Production of Agave's Bioproducts: A Short Review

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The energy transition has become one of the most widely discussed topics in the past decade, driven by the adverse effects of fossil fuel usage. In this context, various biomasses have been under study to produce biofuels and other substances serving as synthetic platforms for more complex molecules. Among these biomasses, Agave, a species known for its high resistance to environmental factors typical of Brazil and intriguing characteristics for generating bioproducts, has emerged as a prominent candidate. This brief review aims to explore the potential of Agave as a significant platform for generating higher value-added products and to highlight the potential socio-economic impacts in Brazil, particularly in the Northeast region.
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In the past decade, considerable discussion has concerned the imperative to shift the composition of the world's energy matrix. Currently dominated by non-renewable fuels, these processes are directly linked to the generation of greenhouse gases (GHGs), resulting in various environmental and health hazards. Research centers and some chemical processing companies have advocated for using various types of biomass as an alternative to fossil fuels [1]. Biomass, classified as a group of energy products and renewable raw materials originating from organic matter formed through biological processes, provides energy and offers a range of high-value bioproducts [2].

Using biomass as a raw material, exemplified by Agave, sugarcane, and corn, holds promise in facilitating the world's energy transition. For perspective, biomass can be replenished at almost 100 billion tons annually, equivalent to 515 billion barrels of oil equivalents [3]. In Brazil, biofuel production is a prominent global player, ranking the country as the second-largest ethanol producer, primarily utilizing sugarcane as its raw material. Brazil consumed approximately 20 billion liters of ethanol in 2018, with production expected to increase by 5.5% by 2025 [4]. However, challenges associated with the use of sugarcane, such as competition with the food industry, water resource requirements, negative impacts from fertilizer use [5], and the necessity for agriculturally valuable lands, underscore the importance of considering investments in other biomass species.

In this context, the utilization of Agave in established or innovative processes holds significant potential, potentially emerging as a protagonist in the realm of biofuels and various bioproducts in the country. The Agave genus comprises over 300 species distributed across the globe, predominantly found in arid and semi-arid regions, constituting 12% of the Brazilian territory [6]. These regions are characterized by high temperatures, scarce rainfall, and water deficit [7,8]. Agave, with its high sugar content, which is crucial for biofuel production, its ability to thrive in extreme environments, and the abundance of available cultivation areas without competing as food, presents promising potential in the energy transition.

Additionally, Agave exhibits potential for producing other bioproducts applicable in pharmaceuticals, composites, fibers, and various materials, thus expanding its applications. Intermediate products derived from Agave processing, such as flavonoids, saponins, and terpenes, can be an intermediate platform for producing higher-value molecules in various chemical processes [9,10].

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Thus, this work provides a concise review of studies focusing on the utilization of Agave species in generating high-value bioproducts.

Materials and Methods

The brief review presented in this study was conducted in two stages. The first stage involved utilizing platforms such as Science Direct, Google Scholar, Elsevier, and Scopus to search for academic articles using the keywords "*AGAVE*" AND "BIOREFINERY," "*AGAVE*" AND "PHARMACEUTICAL," and "*AGAVE*" AND "BIOPRODUCTS." The search prioritized articles published from 2013 onwards.

Upon identifying papers in the first stage, the second stage commenced. This subsequent stage entailed examining the references to identify any documents of interest using keyword searches and operators. After selecting the articles, brief descriptions of their contributions regarding the utilization of Agave were provided.

Results and Discussion

Most selected articles were published in the last decade, highlighting the conversion of various types of Agave into higher-value products using different methodologies. Some methodologies have already been established from a technical-economic perspective, while others are still in the developmental stage. Among these studies, a significant focus was placed on the production of biofuels. However, substantial research has also been dedicated to obtaining bioproducts serving as synthetic platforms for other higher-value substances. Table 1 presents key results related to the generation of intermediate bioproducts, while Table 2 summarizes the main biofuels produced, along with their respective production methodologies.

Several research studies have delved into utilizing different Agave species across various sectors, including healthcare, cosmetics, and recycling. Mestre and colleagues utilized *Agave sisalana* to produce high-quality nanoporous carbohydrates for pharmaceutical product removal [11]. The raw material underwent a digestion and polycondensation process with sulfuric acid at a temperature below 100°C and ambient pressure, followed by chemical activation with potassium hydroxide or carbonate. The authors employed the resulting product to remove ibuprofen and iopamidol from aqueous solutions. The findings revealed that acid concentration influenced the structure and density of the intermediate product, with activation using KOH proving twice as efficient in pollutant removal compared to the commercially available material for this purpose, activated gold charcoal.

Table 1. Intermediate bioproducts, main processes, and raw materials.

Product class	Agave type	Applied method	Product	Reference
Bioproducts	*Agave sisalana*	Digestion and policondensation with H_2SO_4, chemical activation with KOH or K_2CO_3	Nanoporous carbohydrates	[11]
	Agave sisalana	*In vitro* and *in vivo* tests	Skin anti-oxidative and anti-aging products	[12]
	Agave tequilana	Injection molding with compatibilizer	Agave fiber-reinforced polymeric composite	[13]
	Agave lechuguilla	Fibers pre-treated with NaOH	Epoxy composites	[14]

Tabela 2. Biofuels, main processes, and raw materials.

Product class	Agave Species	Applied Method	Product	Reference
Biofuels	*Agave tequilana*	Two-stage acid and enzymatic hydrolysis	Hydrogen and methane	[15]
	Agave tequilana	Auto-hydrolysis, hydrolysis with cellulose cocktail, and fermentation with *Saccharomyces cerevisiae*		[16]
	Agave tequilana and *Agave Salmiana*	Pre-treatment using ammonia fiber expansion and fermentation	Ethanol	[17]
	Agave lechuguilla	Pre-treatment with sulfuric acid, saccharification, and fermentation with co-fermented *Escherichia coli* MM160	Ethanol	[18]
	Agave sisalana	Acid-base pre-treatment, followed by hydrolysis and fermentation with *Saccharomyces cerevisiae*	Ethanol	[19]
	Agave tequilana	Pre-treatment with ionic liquid and anaerobic digestion	Methane	[20]
	Agave tequilana	Enzymatic saccharification without detoxification and fermentation	Ethanol	[21]

On the other hand, Barreto and colleagues evaluated the utilization of residues from the same Agave to generate products combating oxidative stress and skin aging [12]. The authors assessed antioxidant activity in vitro and *in vivo* using the Caenorhabditis elegans organism model. The results demonstrated antioxidant activity in all *in vitro* tests, and vivo a reduction in free radicals was observed. Thus, the Agave residue exhibited promising results as an antioxidant agent.

Iftekhar and colleagues investigated the properties of a compound prepared by injection molding from a mixture of linear low-density polyethylene, polypropylene, and 25% by weight of fibers derived from *Agave tequilana* waste, with a compatibilizer content ranging from 1% to 3% [13]. The authors synthesized a compatibilizer in the laboratory and concluded that the adhesion of the plastic to the Agave fiber improved compared to a specific industrial compatibilizer. Furthermore, the results demonstrated that using 2% of the synthesized compatibilizer enhanced tensile strength by approximately 24% and flexural strength by 14% compared to non-compatibilized composites.

Majhi and colleagues utilized *Agave lechuguilla* fibers to reinforce epoxy composites to enhance the material's mechanical strengths [14]. Initially, the authors treated the fibers with 5%, 10%, and 15% NaOH concentrations and analyzed tensile strength and interfacial shear strength, with the 5% concentration yielding the best results. Subsequently, the authors discussed using the 5% NaOH-treated fiber and untreated fiber as reinforcement material, with concentrations ranging from 10% to 40%. The treated fiber exhibited approximately 8% better results in tensile and flexural strength than the untreated fiber.

Various research groups have explored processes for obtaining biofuels, mainly focusing on proposing new routes for ethanol, hydrogen, and methanol, among others. Vargas et al. conducted a comparative study of single-phase and two-phase anaerobic digestion to produce hydrogen and methane from the acid or enzymatic hydrolysis of *Agave tequilana* bagasse [15]. The experiments were performed in batch reactors, with hydrolysate concentrations ranging from 20% to 100%. The results indicated that a high concentration of hydrogen could be achieved with enzymatic hydrolysis at 40% and a high methane concentration for hydrolysates at 20%. Thus, the two-stage process proved approximately three times more efficient than the single-stage process.

González and colleagues employed *Agave tequilana* bagasse for biofuel production [16]. The authors subjected the bagasse to auto-hydrolysis, hydrolysis using a cellulase cocktail, and fermentation with Saccharomyces cerevisiae. The process was conducted in a high-pressure Parr reactor, with a solid-liquid ratio of 1:6 and agitation at 200 rpm. The result obtained after a 10-hour fermentation period showed a 98.4% ethanol conversion rate relative to the theoretical value.

Gómez and colleagues utilized residues from *Agave tequilana and Agave salmiana* for bioethanol production [17]. The raw material underwent a chemical pre-treatment with ammonia under optimized conditions at temperatures between 100-120°C. The results demonstrated about 85% selectivity to sugars during pre-treatment and metabolic ethanol concentrations above 90% during fermentation. *Agave salmiana* exhibited a high content of converted sugars; however, it could not be fermented with high solid content due to the presence of inhibitory agents.

Blanco and colleagues utilized *Agave lechuguilla* as a raw material for ethanol production through pre-treatment with dilute sulfuric acid [18]. The study involved varying temperatures between 160°C and 200°C and acid concentrations between 0.5% and 1.5% (w/v), expressed as a combined severity factor. Optimal pre-treatment conditions were 180°C and 1.24% (w/v) sulfuric acid. Following the pre-treatment process, the product underwent saccharification and co-fermentation with Escherichia coli MM160, producing an ethanol yield of 73.3%.

Ethanol production was also investigated by Veloso and colleagues using *Agave sisalana* bagasse [19]. Initially, the material underwent pre-treatment with sulfuric acid and sodium hydroxide, followed by enzymatic hydrolysis and fermentation with Saccharomyces cerevisiae yeast. The results revealed a glucose-to-ethanol conversion factor of 0.47, corresponding to a conversion efficiency of 92%, and a volumetric ethanol productivity equal to 1.2 g/L.

Biomethane production via anaerobic digestion was studied by Pimienta and colleagues using pre-treatment of *Agave tequilana* bagasse with the ionic liquid choline lysine [20]. The authors evaluated the optimized pre-treatment conditions, which were 124°C, 205 minutes, and 20% solid load. The results demonstrated the possibility of obtaining 12.5 kg of methane per 100 kg of untreated raw material, approximately 86% of the theoretical value.

Gaxiola and Gaxiola conducted a study on ethanol production from *Agave tequilana* leaves [21]. The authors utilized powdered species leaves and performed two processes of enzymatic saccharification without detoxification, followed by fermentation using Saccharomyces cerevisiae. Results were evaluated for different fermentation times, ranging from 0 to 40 hours, with 18 hours being the optimal time, resulting in ethanol production with a yield of 81% of the theoretical value.

This study highlights Agave as a promising raw material for generating various bioproducts, biofuels, and pharmaceutical products using diverse methods. Agave holds significant potential to positively impact Brazil's semi-arid areas, such as the northeast. Its innovative utilization can stimulate community economies by fostering development, job creation, and other socio-economic benefits. According to the Digital Agro 2022 Report by Mizokami, 3.3 million hectares of Agave in the Brazilian semi-arid region can produce 30 billion liters of biofuels, equivalent to that produced using 4.5 million hectares of sugarcane. Furthermore, there is already a willingness to utilize Agave in semi-arid regions, with plans to allocate 2 million hectares for biofuel production from this raw material [22].

Conclusion

The literature studies reviewed reveal diverse methodologies for utilizing Agave in producing various bioproducts, mainly focusing on fuels and other substances with inherent high-added value, as well as serving as synthetic intermediate platforms for obtaining commercially valuable molecules across diverse industries. These research findings underscore the significant potential of Agave in generating such products. When combined with its characteristics of ample cultivable land, resilience to extreme conditions, and capacity to stimulate local economies, this potential becomes even more pronounced.

Brazil's semi-arid region offers ample opportunities for cultivating Agave species. Research endeavors targeting the utilization of *Agave sisalana* from this region, exploring the cultivation of new Agave species, and investing in biomass utilization represent promising avenues for energy transition and economic development in the northeastern part of Brazil.

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