Anaerobic Digestion of *Agave sisalana*: Existing Data, Trends, and Potential Applications

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The increasing global demand for renewable energy is driving the search for clean and sustainable sources, such as biogas obtained from the anaerobic digestion of waste, emerging as a promising alternative. This article aims to present an overview of the studies already developed on the anaerobic digestion of *Agave* sp. with a focus on the sisalana variety and possible applications of the generated biogas. The anaerobic digestion process consists of four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, where microorganisms convert organic matter into biogas, mainly composed of methane and carbon dioxide. Studies show that pretreatments, such as aerobic and fungal treatments, and co-digestion with other residues can increase the efficiency of the process. Biogas from *Agave sisalana* has several applications, including power generation injection into gas pipelines. Despite challenges such as the need for investment in infrastructure and technology, the anaerobic digestion of *Agave sisalana* presents significant potential for renewable energy production in Brazil, especially considering the increasing demand for green energy.
Keywords: Sisal. Anaerobic Digestion. Biogas. Bioenergy.

The global demand for renewable energy is rapidly increasing due to concerns about climate change and the declining availability of fossil resources. Biogas, produced through the anaerobic digestion of organic waste, stands out as a clean and sustainable energy source. *Agave sisalana*, or sisal, is a succulent and fibrous plant with CAM (Crassulacean Acid Metabolism) metabolism cultivated primarily to produce natural fibers, generating a significant amount of waste during the defibering process in all production sites [1].

It is estimated that 8% (wet basis) of the plant corresponds to fiber, and the remaining 92% is composed of mucilage (cuticle and palisade and parenchyma tissue), fluff (short fibers), and sap - chlorophyllic sap [2]. Anaerobic digestion of sisal waste offers an opportunity to transform this byproduct into a valuable energy resource, contributing to sustainable resource management and the mitigation of environmental impacts [3-6], including the potential use of the remaining residue after digestion as a biofertilizer to return to the soil [3].

Sisal was introduced to Brazil in the 19th century, and it originated from the African continent. Its production began in Ceará, later spreading to other states in the Northeast. Sisal production experienced its "Golden Age" in the 1950s, when Brazil became the world's largest producer, going into decline in the 1970s. However, Brazil is now the world's largest producer again, surpassing the African continent's total production and historically the most significant producer [7].

Table 1 presents the sisal production between 2020 and 2022 and the projected production in 2032 from the leading producers [7].

Given this context, this study aims to analyze available literature to identify advancements, applications, and trends in biogas production using byproducts from the industrial utilization of *Agave sisalana*.

Materials and Methods

This systematic literature review employed scientific data from the Web of Science (WoS)

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Table 1. Main sisal producers [7].

Country	Production 2020-2022 (kton)	Production 2032-projected (kton)
Brazil	88.2	98.7
China	63.5	65.3
United Republic of Tanzania	36.3	43.5
Kenya	31.6	37.5
Madagascar	6.0	7.0

(Clarivate Analytics®, Boston, USA) with a cutoff date of May 31, 2024. The search equation incorporated types/varieties of Agave with the potential for commercial energy applications and biogas production. The search within the WoS database was restricted to the topic (TS) field, which encompasses terms in the title, abstract, author, keywords, and keywords plus. The established equation was: TS=((Agave OR tequilana OR sisal OR sisalana OR "agave americana" OR salmiana OR fourcroydes OR "agave angustifolia" OR "agave sp") AND (biogas OR methane OR Anaerobic OR digestion OR CH_4)). The search results were filtered to exclude literature reviews and specific research categories within WoS, such as food science and technology, agriculture and animal science, and polymer science, as these areas did not align with the selected topic focused primarily on biogas and energy generation.

Additionally, the language of the selected documents was limited to English, Spanish, and Portuguese, and the analysis timeframe encompassed the period from 1980 to 2024. The collected information was compiled using the open-source software VOSviewer 1.6.6, and using default settings, co-authorship, and keyword co-occurrence networks was generated. Finally, an analysis of the historical series identified, alongside future advancements and trends, is discussed and presented.

Results and Discussion

The search for research on biogas production using byproducts from the Agave production chain yielded 158 consolidated results distributed among review articles (7.6%), research articles (89.2%), and conference papers (3.1%). The terms "anaerobic digestion," "biogas," and "Agave," with 35, 30, and 27 citations, respectively, were the most frequently occurring in the selected database. Figure 1 illustrates the keyword co-occurrence network and clusters obtained using VOSviewer, considering 25 keywords with a minimum of 6 occurrences in the database. As depicted in Figure 1, five main clusters were identified based on color coding (green, red, blue, yellow, and purple). The green cluster, for instance, demonstrates a correlation between studies employing anaerobic digestion, sisal pulp, and anaerobic batch reactors, suggesting that continuous systems are limited, likely due to the need for pretreatment to adjust the physical properties of the residue. Similarly, the yellow cluster, associated with "bioethanol production," is linked to the blue and green clusters as ethanol production, particularly in the form of tequila and mescal, generates residues such as vinasse and agave bagasse, which possess the potential for biogas production, thereby enabling the generation of thermal and electrical energy. Finally, it is crucial to highlight the purple cluster, which features the word "Tanzania." Much of the research focusing on utilizing *Agave sisalana* residues was developed in the context of fiber production in Tanzania, one of the world's leading fiber producers alongside Brazil and China.

Publications on Strategies for Optimizing

Biogas Production

Anaerobic digestion is a biological process that occurs in the absence of oxygen, where microorganisms convert organic matter into biogas, mainly composed of methane (CH_4) and carbon dioxide (CO_2), along with other gases in smaller quantities, such as hydrogen sulfide (H_2S).

The process is divided into four main stages [3]:

Hydrolysis: Degradation of complex macromolecules, such as carbohydrates, proteins, and lipids, into smaller, simpler molecules with higher solubility. This process produces sugars, amino acids, and fatty acids.

Acidogenesis: Fermentation of the molecules resulting from hydrolysis, generating volatile fatty acids (VFAs), such as acetic, propionic, butyric, and valeric acids. Carbon dioxide and hydrogen are also produced during this stage.

Acetogenesis: Conversion of VFAs into acetic acid, hydrogen, and carbon dioxide.

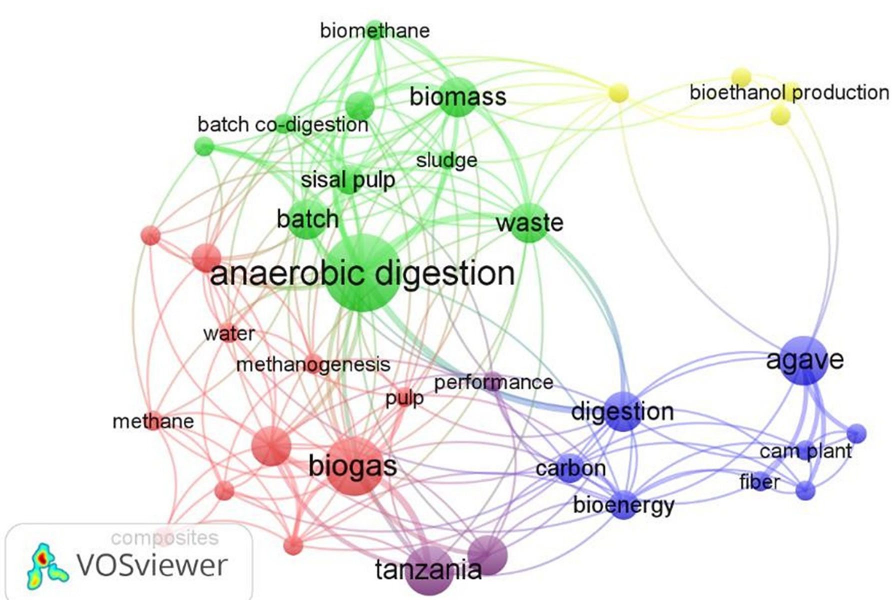
Methanogenesis: Production of methane from acetic acid, hydrogen, and carbon dioxide, a conversion carried out by methanogenic bacteria.

Several factors affect the anaerobic digestion process, such as temperature, pH, solids concentration, retention time (hydraulic and solids), agitation, the type of substrate and inoculum, and the possible presence of inhibitory agents. Numerous studies have been developed to evaluate the impact of changes in these factors on methane generation, with those listed below considered of most significant interest [3, 4, 8-13]:

Pretreatment: Sisal pretreatment aims to increase the material's biodegradability by facilitating the action of microorganisms and modifying the substrate's initial characteristics. Various pretreatment methods can be used, such as aerobic pretreatment, which involves the oxidation of organic matter by aerobic microorganisms, and treatment with fungi, which decomposes lignin and increases the accessibility of cellulose and hemicellulose [8-9].

Co-digestion: Co-digestion of sisal with other organic residues aims to improve the digester's

Figure 1. Network co-occurrence of keywords using the reported search equation.



nutrient balance, increase biogas production, and reduce digestion time [10-12].

Particle size: Reducing the size of sisal particles increases the surface area available for microorganisms, accelerating degradation and increasing methane production. Alterations to this factor have consequences similar to agitation for the digestion process [13].

The literature highlights two strategies for increasing methane production from sisal pulp pretreatment: aerobic pretreatment and fungal treatment.

The results for aerobic pretreatment were positive for short periods, with a peak in methane production for 9 hours, generating 24 m³/VS and a 26% increase compared to digestion without pretreatment. However, this process can reduce methane generation, as observed for 72 hours of pretreatment, where methane production was reduced to 12 m³/VS [8].

Pretreatment using fungi, developed in a previously published study using CCHT-1 and *T. reesei fungi*, varied the application sequence of the fungi for treatment. When CCHT-1 was applied initially, a 101% increase in methane generation was observed compared to production without pretreatment. In the reverse sequence, production increased by only 46% [9].

The co-digestion of sisal with other residues has been studied, with associations found in the literature with fish waste, zebu manure, and palash leaves. Table 2 compares methane production from pure sisal residue and in the case of co-digestion [10-12].

As demonstrated in previous studies, particle size is directly related to methane production. For sisal fiber particles of 2 mm, a 23% increase in methane production was observed compared to production without size reduction, with a generation of 0.22 m³ per VS. Figure 2 illustrates the methane production for different particle sizes studied [13].

While published studies present a wide range of methane production values, only the underlying concepts can be compared across different references. These experiments were conducted under varying conditions and should only be directly compared within the same study.

Typical Application of Biogas

Biogas produced from the anaerobic digestion of sisal has been used in various ways globally, as listed below [3,4,14-16]:

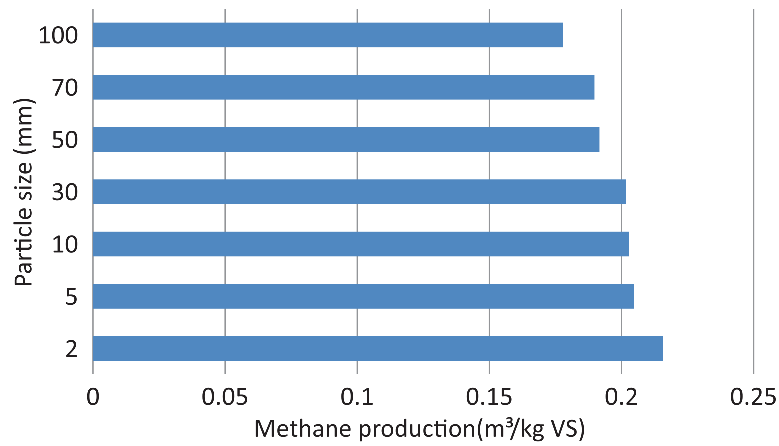
Power Generation: Biogas can be directly used in internal combustion engines to generate electricity [3,4,14-16]. This is the primary application in Brazil currently, and it is widely used in sanitary landfills.

Injection into Natural Gas Pipelines: Biomethane, methane obtained through biogas

Table 2. Methane production through co-digestion of sisal [10-12].

Substract	Configuration	Methane Production
Sisal + Palash co-digestion	Digestion of sisal	130 mL/day
	Co-digestion	320 mL/day
Sisal + Fish Residues	Digestion of sisal	0.32 m³/kg VS
	Co-digestion (67% sisal + 33% fish residues)	0.62 m³/kg VS
Sisal + Zebu Manure	Digestion of sisal	Uninformed
	Co-digestion	166 mL/g VS

Figure 2. Methane production for different particle sizes [13].



Source: Adapted from MSHANDETE, A. et al., 2006.

purification, can be injected into natural gas pipelines, providing a clean and sustainable alternative. However, the main limitation of this application is the presence of pipelines in the area of biogas production [15].

Cooking Gas Supply: Biogas can replace LPG (liquefied petroleum gas) for burning in stoves and cooking. This application is uncommon in Brazil but is more prevalent in lower-income countries.

In regions where this application is used, it is often not subject to strict controls, raising the possibility of accidents related to its use. Biogas can replace LPG, reducing dependence on fossil fuels and lowering energy costs for families and businesses. However, regulations, as well as the necessary infrastructure, must be defined to ensure safe utilization [3,4,14-16].

Challenges and Perspectives of Anaerobic Digestion of *Agave Sisalana*

Anaerobic digestion of sisal has been studied in various parts of the world, primarily in countries that are major producers. This results in a massive waste generation, typically without any use, making its disposal challenging. It is expected to increase due to projected production growth in the coming years. However, its digestion allows for the production of biofuels, such as butanol, hydrogen, and primarily biogas, containing biomethane [7, 16]. Despite this potential, several for its large-scale implementation, challenges need to be overcome, such as the construction of necessary infrastructure, technological advancements, cost reduction for installation, and defining logistics for transporting sisal waste and delivering the generated biogas [1,17].

Research and development of innovative technologies, such as co-digestion, pretreatment, and the use of different types of support for biofilms, are crucial for enhancing the efficiency of anaerobic digestion of sisal and reducing biogas production costs [4, 8-12, 15].

It is essential to promote the implementation of pilot projects in various contexts to assess their technical, economic, and social feasibility. The biogas produced has several possibilities in the current Brazilian context, such as direct electricity generation, a process already widely utilized in sanitary landfills, and its purification for feeding and mixing into natural gas pipelines, which are expected to be encouraged in the coming years due to recent legislative changes.

Additionally, the increasing demand for green energy must be considered, driven by the numerous green hydrogen plants announced or under study in the country. These plants are currently linked to wind or solar generation, with their main parks in the Northeast region. The use of biogas to generate green energy for these plants, besides allowing their installation in other regions of Brazil, would also solve the major drawback of dependence on solar and wind energy generation, which is its reliance on weather conditions, a factor not applicable to biogas generation.

Conclusion

Anaerobic digestion of sisal emerges as a promising solution for renewable energy production in Brazil, leveraging the growing volume of residues generated by its production. Furthermore, studies indicate the potential of this technique to generate biogas, which can be used for various applications such as electricity generation, injection into gas pipelines, and supplying cooking gas.

As highlighted in this article, numerous strategies exist to optimize the utilization of this potential. However, challenges remain, such as investments in infrastructure, technological development, and process optimization. Continued research into potential applications and maximizing its energy potential is crucial for large-scale adoption.

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