waste is used to produce biogas. Corn produces about 2,500 liters of ethanol and up to 18,540 m³ of biogas per hectare, generating between 6 and 12 tons of crop residues per hectare, such as stalks, leaves, and cobs, which can be used for energy generation. Sugarcane, on the other hand, has a productivity of around 7,000 liters of ethanol per hectare, generating approximately 280 kg of bagasse and straw for every 1,000 kg of processed cane. Vinasse, a liquid waste produced on a large scale in Brazil (around 360 billion liters/year), is used in the production of biogas and biomethane, where it is used to replace natural gas. In addition, the dispute over land that can be used for cultivation and over more water resources for food production has sparked debates about the sustainability of these crops [4]. In this case, the search for new raw materials that do not compete with food and are ready for difficult climate conditions becomes very important. Agave Sisalana is a succulent plant that comes from dry and semi-arid regions, and has shown great potential for producing biofuels. Its particular resistance to drought, high mass, and ability to store fermentable sugar make it a strategic choice for places such as the Brazilian semi-arid region, where water scarcity is a major problem for normal agriculture [5]. In addition, we have observed that agave sisalana shows promising potential for biofuel production, especially in the semi-arid regions of Brazil. Estimates indicate that agave can produce about 7,400–10,000 liters of ethanol per hectare per year. These yields are competitive with sugarcane, especially in regions with limited water resources.

Agave, a plant adapted to arid and semi-arid regions, has high biomass productivity, low water consumption, and does not compete directly with food crops, characteristics that make it a strategic alternative for energy transition. This study aims to conduct a bibliographic evaluation of the potential of agave as a raw material for the production of biofuels in the Brazilian semi-arid region, considering agronomic, technological, and environmental aspects.

2. Agave as a Product for Biofuels

Agave spp. is a perennial plant highly adapted to poor soils and low rainfall conditions, typical characteristics of arid and semi-arid regions. The high water efficiency of agave is attributed to crassulacean acid metabolism (CAM), an adaptive biochemical mechanism that optimizes water use in arid and semi-arid environments. During the night, when the temperature is lower and the relative humidity is higher, the stomata remain open to allow carbon dioxide (CO_2) to enter, minimizing water loss through evapotranspiration. CO_2 is initially fixed by the enzyme phosphoenolpyruvate carboxylase (PEPC) in the cytoplasm, forming oxaloacetate (OAA), which is rapidly converted to malate by a malate dehydrogenase. Malate is then stored in cell vacuoles in the form of organic acids. During the day, with the stomata closed to prevent water loss, malate is transported to the chloroplast, where it is decarboxylated to release concentrated CO_2, which is fixed again by Rubisco in the Calvin cycle, allowing the synthesis of carbohydrates. This temporary carbon fixation system maximizes CO_2 assimilation and drastically reduces transpiration, giving agave high water use efficiency, which is essential for its survival and productivity under water stress conditions. In addition to its resilience in adverse environments, agave accumulates large amounts of carbohydrates in the form of fructans, predominantly inulin, stored in its stem and leaves. Biochemically, inulin is a polysaccharide formed by chains of fructose units linked by β (2→1) bonds, with a terminal glucose molecule, which serves as an energy reserve. These polymers can be hydrolyzed by specific enzymes called inulinases, which break the glycosidic bonds, releasing simple sugars such as fructose. These sugars are then fermented by microorganisms, mainly yeasts of the genus Saccharomyces, which metabolize fructose via glycolysis, converting it into ethanol and carbon dioxide, a process known as alcoholic fermentation. After the extraction of fermentable sugars or fibers, the residual bagasse remains rich in lignocellulosic material and other organic compounds. This residue is a viable substrate for biogas production through anaerobic digestion, a microbial process in which complex polysaccharides are initially degraded into simple sugars, fermented into organic acids, and finally converted into methane and carbon dioxide by methanogenic microorganisms. In this way, the energy use of the crop is expanded, promoting the integration of sustainable bioenergy routes. [6].

2.1. Potential for Ethanol

The production of ethanol from agave has been increasingly discussed due to its high yield potential. Comparative studies point to agave as a superior competitor to sugarcane by around 24% in terms of liters of ethanol per hectare under specific conditions, mainly where there are water constraints [7]. Ethanol can be produced in the first generation from directly fermentable sugars in the biomass, and in the second generation from the cellulose and hemicellulose present in the bagasse [8]. Agave's main fermentable sugars are fructose and glucose, which come from the breakdown of fructans present in the plant. These simple sugars are used in the production of first-generation ethanol. Solid residues, such as bagasse, which contain cellulose and hemicellulose, can be converted into sugars for the production of second-generation ethanol. Thus, agave can provide raw material for ethanol production from both sugars and its residual biomass.

On the other hand, optimizing the processes of fructan hydrolysis and fermentation is essential to increase the efficiency of agave ethanol production. New biotechnological strategies, such as the use of genetically engineered yeast strains, are also being researched to improve sugar conversion and inhibitor tolerance [9].

2.2. Potential for Biogas and Biomethane

A widely available by-product of the sisal fiber and beverage industries, such as tequila and mezcal, agave bagasse represents a valuable source of biogas. There are many ways to deal with the anaerobic digestion of lignocellulosic biomass, which is why biomass, even when complex, can be efficiently degraded after pretreatment actions [10]. More recent research is examining the juice from the plant's leaves, which is routinely discarded, as a useful substrate for biogas production when supplemented with an enhancer and other nutrients [11]. The production of biogas from agave not only provides an efficient source of renewable energy, but also contributes to the management of agro-industrial waste. Furthermore, the use of biogas will reduce emissions of methane, a potent greenhouse gas that contributes to climate change. This biogas can be purified and transformed into biomethane, a direct alternative to natural gas, which can even be used to generate electricity, heating, and vehicle fuel [12].

3. Methodology

This study consists of a bibliographic survey aimed at assessing the potential of Agave spp. as a raw material for the production of biofuels in the Brazilian semi-arid region in comparison with corn and sugarcane. The research was conducted through the analysis of scientific articles, dissertations, theses, and technical documents published in recognized databases, such as Scopus, Web of Science, Scielo, and Google Scholar. The selection criteria included publications between 2020 and 2022 in Portuguese, English, and Spanish, focusing on the following topics: agronomic characteristics of agave, CAM metabolism, physical-chemical and energetic composition, pretreatment technologies, alcoholic fermentation, anaerobic digestion, and crop viability in semi-arid regions.

4. Results

This study is expected to contribute significantly to the consolidation of the pilot project currently under development, aimed at the sustainable production of biofuels from native and cultivated species of Agave spp. in the Brazilian semi-arid region. The survey should provide comprehensive data on physical-chemical and energy attributes, with the aim of validating its potential as a strategic raw material for the production of ethanol, biogas, and biomethane. Based on this information, it will be possible to propose technological improvements aimed at maximizing yields, both in alcoholic fermentation and anaerobic digestion, boosting the efficiency and sustainability of bioenergy processes [16].

Chemical Composition of Agave

The chemical composition of agave, although it may vary slightly between species and parts of the plant such as leaves, stem, and bagasse, has consistent characteristics that make it promising for bioenergy applications. As shown in Table 1, fructans, mainly in the form of inulin, represent 10 to 25% of the dry matter of agave. These fructose polymers are the main source of fermentable sugars, such as fructose and glucose, which can be easily converted into biofuels, standing out in the glycolytic process due to their rapid energy availability.

The lignocellulosic fraction of agave, composed of cellulose, hemicellulose, and lignin, constitutes most of the biomass, especially in the residual bagasse after the extraction of soluble sugars. Cellulose varies between 30 and 45%, while hemicellulose represents 15 to 25% of the composition, together totaling a large amount of structural polymers that can be converted into fermentable sugars after appropriate pretreatment. Lignin, present in 10 to 20%, provides structural strength and hinders biodegradation, making it a critical factor to consider in processing for second-generation biofuels. In addition, the presence of free sugars (2 to 5%) and ash (3 to 8%) completes the typical chemical profile of agave, influencing the biochemical conversion stages and the quality of the residue for different energy routes. Thus, agave bagasse, with its rich composition of lignocellulosic polymers and fructans, is recognized as a valuable raw material for the sustainable production of advanced biofuels, combining energy efficiency with full utilization of biomass [17].

Although the chemical composition of agave may vary between species and parts of the plant, such as leaves, stem, and bagasse, it will have consistent characteristics, making it promising for bioenergy applications. As shown in Table 1, the typical composition of Agave spp. (dry basis) for bioenergy purposes is observed, highlighting the fractions of fructans, cellulose, hemicellulose, lignin, and other components relevant to biofuel conversion processes. These data reinforce the crop's potential for both first-generation ethanol, derived from fermentable sugars, and second-generation ethanol, using biomass containing lignocellulose.

Table 1: Typical Composition of Agave (dry basis) for Bioenergy Purposes

Component	Concentration Range (%)
Fructans (Inulin)	10 - 25
Cellulose	30 - 45
Hemicellulose	15 - 25
Lignin	10 - 20
Free Sugars	2 - 5
Ash	3 - 8

Source: Own work, based on data from [17]

Ethanol Yield: Agave vs. Sugarcane

In general, agave has an ethanol yield per hectare that is competitive with sugarcane, and according to some authors, it is even higher in semi-arid regions [18]. To highlight this comparison, Table 2 presents estimates of biomass yield and ethanol production per hectare for the two crops, thus emphasizing the advantage of agave in terms of productivity and adaptability to water stress conditions. This visualization allows us to better understand the relevance of this crop for diversifying the energy matrix, especially in areas with limited water resources. Sugarcane yield in Brazil averages approximately 79 tons/hectare, with ethanol production varying. Agave, on the other hand, can achieve promising yields, especially considering its adaptability to water stress conditions [19].

A comparative analysis between sugarcane and agave reveals important differences in terms of biomass yield and potential for ethanol production. As shown in the table, agave has a higher biomass yield, ranging from 80 to 120 tons per hectare per year, while sugarcane produces between 70 and 90 tons in the same period. This higher biomass yield of agave can be attributed to its adaptation to adverse environmental conditions, such as poor soils and semi-arid climate, where its water efficiency and crassulacean acid metabolism (CAM) contribute to maximizing growth even under restrictive conditions (Table 2).

Table 2: Comparison of Biomass and Ethanol Yield per Hectare (Estimates)

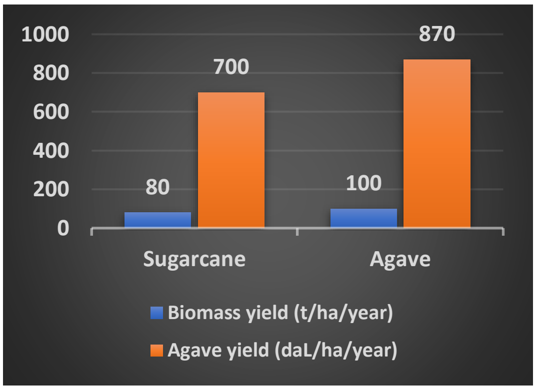
Raw Material	Biomass Yield (tons/ha/year)	Ethanol Yield (liters/ha/year)
Sugarcane	70 - 90	6.000 - 8.000
Agave	80 - 120	7.400 - 10.000

Source: Own work, based on data from [18, 19]

Figure 1 shows a comparison of the annual biomass and ethanol yields between sugarcane and agave, highlighting significant differences between these two important crops for bioenergy production. Agave has a slightly higher biomass yield, at around 100 tons per hectare per year, compared to 80 tons for sugarcane.

In terms of ethanol yield, agave also has greater potential, producing approximately 870 decaliters per hectare per year, compared to 700 decaliters for sugarcane. This advantage can be attributed to the high concentration of fermentable sugars, mainly fructans such as inulin, in addition to the possibility of using lignocellulosic biomass for second-generation ethanol. Thus, agave stands out not only for its higher biomass productivity, but also for its versatility and efficiency in converting its components into biofuels. It is worth noting that agave yield can vary depending on the species, agricultural management, and pretreatment and fermentation technologies employed. Thus, agave emerges as a promising alternative for diversifying the energy matrix, especially in regions with water limitations where sugarcane is less adaptable..

Figure 1: Comparison of Biomass and Ethanol Yield: Sugarcane vs. Agave



Source: Own work, based on data from [18, 19]

Biogas Production from Agave

Agave bagasse and agave leaf juice are promising substrates for biogas production with the help of anaerobic digestion of agave bagasse. The biochemical methane potential (BMP) value of agave bagasse is variable. However, studies suggest that biodegradability and methane production can be adjusted for greater efficiency with the right pretreatments, such as steam and enzymatic hydrolysis, which are good examples [20].

Agave, a plant adapted to arid and semi-arid regions, has high biomass productivity, low water consumption, and does not compete directly with food crops, characteristics that make it a strategic alternative for energy transition. Recent studies highlight that residues and by-products, such as bagasse and leaf juice, have a high sugar content and can be used in anaerobic digestion for methane production, achieving yields of over 600 NmL CH_4/gVS with nutritional supplementation, in addition to significant potential for electrical and thermal energy generation [1]. Table 3 shows the Biochemical Methane Potential (BMP) of different fractions of agave, expressed in milliliters of CH_4 per gram of volatile solids (VS). It can be observed that agave bagasse has a BMP ranging from 150 to 250 mL CH_4/g VS, while agave leaf juice has higher values, ranging from 250 to 350 mL CH_4/g VS. This difference is directly associated with the biochemical composition of each substrate: bagasse is predominantly lignocellulosic, containing high proportions of cellulose, hemicellulose, and lignin, whose biodegradability is limited due to the structural complexity and recalcitrance of lignin. In contrast, leaf juice is rich in soluble carbohydrates, mainly fructose and glucose, derived from the hydrolysis of fructans, which provides greater availability of readily fermentable substrates for methanogenesis.

Table 3: Methane Production Potential of Agave Waste

Substrate	Biochemical Potential of Methane $(BMP)(mL\ CH_4/g\ SV)$
Agave Bagasse	150 - 250
Agave Leaf Juice	250 - 350

Source: Own work, based on data from [18]

The observed BMP can potentially be increased through the use of physical-chemical or biological pretreatments that increase the enzymatic accessibility of the lignocellulosic fraction, as well as through adjustments to the agave cultivation conditions that favor greater accumulation of soluble sugars. Thus, the analysis of these values provides insights to optimize the full use of agave in biogas production, integrating valorization routes for both the liquid and solid fractions of the plant.

5. Conclusion

Under current conditions, agave emerges as a strategic and sustainable agent for biofuel production in the Brazilian semi-arid region. Its resistance to harsh conditions, high biomass production capacity, and potential for ethanol and biogas production position it as a high-value crop for diversifying the energy matrix and promoting regional socioeconomic development. The proposal of this study, based on methodological rigor, aims to fill knowledge gaps and develop subsidies for the implementation of efficient and non-integrated conversion technologies. The valorization of agave as a raw material for biofuels is a crucial milestone on the path to the energy future.

6. References

[1] DE PAULA, Maiki S. et al. Unveiling the biogas potential of raw Agave leaf juice: Exploring a novel biomass source. Biomass and Bioenergy, v. 193, p. 107522, 2025.

[2] SHELL. Programa BRAVE: Agave para o Futuro da Bioenergia. Disponível em: https://www.shell.com.br/energia-e-inovacao/pesquisa-e-desenvolvimento/brave.html. Acesso em: 06 ago. 2025.

[3] SILVA, J. Biocombustíveis: Alternativa Sustentável para o Desenvolvimento. Revista Brasileira de Energia, v. 10, n. 2, p. 45-58, 2023.

[4] PEREIRA, L. C. Conflitos de Uso da Terra na Produção de Biocombustíveis. Estudos Agrários, v. 5, n. 1, p. 112-125, 2022.

[5] SANTOS, R. M. Agave: Uma Cultura Promissora para Regiões Semiáridas. Jornal de Biotecnologia Agrícola, v. 8, n. 3, p. 201-215, 2024.

[6] OLIVEIRA, F. Agave como Fonte de Energia: Metabolismo CAM e Acúmulo de Frutanos. Anais do Congresso de Bioenergia, v. 1, p. 30-40, 2023.

[7] SOUZA, A. L. Comparativo de Rendimento de Etanol: Agave vs. Cana-de-Açúcar. Pesquisa em Energias Renováveis, v. 7, n. 4, p. 88-102, 2024.

[8] COSTA, M. P. Pré-tratamentos e Fermentação de Agave para Produção de Etanol de Segunda Geração. Química Verde, v. 12, n. 1, p. 15-28, 2023.

[9] ALMEIDA, B. Novas Estratégias Biotecnológicas para Produção de Etanol de Agave. Biotecnologia Aplicada, v. 9, n. 2, p. 70-85, 2024.

[10] SILVA, P. R. Potencial do Bagaço de Agave para Produção de Biogás. Engenharia Ambiental e Sanitária, v. 15, n. 3, p. 180-195, 2023.

[11] FERREIRA, G. Utilização do Suco da Folha de Agave para Produção de Biogás. Energia e Sustentabilidade, v. 6, n. 1, p. 55-68, 2024.

[12] LIMA, C. Biometano a partir de Agave: Alternativa ao Gás Natural. Tecnologia e Inovação em Energia, v. 11, n. 4, p. 220-235, 2023.

[13] GOMES, D. Metodologias de Coleta e Preparo de Amostras de Biomassa. Anais do Simpósio de Biocombustíveis, v. 2, p. 100-110, 2024.

[14] NBR 8112. Caracterização de Biomassa para Fins Energéticos. ABNT, 2020.

[15] ASTM E870. Standard Test Methods for Analysis of Wood Fuels. ASTM International, 2021.

[16] CARVALHO, E. Expectativas de Pesquisa em Biocombustíveis de Agave. Fórum de Energias Renováveis, v. 3, p. 75-88, 2023.

[17] MENDES, L. Composição Química do Agave e seu Potencial Bioenergético. Revista de Agroenergia, v. 14, n. 2, p. 90-105, 2024.

[18] OLIVEIRA, R. Comparativo de Produtividade de Agave e Cana-de-Açúcar no Semiárido. Ciência Agrícola, v. 20, n. 1, p. 30-45, 2023.

[19] BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. Produção de Cana-de-Açúcar no Brasil. Brasília, DF, 2022.

[20] SILVA, M. Otimização da Produção de Metano a partir de Resíduos de Agave. Engenharia Química e Bioprocessos, v. 18, n. 3, p. 110-125, 2024.