Review [Revisión]

INTEGRAL USE OF HENEQUEN (*Agave fourcroydes*): APPLICATIONS AND TRENDS–A REVIEW †

[USO INTEGRAL DEL HENEQUÉN (*Agave fourcroydes*): APLICACIONES Y TENDENCIAS–UNA REVISION]

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SUMMARY

Background. The Conventional use of henequen (*Agave fourcroydes*), has mainly focused on the use of the leaves for the production of fiber. However, there are other components such as the stem ("pineapple"), the spines, and the by-product of fiber generation (leaf juice) in which we should pay attention to. **Objective.** To provide a systematic analysis of the biotechnological overview from those investigations where the potential of each of the structural components of *A. fourcroydes* is being studied. **Methodology.** A systematic review of the literature was carried out, based on the PRISMA protocol (Preferred Reporting Items for Systematic reviews and Meta-Analyses), search for information was carried out in the most prominent databases (Redalyc, SciELO, Scopus, Elsevier, EBSCO, and Google Academic, using *A. fourcroydes* as the main keyword, using inclusion and later exclusion criteria according to the literature found, in the period from 1990 to 2022, which allowed a broader perspective on this crop and its biotechnological importance. **Main findings.** In the bibliographic review more information was found on the applications of the plant in an integral way, so that bioactive compounds such as fructans, flavonoids, and sterols can be obtained from the henequen stem, which can be incorporated into animal and human diets, while ethanol has been obtained from the juice of the leaves and the development of that of new materials using the fiber in a native and modified way to obtain fiber-reinforced mortars for its sustainable application in the construction industry. On the other hand, contributions were found on promising alternatives for the use of crops such as modified fibers, and combined with other compounds (composites) for the mechanical reinforcement of new materials. **Implications.** The literature consulted allows us to report that henequen (*A. fourcroydes*) is not only cultivated in the Yucatan Peninsula, but also in other regions such as the State of Tamaulipas, Mexico, where its use and commercial exploitation has not well documented. **Conclusion.** The bibliographical review allows us to deduce that the obtaining of new henequen compounds would revalue their integral use and use in different industries.
Key words: Fiber; health ingredients; structural components; composites materials; and fructans.

RESUMEN

Antecedentes. El uso convencional del henequén (*Agave fourcroydes*), se ha enfocado principalmente en el aprovechamiento de las hojas para la producción de fibra. Sin embargo, existen otros componentes como el tallo (piña), las espinas y el subproducto de la generación de fibra (jugo de penca) a los que se les debe prestar atención. **Objetivo.** Proporcionar un análisis sistemático sobre el panorama biotecnológico de aquellas investigaciones donde se estudia el potencial de cada uno de los componentes estructurales de *A. fourcroydes*. **Metodología.** Se realizó una revisión sistematizada de literatura, con base en el protocolo PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses, por sus siglas en inglés), la búsqueda de información se realizó en las bases de datos más destacadas (Redalyc, SciELO, Scopus, Elsevier, EBSCO, Google académico, utilizando como palabra clave principal *A. fourcroydes* utilizando criterios de inclusión y posteriormente exclusión según la literatura encontrada, en el periodo 1999 a 2022, lo que permitió tener una

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perspectiva más amplia sobre este cultivo y su importancia biotecnológica. **Principales hallazgos.** En la revisión bibliográfica se encontró mayor información sobre los usos de la planta de manera integral por lo que del tallo del henequén se pueden obtener compuestos bioactivos como fructanos, flavonoides y esteroles, los cuales pueden ser incorporadas en dietas animales y humanas. Mientras que del jugo de las pencas se ha obtenido etanol. También se ha explorado el desarrollo de nuevos materiales utilizando la fibra de manera nativa y modificada para la obtención de morteros fibroreforzados para su aplicación sustentable en la industria de la construcción. Por otra parte, se encontraron contribuciones sobre alternativas prometedoras de utilización del cultivo como las fibras modificadas y combinadas con otros compuestos (composites) para el reforzamiento mecánico de nuevos materiales. **Implicaciones.** La literatura consultada nos permite informar que el henequén (*A. fourcroydes*) no solo se cultiva, en la Península de Yucatán, sino en otras regiones, como en el Estado de Tamaulipas, México, donde su aprovechamiento y explotación comercial no está bien documentada. **Conclusión.** La revisión bibliográfica nos permite deducir que la obtención de nuevos compuestos del henequén revalorizaría su aprovechamiento integral y utilización en diferentes industrias.
Palabras clave: Fibra; ingredientes saludables; componentes estructurales; materiales compuestos y fructanos.

INTRODUCTION

Natural fibers are constituted by lignocellulosic components, which make up the most abundant photosynthetic renewable biomaterial on earth. Its main use is for the production of biofuels, such as bioethanol; however, as a result of these biotechnological processes, high amounts of waste are generated, which do not receive a comprehensive use, despite being a resource-rich in easily available lignocellulosic materials. The source that contains the greatest amount of fiber has been wood, however, in Mexico, there is a wide variety of agricultural-based fibers that can be used, such is the case of those that can be obtained from annual plants such as henequen (*A. fourcroydes* Lem. 1864) (Tarrés *et al.,* 2019; Ferreira *et al.*, 2020). Henequen fibers contain around 60% cellulose, i.e., a higher content than other natural fibers or wood fibers (Valadez-Gonzalez *et al.*, 1999; Tarrés *et al.,* 2019; Kharbanda *et al.,* 2021).

A. fourcroydes, popularly known in Mexico as “Henequen blanco” (white henequen), “Sac ki” (in the Mayan language) (Trejo-Torres *et al.,* 2018), “sisal yucateco” (Yucatecan sisal) or “sisal Cubano” (Cuban sisal), this plant is native from Mexico and Guatemala, and it was most likely domesticated from varieties of *A. augustifolia* found in Yucatan, so it is stated that this plant is native from this region (García-Marín, 1998; Zimmermann *et al.,* 2020). This species is mainly used for fiber extraction in the Yucatan Peninsula, in Mexico, where a planted area of 20,000 hectares is established, from which high volumes are produced of around 27,000 tons per year (SIAP, 2020). In the southern region of the state of Tamaulipas, Mexico, this crop is being developed (Fig. 1) because it has great potential as a source of natural products such as lignocellulosic fibers that are used for “mecates” (a type of ropes for drying clothes) in “jarcierías” (Shop where objects made from vegetable fibers are sold, such as ropes, sponges, brooms, etc.), rope for tying up boats, cables, nets, lassos and also to make rugs and bags (Cazaurang Martínez *et al.,* 1990; Mohanty *et al.,* 2004; Abreu *et al.,* 2007), steroids and detergents (González *et al.,* 2003).

Figure 1. Crop of Henequén (*Agave fourcroydes*) in the state of Tamaulipas, Mexico. **(Photo: authors).**

In this sense, recent studies signalize the importance of these Agave species due to the potential they represent as raw material in bioenergy production (Cáceres-Farfán *et al.*, 2008; Rendón-Salcido *et al.*, 2009). Likewise, active compounds are extracted that can be used in the pharmaceutical and agricultural industries (Eastmond *et al.*, 2000; Abreu *et al.*, 2007). The conventional form of use of this Agave has mainly focused on the use of the lignocellulosic component of leaves, which forms only a part of the total lignocellulosic biomass of the agave, while the remaining parts are normally discarded. This not only limits the comprehensive utilization of useful resources but also causes secondary environmental contamination (Li *et al.*, 2021). Thus, to maximize the commercial value of this resource is important to have a general overview of the main components that make it up and the functionality of each of them. Therefore, this review aims to provide as much systematized information as possible where the most relevant structural and functional characteristics of henequen (*Agave fourcroydes*) and the potential of its lignocellulosic biomass.

METHODOLOGY

The Systematic collection of information began in March 2022, first applying an inclusion criterion through different databases such as Web of Science, Scopus, Elsevier, EBSCO, Google Scholar, Springer, Redalyc and SciELO, and entering the search for the main keyword *A. fourcroydes*. In this way, publications from 1990 to 2022 were selected. Subsequently, the exclusion criterion was applied, selecting those publications where the keywords intervened: healthy ingredients, structural components, composite materials, and fructans, managing to consult a total of 469 references. Refining until there were 156 articles, excluding those that were irrelevant to our study, leaving a total of 98 documents as shown in Figure 2 where the percentage of articles consulted separated by year is observed. The synthesis and analysis of the information were carried out with the PRISMA 2020 checklist, (Page *et al.*, 2021) As a result of the analysis from the research consulted on henequen, we found that: in the last 20 years, studies have focused on its applications as reinforcing material and fiber reinforced with other compounds, as well as obtaining bioactive compounds for human and animal nutrition, being the period from 2016 to 2020 where the highest biotechnological applications on this crop were developed.

For this selection, keywords in English were used as a reference without using any Boolean operator. Figure 3 shows the characteristics found according to the keywords applied to the search. An 8% was reached for the botanical and agronomic characteristics (cultivated area, edaphoclimatic conditions for its cultivation, and phylogenetic analysis), likewise 64% of structural components (lignin, cellulose, and hemicellulose, being fiber the most studied component), for its mechanical properties, production of ethanol and obtaining composite materials for reinforcement and production of concrete materials). On the other hand, 28% is observed for healthy ingredients used for food and feed applications, with probiotics such as lactic acid bacteria and prebiotics such as fructans being the most studied. This selection served to apply exclusion criteria, through the analysis and classification of the references.

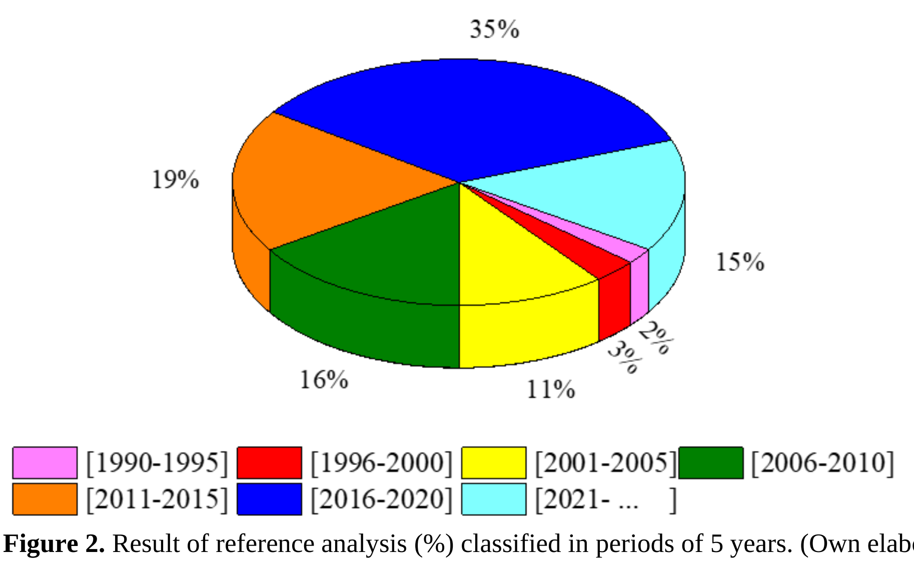

Figure 2. Result of reference analysis (%) classified in periods of 5 years. (Own elaboration).

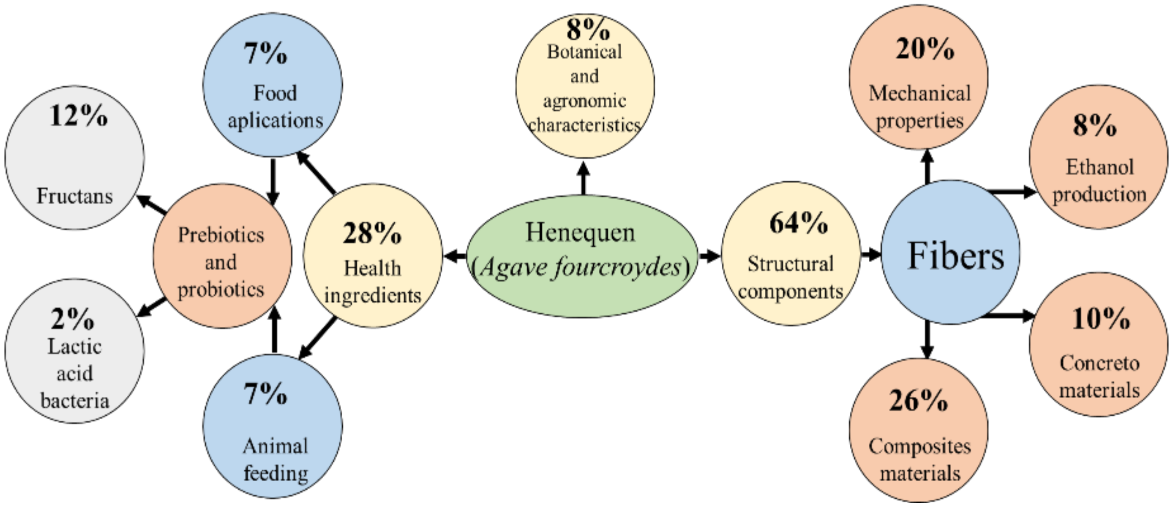

Figure 3. Distribution of the percentage of keywords used to carry out this review. (Own elaboration).

MORPHOLOGICAL CHARACTERISTICS OF THE HENEQUEN PLANT

A. fourcroydes is characterized by having a thick, woody stem, its leaves have a high fiber content and are longer than a meter in length, so it can measure up to 2.5 meters in diameter and with a stem of up to 1.2 meters in high. It forms a rosette of sword-shaped leaves about 100-200 cm high and 10-15 cm wide. Its leaves are greyish-green in color and have triangular-shaped marginal spines 3 to 6 mm long (Fig. 4A). It has a long-life cycle of up to 20 years, producing around 200 to 250 leaves, also called “pencas” (leaves). Fiber is obtained from those leaves, and each one contains approximately 1,000 fiber bundles (Fig. 4B). It grows favorably in tropical and subtropical climates at temperatures above 25 °C, under the sun, and tolerates drought (Infante *et al.*, 2003; Li and Shen, 2015). Qin *et al.*, 2021 studied the complete chloroplast genome of *A. fourcroydes* from the leaves of a 3-year-old plant. For the DNA extraction study, the leaves were ground in liquid nitrogen, finding 132 genes in the cp genome, therefore, according to the phylogenetic tree, the characteristics of *A. fourcroydes* are similar to those of *A. sisalana*.

Figure 4. Morphological characteristics of henequen produced in the state of Tamaulipas, Mexico (A). Bundles of henequen fibers drying in artisanal form (B). **(Photo: Authors).**

STRUCTURAL COMPONENTS OF HENEQUEN FIBERS

The chemical composition of henequen fibers influences their techno-functional properties and fibers themselves and they could be considered fibrous composite materials, which depend mainly on the edaphoclimatic conditions of the site where they are established (Bekele *et al.,* 2022). Henequen fibers have a high content of cellulose from the primary to the secondary wall and it is the main component of this fiber (Table 1).

The technological importance of the structural arrangement of the henequen fiber components sets up in the fact that cellulose is a rigid part of the fiber that provides the rigidity and resistance of the mechanical properties (Cazaurang-Martínez *et al.,* 1991). Hemicellulose is composed of cellulose chains, and a mixture of low molecular weight polysaccharides; its main function is to provide resistance and support to this crop, which allows it to maintain a certain mechanical resistance, in addition to influencing various properties of the cell wall as porosity, surface charge, pH, ionic balance, and transport (Lee *et al.,* 2008; Ferreira *et al.,* 2020). While lignin acts as a cementing matrix for this lignocellulosic component, which has its separate structure, however, its content gradually decreases from middle lamella to the primary wall, and so on to the secondary wall (Tarrés *et al.,* 2019). This component influences the structure, properties, morphology, strength, and moisture absorption of the fiber compared to hemicellulose (Thygesen *et al.,* 2011).

The physical, chemical and mechanical properties of natural fibers are essential and are considered the main criteria for the design and development of industrial products (Shanmugasundaram *et al.,* 2018). Structural characteristics play an important role since they allow elucidation of the morphology and how different components and interaction sites of henequen fibers were distributed. For this reason, scanning electron microscopy is a tool that provides very important information regarding the internal structure of these fibers and therefore allows monitoring of changes they undergo when they are modified. The natural fibers of henequen, are built by a series of microfibrils embedded in hemicellulose and lignin and they are responsible for their porous structure (Han *et al.,* 2006; Lee *et al.,* 2008; Castillo-Lara *et al.,* 2020).

PHYSICOCHEMICAL PROPERTIES OF HENEQUEN FIBER

Identification and physicochemical characterization of henequen fiber are essential to determine mechanical and functional properties. Some of these properties are shown in Table 2.

Determination of tensile properties is crucial because it provides information about elastic modulus, elastic limit, elongation, tensile strength, and other mechanical properties (Rahman and Putra, 2019). The tensile strength of a material is the maximum amount of tensile stress, it can withstand before failure or fracture. While the amount of stretch a material has when under tension provides important information about the tensile strength, ductility, and strength requirements of the material (Geethika and Rao, 2017). In this sense, tensile properties vary between materials, and their differences may be due to intrinsic factors such as the structural composition of lignocellulosic material, spatial location, and physiological age of the crop, as well as extrinsic factors such as geographical location, climate, and soil conditions (Monteiro *et al.,* 2012). Although cellulose is the main component of henequen fiber, hemicellulose is responsible for the biodegradation, moisture absorption, and thermal degradation of these fibers (Rong *et al.,* 2001; Cao *et al.,* 2007; Bekele *et al.,* 2022). Lignin is also thermally stable, and it is responsible for the ultraviolet degradation of the fibers (Akil *et al.,* 2011). Young's modulus, also called longitudinal elasticity, is a parameter that manages to reveal the

Table 1. Lignocellulosic composition of henequen (*A. fourcroydes*).

	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
Fiber	80	5	15	Vieira *et al.,* 2002
	77	4-8	13	Han and Jung, 2008
	75	4–8	14	Kharbanda *et al*., 2021
	68.1	18.2	8.7	Tarrés *et al*., 2019
	60	28	8	Valadez-Gonzalez *et al.,* 1999
	60	25	8	Yasin *et al.,* 2019
Leaves	72	24	2	Morán-Velázquez *et al.,* 2020
Spine	52	45	3	Morán-Velázquez *et al.,* 2020

Table 2. Physicochemical properties of henequen fibers. (Own elaboration).

Property	Values	Reference
Tensile strength	500 ± 70 MPa	John and Anandjiwala, 2008
	350 MPa	Rahman, 2009
Elongation at break	17 %	Rahman, 2009
Young’s modulus	13.2 ± 3.1 GPa	John and Anandjiwala, 2008
Density	1,200–1,480 kg/m^3	John and Anandjiwala, 2008; Tarrés *et al*. 2019
Thermal degradation	180 – 240 °C (Hemicellulose)	Yasin *et al*., 2019
	230 – 310 °C (Cellulose)	André, 2006
	300 – 400 °C (Lignin)	Monteiro *et al*., 2012
Ash	1.3 ± 0.4	Tarrés *et al*. 2019

behavior of an elastic material depending on the type of force applied to it and the consequent increase or decrease in the length of that material Sanchez Olivares *et al.,* 2019 reported that on the fiber of the tequila agave (*A. tequilana* Weber Azul) has Young’s modulus of 2.6-2.9 Gpa, while the fibers of the henequen (*A. fourcroydes*) exhibit a higher value as seen in Table 2. Serra-Parareda *et al.,* 2021 applied a tensile test on henequen fibers estimating Young's modulus with Polypropylene (PP)-based compounds, increasing constantly and linearly up to 50% by weight of fiber content. This demonstrates the ability of henequen fibers in their rigidity to be used as a reinforcement of PP.

USE OF HENEQUEN FIBERS

Conventional use

Henequen is a crop of great importance since pre-Hispanic times in the elaboration of implements for navigation or in the construction of monuments, it was even marketed and exported to various Mesoamerican towns. Later, during the Spanish colonization, it was mainly used in navigation cables (García-Marín, 1998). Since its implementation for commercial purposes, leaves and stems of henequen have been used for the extraction of fibers, which have been used mainly in the textile industry, for the manufacture of Mayan hammocks, binder twine, (Fig. 5), rugs, baskets, carpets, and clothing (Ramesh *et al.,* 2013; Li and Shen, 2015; Zimmermann *et al.,* 2020).

ALTERNATIVE USES

Bioactive compounds

Recent studies in searching for alternatives to the integral use of this plant indicate that the pulp of leaves presents a large number of metabolites such as inulin, saponins (vegetable soap), fructans, flavonoids, and steroids, which are used for different applications in food and pharmaceutical industries (Abreu *et al.,* 2007; Valdivia *et al.,* 2018).

Figure 5. Binder twine is made from fibers of henequen leaves in the state of Tamaulipas, Mexico. (Photo: authors).

Several bioactive compounds that have gained great interest today due to their technological properties and favorable impact on health are agave fructans, which are natural reserve carbohydrates in agave plants (Espinosa-Andrews *et al.,* 2021). These polysaccharides are a heterogeneous mixture of branched fructose polymers, linked by β(2-1) and β(2-6) fructose-fructose glycosidic bonds, with intermediate or terminal glucose units, which are healthy ingredients that promote the growth of beneficial bacteria, regulate serum glucose, decrease health problems associated with obesity and overweight, promote calcium absorption and promote chemoprotective, immunomodulatory and antioxidant effects (Lopez *et al.*, 2003; García-Curbelo *et al.,* 2015a; García-Curbelo *et al.,* 2015b; Espinosa-Andrews *et al.*, 2021).

According to García-Curbelo *et al.*, (2010 y 2015b), *A. fourcroydes* have shown high concentrations of fructans in its stems and leaves, in addition, García-Albornoz (2006) reported the presence of inulin and poly-fructans in studies carried out with *A. fourcroydes*, and indicated that the highest concentration of these bioactive is found mainly in stems of adult plants ("piña"), followed by the leaves ("pencas"), which is where an accelerated synthesis of fructans is carried out, that are then translocated to the growth zones (base of the leaves) or storage zones ("piña"); it also mentions that the season of the year also influences the concentration of total sugars and fructose, being the high-temperature season, where the highest concentration of these sugars occurs; however, to determine the structural characteristics of these bioactive ingredients, present in *A. fourcroydes*. García-Curbelo *et al.*, (2015b) performed a structural characterization using thin-layer chromatography, gas chromatography coupled to mass spectrometry, and anion-exchange chromatography of high resolution coupled to an amperometric detector. From these results, they proposed the structures detailed below (Fig. 6).

García-Curbelo *et al.* (2015b) indicate that unlike commercial fructans (Raftilose®P95) from inulin, *A. fourcroydes* fructans were more complex because of not only chitose, nystose, and questopentaose, but also carbohydrates such as Agavins, linked by β(2-1) and β(2-6) glycosidic bonds, may be present in branched gram fructans and neo-fructans, characteristic of the *Agave sp.* (Fig. 6A) (González-Díaz *et al.*, 2020). Figure 6B shows GFn fructans, which are other carbohydrates of the inulin series, which indicate the presence of several fructose units linked to terminal glucose by β-(2-1) glycosidic bonds. While Figure 8C shows the Fn fructans, which contain only fructose units bound linked together (Corzo *et al.*, 2015). This analysis established the structural difference between *A. fourcroydes* fructans and inulin-type prebiotics. For this reason, García Curbelo *et al.* (2015a) evaluated a prebiotic effect of henequen fructans in an animal model. Results of this study indicate that the inclusion of these fructans in the diet of mice induced a prebiotic response similar or superior to fructans extracted from chicory (*Cichorium intybus*) (Raftilose P95; commercial name), increasing total weight, and colon and cecal walls, therefore, henequen fructans constitute a promising alternative with potential use not only in the animal diet but could also be considered in the human diet.

Composites

Henequen (*A. fourcroydes*), has been cultivated especially for fiber extraction, however, in recent years it has been the subject of study by the scientific community, being studied as an option for the reinforcement of sustainable composite materials (Frazâo, *et al.*, 2018) and as reinforcement in different polymeric compounds or matrices (May-Pat *et al.*, 2013; Velásquez-Restrepo *et al.*, 2016; Yasin *et al.*, 2019; Franco-Urquiza *et al.*, 2021). Fibers are the most common components used as composites, since they provide a large part of rigidity and strength attached to a matrix that can be a plastic, a resin, or another cement-based material which, apart from joining it, protects from any environmental attack. Franco-Urquiza *et al*. (2021) and Torres *et al.* (2022a,b) used henequen and ixtle fabrics as vegetable fiber as reinforcement to obtain biolaminates through a carbonization process with epoxy resin, obtaining lightweight laminated composites due to the presence of microvoids. During the process, they observed that the use of both, carbonized henequen

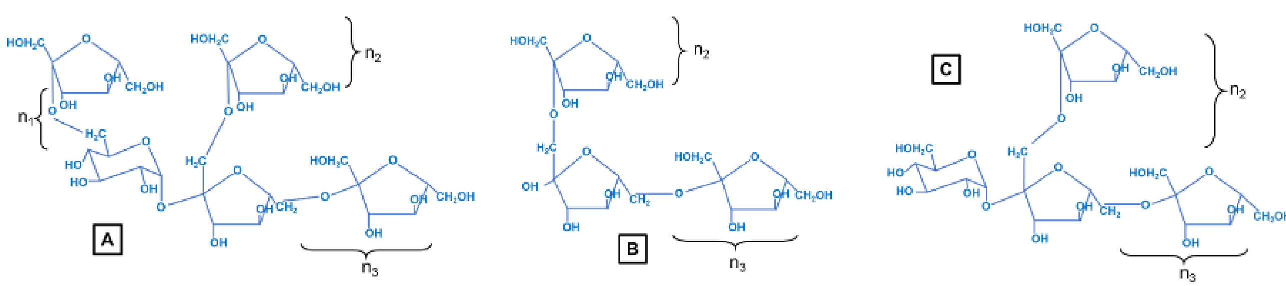

Figure 6. A polydisperse mixture of oligofructans in the dry extract of *A. fourcroydes*. A) Agavina with few branches (neo-fructan series). B) Graminian (of the GFn series) and C) Fructans (of the Fn series). (Own elaboration based on García-Curbelo *et al.*, 2015b).

and ixtle presented a higher density of voids, which shows that the use of carbonized fibers is an effective method as composite fillers. On the other hand, Kim and Cho *et al.* (2022) carried out an alkaline process on the henequen fibers extracted from the leaves, managing to increase the technical, mechanical, and impact properties of the compound after the extrusion process.

Rahman, (2009) mentions that due to their high cellulose content, henequen fibers, currently used in the preparation of composite materials, have a hydrophilic character. This in turn, together with a high level of water absorption, can cause microcracks in the composite and, therefore, a degradation in mechanical properties (Rahman, 2009; Arbelaiz *et al.*, 2005; Valadez-Gonzalez *et al.*, 1999). However, this characteristic can be improved by modifying the surface before being embedded in hydrophobic polymers (Herrera-Franco and Valadez-Gonzalez 2005). It has been observed that adherence to hydrophobic surfaces prevents henequen fibers from being used as composites (materials made of two or more components with properties superior to those they present by themselves). To counteract this drawback, efforts have been made to improve fiber/matrix adhesion through different modification reactions (Gurunathan *et al.*, 2015; Ferreira *et al.*, 2021), such as the use of adhesion agents (silanes, titanates, zirconates, triazine compounds), anhydride alkyl succinic, stearic acid and utilization of surface copolymer fibers, from which promising results have been obtained in terms of improving stress transfer, some mechanical properties of these compounds, as well as the adhesion between cellulosic fibers and the polymeric matrix, the latter makes it possible to reduce hygroscopicity of materials with lignocellulosic characteristics (Yasin *et al.*, 2019; Vilaseca *et al.*, 2008; Arbelaiz *et al.*, 2005; Mohanty *et al.*, 2004; Herrera-Franco and Valadez-Gonzalez, 2004). Hintze *et al.*, 2021 used the henequen fiber through a functionalization process based on an immersion method using a mixture of a commercial ferrofluid and stearic acid to change its properties and causing the fibers to be hydrophobic and magnetic and can be used in the manufacture of textiles and as protection by removing grease or any oily substance that is spilled on hard surfaces.

Literature mentions that fibers of *A. tequilana* Weber Azul and *A. fourcroydes* have been used to develop different fiber modification methods and characterization techniques, as well as reinforced polymeric compounds, obtaining excellent results (Muñoz, *et al.*, 2016).

Even though henequen is part of the Agave genus, there is a difference in the microstructural morphology, as reported by Sanchez-Olivares et al., (2019) when indicating that the *A. tequilana* fiber presents a nearly smooth surface and micro-fibers bound in a longitudinal arrangement, in contrast, *A. fourcroydes* fiber morphology showed a rough surface topography and begins to see fibrillation when this fiber is modified by alkaline treatment.

When 30 wt.- % of henequen fiber is added to the thermoplastic starch biopolymer (TPS), henequen fibers show spaces around the fibers, indicating poor adhesion with TPS, even though the surface of the fibers was modified. Therefore, these henequen fiber concentrations do not contribute to good stress transfer, resulting in a brittle fracture mechanism. However, the morphology of the TPS+10 (wt.- %) henequen fiber + 10 (wt.- %) Aluminum diethyl phosphinate (AlPi) composites appear well embedded in the polymer matrix, and some traces of polymer adhesion are observed. This combination contributes to improving matrix-fiber stress transfer, as has been reported in fiber-reinforced composites. Therefore, a high henequen fiber content (30% by weight) produces a brittle fracture, while a low content (10% by weight) in combination with AlPi results in a ductile fracture mechanism. According to May-Pat *et al.*, 2013, this morphology contributes to improving stress transfer between the matrix and fibers in composites reinforced with them.

Construction Industry

A study of natural fibers as reinforcement of cement matrix composite materials for applications in the construction industry is of great interest due to increased environmental awareness and growing concern about global warming. For this reason, the construction industry is looking for new alternatives to manufacture sustainable materials at low cost and with minimal energy consumption (Frazão *et al.*, 2018; Flores-Johnson *et al.*, 2020). Fujiyama *et al.*, (2014) found that the inclusion of henequen fibers in a cement mortar (mixture of sand, cement, and water) increases resistance to fracture, therefore, fiber-reinforced mortars present a delay during the failure process, characterized by greater deformations and a gradual drop in applied load, compared to simple mortar (which does not contain henequen fibers). This improvement is manifested by an increase in values of the J-integral (a way of calculating the rate of strain energy release or work per unit area of fracture in a material). (Bai and Bai, 2014). In addition, impact test results indicate a pronounced improvement in the impact energy of the mortar due to the presence of henequen fibers, particularly for those that are 45 mm thick compared to those of 25 mm. While, Liu *et al.*, (2020) found that adding henequen fibers to foamed concrete (foamed concrete is a lightweight material made from cement mortar with a porous structure, which is achieved by injecting a preformed foam (Flores-Johnson *et al.*, 2018 and 2020), at a concentration of 0.75% and a fiber length of 5 mm, the mechanical properties of foamed concrete were improved, as well as compressive and flexural strength with an increase of 17.8% and 47.6%, respectively. Therefore, henequen fiber can effectively improve the contraction performance of foamed concrete. So, the longer the henequen fiber, the lower the foamed concrete contraction value. This was consistent with what was reported by Flores-Johnson *et al.*, (2018) and Castillo-Lara and Flores-Jhonson (2020) who report that adding henequen fiber to foamed concrete improves the mechanical performance and fracture resistance of this material. There are different foamed concrete materials reinforced with henequen fiber that have been manufactured in “Unidad de Materiales del Centro de Investigación Científica de Yucatán, A.C.” for applications in the construction industry. This type of material is obtained thanks to the injection of foam, which generates air cells in their interior. In the internal structure, the inclusion of henequen fibers, which interact with other components, can also be made. This inclusion changes the brittle behavior of unreinforced foamed concrete to a ductile behavior with more deformation capacity in fib-reinforced material (Flores- Johnson *et al.*, 2018). These studies demonstrate the potential capacity of henequen fibers to be used in the manufacture of sustainable materials to reduce the greenhouse effect (Castillo-Lara and Flores-Johnson, 2020; Castillo-Lara *et al.*, 2020).

Bioethanol production

Currently, different Agave species are being considered for their potential use as bioenergy, through the production of bio-oil, biochar, and gas. Canché-Escamilla *et al.* (2022) applied pyrolysis processes at high temperatures to the trunk and peduncle of henequen to obtain it, reaching maximum yields of 40, 27, and 46% respectively. Martínez-Torres *et al.*, (2011) obtained ethanol from the stem of two varieties of *A. fourcroydes*, taking into account certain conditions, such as stem age, sugar content, soluble solids, and fermentation time. Results of this study indicated that to obtain one liter of ethanol, 48 kg and 23 kg of “Sac ki” stem need to be processed, for plantations aged 5 and 9 years, respectively. While for “Yaax ki” (green henequen in the Mayan language) variety, 29 and 19 kg of stem with the same physiological age are needed. However, for other Agave species, a smaller amount of raw material is needed to produce the same amount of ethanol. For example, for mezcal production, 12-14 kg of *A. angustifolia* stem is required. On the other hand, to obtain tequila, 8-10 kg of *A. tequilana* Weber azul stem is needed (García-Marín *et al.*, 2007). Another parameter to consider for increasing ethanol yield is the influence of the time of year since it has been reported that the longer the cultivation time, the lower the volume of stems needed to produce a greater amount of ethanol (Rendón-Salcido *et al.*, 2009). Optimization of these conditions that favor an increase in ethanol yield can be used as a reference parameter to determine the suitability of an agave variety for these purposes. Cáceres-Farfán *et al.*, (2008) and Villegas-Silva *et al.*, (2014) evaluated the effect of thermal acid hydrolysis and enzymatic hydrolysis in henequen leaf juice on an amount of reducing sugars released, followed by fermentation with *Kluyveromyces marxianus* to determine alcoholic yields. Fermentation with *K. marxianus* resulted in ethanol yields of 50.30 ± 4.00 % and 80.04 ± 5.29 % respectively. Therefore, henequen leaves represent a non-negligible amount of biomass and an important source of carbohydrates that can be used for biofuel generation.

Other applications

Stems of *A. fourcroydes* have also been used to obtain a meal, which can be incorporated as a nutraceutical product in animal feeding (Iser *et al.*, 2020). According to the American Veterinary Nutraceutical Council, nutraceuticals are products that contain compounds necessary for proper biological development either extracted or purified (Telrandhe *et al.*, 2012). In this regard, Rondon *et al.*, (2019), used a mixture of henequen pulp (*A. fourcroydes*) with PROBIOLACTIL® in obtaining a symbiotic preparation for application as a nutritional additive in calf feed. While García-Curbelo *et al.* (2009) have reported that stems obtained from *A. fourcroydes* contain a high concentration of fructans which can be used for the utilization and production of food additives such as prebiotics, which can be applied in small concentrations in animal feed (Adhikari and Kim, 2017). Iser *et al.,* (2016) and Iser *et al.,* (2020), reported that its use could improve animal health and animal biological indicators. On the other hand, at the Animal Science Institute in Cuba, *in vitro* fermentation studies about the dry extract of *A. fourcroydes*, rich in fructan oligosaccharides, are being carried out, using it as a substrate of lactic bacteria to obtain prebiotics for animal feed (García *et al.,* 2012). Juice of the leaves is also used as an antiseptic for wounds and sores, and green bagasse is used as animal feed; although it also serves as organic fertilizer in crops when dry (García-Suárez and Serrano, 2012). Also, lignocellulosic biomass produced by henequen represents a novel source for the formulation of hydrogels, attributed to hydroxyl functional groups present in a large number of their main macromolecular constituents (cellulose, hemicellulose and lignin)., Hydrogels are network materials generally obtained from a polymeric solution by physical or chemical crosslinking of its macromolecules (Queiroz *et al.,* 2021). These hydrogels can be produced from synthetic or natural sources and can be designed with different geometric morphologies, such as cylinders (Xiao *et al.,* 2012; Isobe *et al.,* 2018), film-like structures (Koneru *et al.,* 2020; Le *et al.,* 2020) and beads (Shehzad *et al.,* 2020; Rashidzadeh *et al.,* 2020), among others. Versatility oThe versatility could allow their application in agriculture, thanks to their biodegradability (Saruchi *et al.,* 2019; Khushbu *et al.,* 2019). Also, due to their biocompatibility, they can be used as promising candidates using in contact with living tissues, such as those in the human body (Zheng *et al.,* 2017; Qu *et al.,* 2019; Koneru *et al.,* 2020). Moreover, the possibility to tailor this porous structure to support the controlled release of substances multiplies opportunities for hydrogel selection (Saruchi *et al.,* 2019; Qu *et al.,* 2019; Culebras *et al.,* 2021).

Morán-Velázquez *et al.,* (2020), performed a characterization of *A. fourcroydes* spines and found that cellulose content is lower in spines than in leaf fibers (52 and 72%, respectively), but reaching slightly more than twice that of hemicelluloses and lignin. The total lignin content in those spines was 1.5 times higher than that found in the fibers. In addition, mass spectrometric studies revealed that phenolic compounds including quercetin, kaempferol, (+)-catechin, (-)-epicatechin and condensed tannins are present in those spines of *A. fourcroydes*. The abundance of (+)-catechins could also explain the proanthocyanidins found in spines. Therefore, henequen spines can become a plant reference to obtain more information about cellulose and lignin interactions and thus their potential use in the bioenergy industry in the development of natural dyeing of fibers. Stem and leaves of henequen have been used for the manufacture of alcoholic beverages. The process begins with the selection of the plants, which consists of harvesting those that are between 7 and 20 years old. For fermentation, *Saccharomyces cerevisiae* yeast is used, and after a double distillation process, a beverage of between 70 and 75 degrees G.L. (Gay Lussac degrees) is obtained, which must then be diluted until desired commercial G.L. concentration is obtained, which ranges between 30 and 35 degrees G.L. (Larqué-Saavedra *et al.,* 2004). Therefore, stem and henequen leaves meet the requirements to obtain a quality alcoholic beverage. Rendón-Salcido *et al.,* (2007), used henequen stem from 15 to 18 years old to obtain syrup, whose composition was 85.7% fructose and 13.7% glucose and other minerals such as Ca, Mg, K, Zn, Fe, Al, Cu, Mn and Cr. Due to its richness in these constituents, henequen syrup can be incorporated into the human diet and has characteristics comparable to those of other agaves; therefore, this new product can add value to this plant and promote its use.

CONCLUSIONS

Henequen (*A. fourcroydes*) has proven to be a plant species of both great agricultural and ecological values, known worldwide for the quality of its fiber used for industrial purposes. However, residues of this plant could be used as an alternative for biotechnological utilization, either as an important source of natural fibers or as a bioenergy source for ethanol production. The properties of these fibers depend mainly on their chemical composition and structure, which are related to the extraction method, collection period, growth conditions, and chemical treatment. Natural fibers are rich in cellulose, hemicelluloses, lignin, and pectins, and this chemical composition influences their techno-functional properties. In addition, the composition of the stem and the pulp of leaves of this Agave could highlight the importance in the generation of important metabolites such as inulin, saponins, fructans, and flavonoids, of great interest for both food and pharmaceutical industries. In addition, the composition of the stem and the pulp of leaves of this Agave could highlight the importance in the generation of important metabolites such as inulin, saponins, fructans and flavonoids, of great interest to food and pharmaceutical industries.

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