Methods to assess accurate mechanical properties of natural fibers as reinforcement for composite materials

Métodos para evaluar con precisión las propiedades mecánicas de las fibras naturales como refuerzo de materiales compuestos

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***Abstract*— In some cases, the use of natural fibers as reinforcement in composite materials has not been fully optimized due to the lack of rigorous methodologies for determining their physical and mechanical properties. Often, the protocols employed are not sufficiently standardized or fail to incorporate appropriate correction processes that account for the inherent variability and nature of these materials. The objective of this study is to analyze the mechanical behavior of technical fique fibers through a rigorous and validated experimental methodology. This research highlights the importance of adopting precise and validated methods to ensure accurate evaluation of natural fiber properties. The fiber density was measured using helium gas pycnometry. Moreover, the fiber's modulus was determined through an extrapolation technique, from individual fiber tensile test at four span lengths, providing a more accurate assessment of its mechanical behavior. Additionally, a two-parameter Weibull statistical distribution was applied to analyze the tensile strength and its variability, offering a comprehensive understanding of the fiber's performance under stress. These methodologies were validated through a case study on fique fibers, demonstrating their reliability in accurately determining the mechanical properties of natural fibers. The outcomes revealed that fique fibers exhibit linear-elastic behavior up to failure, with a mean tensile strength of 506.7 MPa and a Young's modulus of 24.9 GPa. These results significantly exceed previously published values, highlighting the true potential of these fibers as reinforcing material.**

***Index Terms*— fique fiber, mechanical properties, natural fiber, natural fiber composites, Weibull distribution.**

***Resumen*— En algunos casos, el uso de fibras naturales como refuerzo en materiales compuestos no se ha optimizado debido a la falta de metodologías rigurosas para determinar sus propiedades físicas y mecánicas. A menudo, los protocolos empleados no están suficientemente estandarizados o no incorporan procesos de corrección adecuados que tengan en cuenta la variabilidad y la naturaleza de estos materiales. El objetivo de este estudio es analizar el comportamiento mecánico de las fibras técnicas de fique mediante una metodología experimental rigurosa y validada. Esta investigación destaca la importancia de adoptar métodos precisos y validados para garantizar una evaluación real de las propiedades de las fibras naturales. La densidad de la fibra se midió mediante picnometría con gas helio. Además, el módulo de la fibra se determinó mediante una técnica de extrapolación, a partir de ensayos de tensión de fibras individuales en cuatro longitudes, lo que proporcionó una evaluación más precisa de su comportamiento mecánico. Adicionalmente, se aplicó una distribución estadística de Weibull de dos parámetros para analizar la resistencia a la tensión y su variabilidad, lo que permitió comprender el comportamiento de la fibra bajo tensión. Estas metodologías se validaron mediante un estudio de caso sobre fibras de fique, demostrando su fiabilidad para determinar con precisión las propiedades mecánicas de las fibras naturales. Los resultados revelaron que las fibras de fique presentan un comportamiento elástico lineal hasta la rotura, con una resistencia a la tracción media de 506.7 MPa y un módulo de Young de 24.9 GPa. Estos resultados superan los valores publicados anteriormente, lo que expone el verdadero potencial de estas fibras como material de refuerzo.**

***Palabras claves*— compuestos de fibra natural, distribución de Weibull, fibra de fique, fibra natural, propiedades mecánicas.**

I. INTRODUCTION

Given the growing scarcity of petroleum-derived resources and the need to reduce CO2 emissions, the exploration of materials from renewable natural resources becomes crucial for environmental conservation and reducing the carbon footprint. Natural fiber-reinforced polymer composites have gained substantial attention due to their potential to replace synthetic fibers, such as glass and carbon fibers, in various structural applications. These materials are abundant in nature and require less energy for extraction compared to traditional synthetic fibers. Additionally, the ecological benefits of natural

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fibers, such as biodegradability, sustainability, and low carbon footprint, make them highly attractive for industries seeking greener alternatives to conventional materials.[1] Additionally, the lightweight nature, high specific strength, and biodegradability of fibers such as flax, sisal, hemp, and abaca demonstrate their potential for sustainable engineering applications.[2]

Plant fibers have a complex hierarchical microstructure and are classified according to the part of the plant from which they are extracted: stem, leaves, or seeds. The location and function of the fiber within the plant determine its morphological, physical, mechanical, and chemical properties, which are fundamental for selecting the appropriate application of the fibers, in conjunction with a suitable polymer matrix, the desired performance of the composite material can be achieved.[3]

Nowadays several studies are focused on improving the mechanical strength, chemical resistance, biodegradability and fiber-matrix bonding of natural fiber composites to guarantee durability and high performance.[4] Life Cycle Assessment (LCA) analysis have demonstrated that natural fiber-reinforced composites are environmentally superior to glass fiber composites at all stages of their life cycle.[5], [6], [7] Moreover, incorporating these types of fibers into a composite material can offer several advantages, such as increased tensile strength, as the fibers act as reinforcement elements that help the matrix withstand tensile loads, and improved toughness, given that natural fibers, with their porous internal structure, help absorb energy and slow down or halt the growth of cracks.[8] In this regard, natural fiber-reinforced composites are playing an important role in the development of new biomaterials and in harnessing the mechanical properties that these types of fibers can provide in a composite material.

As shown in Fig. 1, some natural fibers such as bamboo fibers and sisal fibers, exhibit mechanical similarities with glass fibers and show a very similar linear elastic behavior under tensile load, which is a desirable characteristic for reinforcing materials, and can be compared to glass fibers in terms of specific mechanical properties (normalized to the density of the materials).[9]

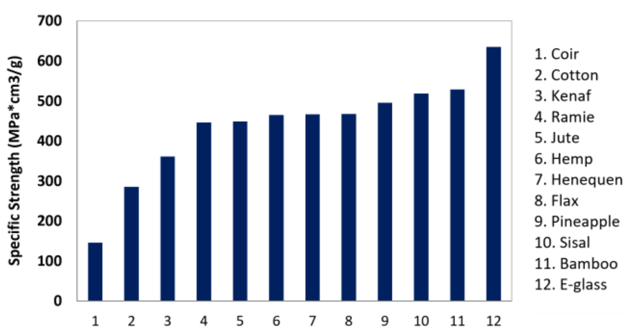

Fig. 1. Specific tensile strength of different natural fibers and glass fibers. [10]

Therefore, in order to develop natural fiber composite materials for structural applications, it is essential to carry out precise characterization methodologies — ensuring the growth of the plant fiber-reinforced composites market and meeting the growing industrial demand for these natural reinforcements. Accurately evaluating the mechanical properties of natural fibers requires a deep understanding of the various factors that influence these properties, along with standardized testing methods that accommodate their inherent anisotropic characteristics. [11], [12] Refining these assessment techniques is key to unlocking the full potential of natural fibers, enabling composite materials that can compete with traditional synthetic composites in performance while offering a more sustainable alternative. [13]

This research focuses on the study of fique fibers as a case study, to be used as reinforcement in composite materials. The fique plant (Fig. 2), is native to South America, with plantations mainly found in Colombia, and to a lesser extent in countries such as Venezuela and Ecuador. It belongs to the Agavaceae family and is part of a group of xerophytic monocotyledonous species, making it suitable for cultivation in arid regions with low humidity.[14] This family of plants also includes species such as maguey, yucca, and sisal.[15] Sisal fibers have been used in various industries, including textiles, construction, and in the reinforcement of composite materials, among others.[16], [17], [18], [19]

Fig. 2. Fique plant.

From the manual extraction process of fique, fibers known as “cabuya” are produced, which represent about 5% of the total weight of the plant, while fique juice accounts for approximately 75% of the weight, and bagasse makes up about 20% of the weight.[20] Fique fibers are located in the leaf, providing strength and flexibility; they are the most valuable by-product of the plant, with production volumes in Colombia close to 24,000 tons per year,[21] generating employment for around 70,000 families.[22] The fiber is mainly used in the manufacture of packaging, crafts, and in the textile industry.

Most of the fiber extraction is carried out using defibrillation machines, which use an electric motor to drive a defibrillator cylinder consisting of a shaft, a cylinder, and blades. The leaf passes through this system to remove the epidermal tissues, leaving the fiber exposed.[14]

Currently, fique fiber has been used in various industries due to its mechanical properties, durability, and biodegradability.[23], [24] From packaging products to textile manufacturing, fique fiber has demonstrated its potential as a sustainable alternative that can expand its use into other, yet unexplored, sectors.

Since the applications of natural fibers depend on their physical and mechanical characteristics, the objective of this study is to analyze the mechanical behavior of fique fibers, through a detailed and validated experimental methodology encompassing density determination, tensile testing at multiple span lengths, and Weibull statistical analysis, aiming to provide accurate mechanical property data for their use as reinforcement in composite materials.

It is hypothesized that the application of a rigorous experimental methodology — incorporating density-based cross-sectional area determination, multiple span-length tensile testing with machine-compliance correction, and Weibull statistical analysis — will yield more precise and higher mechanical property values for fique fibers than those reported in previous studies using less rigorous testing protocols.

Reliable mechanical characterization of natural fibers relies on the joint use of complementary methodological principles. Fiber density, essential for calculating the true cross-sectional area of irregular, non-circular natural fibers,

is commonly determined by helium gas pycnometry, a technique that measures the volume of a solid sample by gas displacement, providing higher accuracy than liquid-based methods such as Archimedes' principle, particularly for porous or fibrous materials.[25] In single-fiber tensile testing, the recorded crosshead displacement includes not only the actual elongation of the fiber but also deformation contributed by the testing machine and grips (machine compliance); correcting for this effect, typically by testing multiple span lengths and extrapolating to an infinitely long fiber, is essential to obtain accurate values of strain and Young's modulus.[26] Finally, because natural fibers exhibit brittle, defect-dependent failure behavior with inherent variability along their length, the two-parameter Weibull distribution provides a statistical framework that describes this variability through a shape parameter (m, related to defect density and data dispersion) and a characteristic strength parameter (σ_0), allowing a more reliable estimation of tensile strength than a simple average of individual test results.[26]

II. EXPERIMENTAL METHOD

This study corresponds to an experimental research with a quantitative approach. The population (universe) consisted of fique fibers, and the sample comprised fique fibers sourced from the municipality of Aranzazu, Caldas, Colombia. A completely randomized experimental design was applied, considering span length (5, 10, 25, and 40 mm) as the independent variable, and tensile strength, Young's modulus, and strain to failure as the dependent variables; fiber density was treated as an independent physical characterization variable. The sample size (120 tensile tests, 30 per span length, and 600 fibers for density determination in three groups of 200) is consistent with sample sizes reported in previous validated studies on natural fiber characterization.[25], [26], [27] The dispersion of the results obtained, reflected in the standard deviations reported for each span length (Table II) and in the shape parameter m of the Weibull distribution, is consistent with the natural variability inherent to plant-based fibers, statistically supporting the adequacy of the sample size used.

A. Material

Technical fique fibers were obtained using defibrillation machines and following the process described in the introduction. The fibers were sourced from the department of Caldas, Colombia.

The fibers were physically and mechanically characterized for all experiments. Each fiber was manually selected to ensure that no defects were present along its length; this was verified using a loop test, as shown in Fig. 3, where only fibers that bend without visible breaks or twists are selected.

Fig. 3. Loop test to verify the absence of defects along the technical fiber.

The next selection parameter for the fibers is the diameter along their length, choosing fibers with uniform thicknesses based on visual inspection.

To complement the geometric characterization of the fibers, scanning electron microscopy (SEM) was performed at

TecnoAcademia de Manizales, using a TESCAN VEGA3 microscope with a backscattered electron (BSE) detector. Fig. 4 shows the cross-section of a fique technical fiber, revealing a heterogeneous, highly irregular internal structure composed of the bundled elementary fibers, with visible porosity and voids between them rather than a solid, uniform cross-section. This observation confirms that the fiber does not correspond to a circular, solid geometry, supporting the density-based method used to calculate the cross-sectional area later in this study (Eq. 2–4).

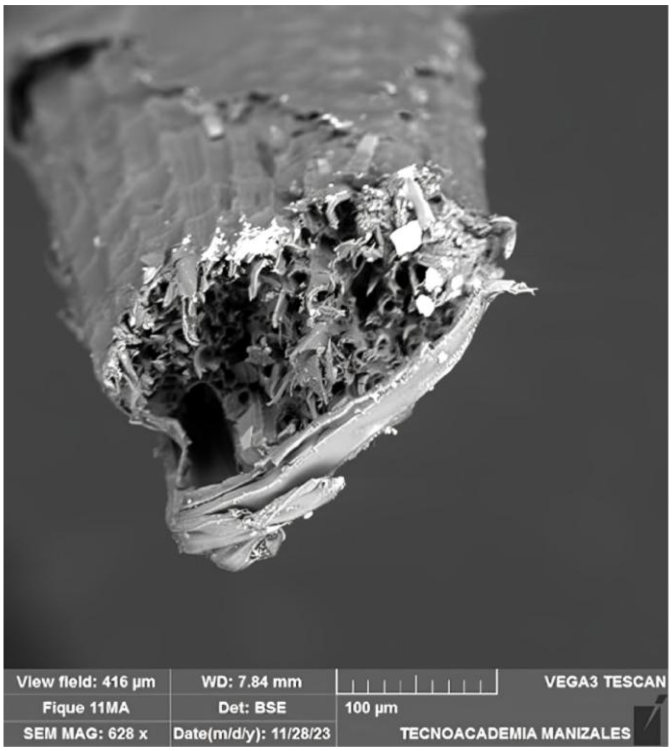

Fig. 4. Cross-section microscopy of a fique fiber.

B. Density

The apparent density of fique fibers was determined using the volume displacement method (Archimedes' principle). A total of 600 fibers were used, each individually cut to a length of 40 mm, and then arranged into 3 groups of 200 fibers each Fig. 5, tied with a fique fiber for subsequent weighing on a Sartorius Entris II analytical balance, with a maximum capacity of 220 g and a precision of 0.1 mg.


Fig. 5. Groups of 200 fique fibers for density measurement using Archimedes' principle.

For the measurement, the average of three readings was calculated, using an equal number of graduated test tubes with 0.1 ml divisions and a volume of 15 ml. Each test tube contained 7 ml of ethanol, into which each group of fibers was individually submerged. The change in volume in the test tube was immediately recorded. The apparent density of the fibers was calculated using (1).

$$\rho_f = \frac{m_f}{V_d} \quad (1)$$

Where: m_f is the mass of each fiber group, V_d is the difference between the initial and final volume, and ρ_f is the density of fique fiber.

Additionally, the density of fique fibers was confirmed at the Analytical Resources and Calibration Laboratory of the Faculty of Chemical Engineering at the State University of Campinas in Brazil, using a Helium Gas Pycnometer, model AccuPyc 1330 (Norcross, USA), with 1 g of fique fibers.

C. Tensile test

After estimating the density, 160 fibers from those previously selected using the loop test were taken, cut to a length of 10 cm, weighed, and individually marked to determine the cross-sectional area based on the density (ρ). The length of the fibers was kept constant. The cross-sectional area was calculated using (2), (3) and (4).

$$\rho = \frac{m}{V} \quad (2)$$

Which corresponds to: $\rho = \frac{m}{A*L}$ (3)

Where: m is the mass, V is the volume, A is the cross-sectional area, ρ is the density, and L is the length.

Therefore,

$$A = \frac{m}{\rho * L} \quad (4)$$

The selected fibers were glued onto a paper frame to ensure proper grip and alignment of the fibers during the tensile test Fig. 6. The paper frame is placed between the grips of the testing machine and then carefully cut before proceeding with the tensile test. The span lengths used for this experiment were 5 mm, 10 mm, 25 mm, and 40 mm; 30 successful tests were conducted for each span length.

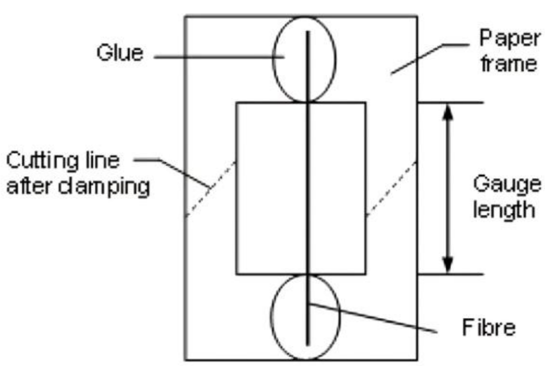

Fig. 6. Schematic representation of the paper frame for single fiber tensile testing.

The tensile tests were performed on a MARK-10 universal testing machine at the Computational and Experimental Mechanics Laboratory of the Universidad Autónoma de Manizales, Colombia (Fig. 7). The test speed was set at 0.8 mm/min, and a 50 N M5-10 load cell was used. The load and displacement of the grips were recorded throughout the entire test.

Fig. 7. Universal testing machine MARK-10.

The strength (σ) was calculated for each test using (5), where F is the maximum force recorded during the test, and A is the previously calculated cross-sectional area for each fiber according to (4).

$$\sigma = \frac{F}{A} \quad (5)$$

The modulus of elasticity (E) was calculated for each span length using (6), where ε is the strain calculated from the machine displacement. To determine the actual value of, E the data were plotted and extrapolated for an infinitely long distance, where machine compliance can be disregarded.

$$E = \frac{\sigma}{\varepsilon} \quad (6)$$

D. Description of tensile strength using the two-parameter Weibull distribution

Additionally, to obtain a reliable value of the ultimate tensile strength of the fibers used, statistical tests were conducted that account for the variability of the data for each span length. Given the brittle and linear-elastic behavior exhibited by fique fibers, as well as the dependence of strength on the presence of defects, the two-parameter Weibull distribution is used to describe the tensile strength of the material (7).

$$P = 1 - exp\left[-\left(\left(\frac{\sigma}{\sigma_0}\right)^m\right)\right] \quad (7)$$

Where:

The shape parameter m primarily defines the variability of the data. The higher the value of m, the narrower the distribution, leading to more consistent fiber strength with less variability, making it an indicator of the quality of the fiber group. The second parameter σ_0, is a characteristic measure of the material's strength at failure, and P is the probability of failure of a fiber at a stress less than or equal to σ [26]. The probability of failure for each fiber was calculated by arranging their tensile strengths in ascending order and applying the following estimator.[26], [28]

$$P = \frac{n-0.5}{N} \quad (8)$$

In equation (8), N is the total number of fibers in the group, and n is the index or position of each data point in this ordered list.

To obtain the two-parameter Weibull distribution through linear regression, it is necessary to rearrange the distribution (Equation 2.7) by taking the natural logarithm twice and rewriting it in the linear form y= mx+C, resulting in (9).

$$\ln\left(\ln\left(\frac{1}{1-P}\right)\right) = m(ln(\sigma)) - m(ln(\sigma_0)) \quad (9)$$

After plotting $y = ln(\sigma)$ against $x = \ln\left(\ln\left(\frac{1}{1-P}\right)\right)$, linear regression was performed to determine the parameter m, which corresponds to the slope of the line, and $(ln(\sigma_0))$, which is the intercept of the line with the vertical axis. Finally, the parameter σ_0 was determined by rearranging (10).

$$C = -ln\, \sigma_0 \quad (10)$$

The two-parameter Weibull distribution was estimated for each span length used in this study.

III. RESULTS

A. Material characterization

Table I presents the results of the density of fique fibers, obtained using Archimedes' principle, helium gas pycnometry, and a comparison with data reported in the literature.

TABLE I.
DENSITY OF FIQUE FIBERS

Density - Archimedes' principle (g/cm^3)	Density - gas pycnometry (g/cm^3)	Density - literature (g/cm^3)	References
1.01	1.15±0.004069	0.65-1.14	[28], [29], [30], [31]

B. Determination of tensile strength

Fig. 8 shows a typical stress-strain curve for fique fibers, where it can be observed that fibers exhibit brittle behavior, with strain at failure close to 2%. Under tensile loading, a linear elastic behavior was observed up to the fracture in all tests.

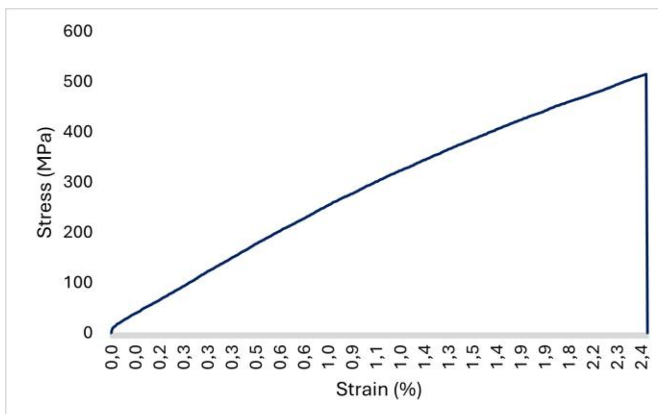

Fig. 8. Stress-strain curve for fique fiber at a span length of 10 mm.

Table II presents the general test data for four span lengths, along with the average diameter of the tested fibers and their respective standard deviations. In the case of fique fibers, the diameters show relatively low variability, ranging from 10% to 19%, with values around 200 µm, which is similar to those reported for other natural technical fibers.[25]

TABLE II.
DATA OF FIBERS TESTED IN THE EXPERIMENT

Span length (mm)	Average fiber diameter (µm)	Number of successful tests
5	188±26	30
10	203±25	30
25	187±35	30
40	208±21	30

Fiber tensile strength results are presented in Table III. Additionally, the results of the two parameters of the Weibull distribution for each span length, the failure strength σ_0, and the shape parameter m are indicated. The m values are similar to those reported for bamboo technical fibers, when the shape parameter m is related to the defect density along the fiber length.[26] In the case of fique fibers values remain around 7, reflecting the consistency and low variability in fiber strength.

TABLE III.
TENSILE STRENGTH OF FIQUE FIBERS AT DIFFERENT SPAN LENGTH AND WEIBULL DISTRIBUTION PARAMETERS

Span length (mm)	Average tensile strength (MPa)	Characteristic strength $\boldsymbol{\sigma_0}$ -Weibull (MPa)	m Parameter Weibull
5	535.4±85,0	575.0	6.6
10	524.9±84,6	560.6	7.1
25	500.3±78,1	534.5	7.2
40	466.3±64,0	493.4	8.6

Fig. 9 shows tensile strength values obtained from experimental results and the characteristic strength obtained from the Weibull distribution. Additionally, a linear regression is performed for both cases, and the corresponding equations are presented.

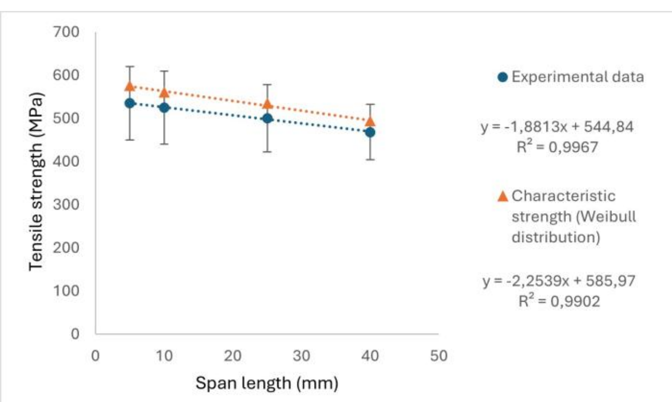

Fig. 9. Fiber tensile strength values as a function of the span length.

C. Determination of the actual value of Young's modulus

Fig. 10 shows the Young's modulus of fique fibers versus 1/span length. The actual modulus value is 24.9 GPa, determined from the linear regression at the point where 1/span length equals zero, corresponding to an infinitely large span length, where any machine compliance has no influence on the strain measurement. This result highlights the need to apply correction procedures when calculating this mechanical property, as the displacements measured by the testing machine tend to lead to underestimated values.

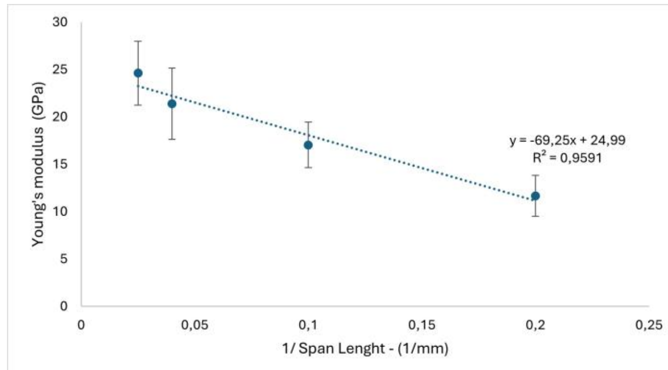

Fig. 10. Young's modulus for each 1/span length.

D. Determination of the actual strain percentage

The values for true strain were obtained using the Young's modulus of 24.9 GPa. The strain percentages for each gauge length are presented in Table IV. Strain values show low variation and remain around 2%. This result is similar to what is commonly reported for other natural fibers like bamboo, hemp and flax.[27], [32]

TABLE IV.
ACTUAL STRAIN OF FIQUE FIBERS

Span length (mm)	Strain to failure - corrected $\Delta \boldsymbol{l_{fiber}}$ (%)
5	2.1
10	2.1
25	2.0
40	1.9

Fig. 11 displays the diameters of the fibers for the 120 tests conducted versus the tensile strength reported for each of them. The small variation in tensile strength when considering the sample's diameter is also an indicator of the fiber's quality. It can be concluded that the fiber's structure retains its natural mechanical properties. In other words, the small variation may be a consequence of the intrinsic defects present in the fibers while still in the leaf, rather than being introduced during the fiber extraction process.

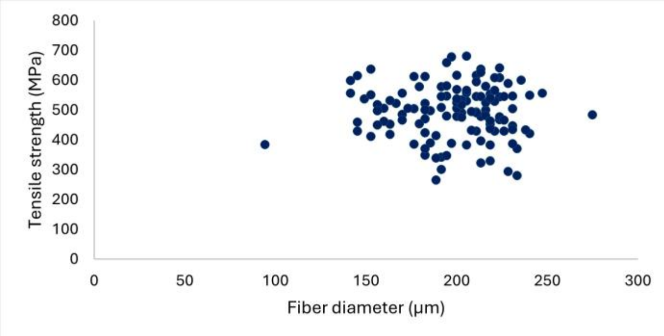

Fig. 11. Influence of fiber diameter on tensile strength of fique technical fibers.

Table V shows mechanical properties of some natural technical fibers. It can be stated that the values obtained in this study for the Young's modulus and the tensile strength of fique fiber are similar to those reported for other fibers in the Agave family, such as sisal, and are higher than the values traditionally reported for fique fibers in other studies. [33], [34], [35]

TABLE V.
MECHANICAL PROPERTIES OF SOME NATURAL TECHNICAL FIBERS

Fiber	Tensile strength (MPa)	Young's modulus (GPa)	Strain to failure (%)	Reference
Flax	345 - 1500	27.6	2.7 – 3.2	[36], [37]
Hemp	690	70	1.6	[36], [37]
Jute	385 - 850	26 - 30	1.5 – 1.8	[36]
Ramie	400 - 940	24 - 65	3.6 – 3.8	[36]
Kenaf	430 - 520	23 - 27	1.8	[36]
Sisal	340 - 600	8 - 12	2.0 – 3.0	[36]
Coir	175 - 200	4 - 6	30	[36]
Bamboo	390 - 715	18 - 55	2.4	[27]
Fique	197 – 331.74	2.4 -10.1	7.7 – 8.2	[33], [34], [35]
Fique	506.7	24.9	2.0	This research

IV. DISCUSSION

From the microstructural analysis of fique fiber, as is generally the case with other natural fibers, it can be observed that the cross-sectional area does not follow a circular geometric shape, as shown in Fig. 4**.** It is commonly observed in other studies, that the fiber cross-sectional area is calculated based on the micrograph of the fiber length, assuming a perfect circular cross-section, as reported by.[38], [39], [40], [41]

Therefore, in cases of cross-sections with irregular geometries, the area should be calculated based on the material's density.

Regarding the tensile strength results, it is common to find high variability in these values for the same type of natural fiber, as shown in Table V. This is due to several factors: on one hand, there is often no rigorous verification of the fiber's quality before the tensile test, and the presence of defects leads to premature fiber failure during the test.

On the other hand, the mounting and alignment of the fiber in the testing machine are crucial to avoid alterations in the results due to slippage in the grip and stress concentrations. In addition, overestimating the cross-sectional area of the fiber results in an underestimation of the tensile strength.

Based on the results of the Weibull distribution, it was concluded that the shape parameter m is relatively high for all span lengths and similar to those obtained in other studies,[25], [26] indicating low data dispersion and good fiber quality. Generally, for natural fibers, m values range from 5 to 15,[42], [43] while for synthetic fibers, this value can be between 3 and 6**.**[26], [44]

Quantitatively, the tensile strength obtained in this study (506.7 MPa) is 53% to 157% higher than the values previously reported for fique fibers (197–331.74 MPa), [33], [34], [35], while the Young's modulus (24.9 GPa) is 2.5 to 10 times higher than previously reported values (2.4–10.1 GPa). This substantial difference is consistent with the methodological factors discussed above: calculating the cross-sectional area from fiber density, rather than assuming a solid circular cross-section, avoids the systematic area overestimation — and consequent strength underestimation — typical of earlier studies; likewise, extrapolating the modulus to an infinitely long span length removes the underestimation introduced by machine and grip compliance when only raw crosshead displacement is used. This latter effect is also evident in the strain results: the actual strain to failure obtained after correction (2%) is approximately four times lower than the uncorrected values reported for fique fibers in the literature (7.7–8.2**%),** [33], [34], [35], confirming that a substantial fraction of the apparent deformation reported in previous studies corresponds to machine-related displacement rather than actual fiber elongation.

For the latter, the presence of defects has a more catastrophic effect than in the case of natural fibers, due to their brittleness and internal structure. In addition, the refining of synthetic fibers to obtain fibers of very small diameters, in the order of 20 microns, involves aggressive processes that also affect their quality. In the case of natural fibers, technical fibers are composed of thousands of elementary fibers of a few hundred microns, which makes them less fragile, and the presence of local defects does not always imply the failure of the entire structure.

V. CONCLUSION

This study analyzed the mechanical behavior of technical fique fibers through a rigorous experimental methodology combining density determination via two independent techniques, tensile testing at multiple span lengths with machine-compliance correction, and two-parameter Weibull statistical analysis. The results confirm the initial hypothesis: applying this rigorous methodology yielded tensile strength (506.7 MPa) and Young's modulus (24.9 GPa) values considerably higher than those traditionally reported for fique fibers in the literature (197–331.74 MPa and 2.4–10.1 GPa, respectively), and comparable to those of other fibers in the Agave family, such as sisal.

The relatively high values obtained for the Weibull shape parameter m indicate low data dispersion and good fiber quality, further supporting the reliability of the proposed methodology. Additionally, correcting for machine misalignment allowed determination of the actual strain value of the fiber (2%), reducing the overestimation typically introduced when raw crosshead displacement is used.

It is important to note the scope of this study: the results correspond to the properties of individual technical fique fibers under the specific extraction process used, and should not be extrapolated directly to the mechanical behavior of finished fique fiber-reinforced composite materials, which depend on additional factors such as fiber-matrix adhesion and fiber volume fraction. Although the fibers characterized in this study were sourced from a single region (municipality of Aranzazu, Caldas, Colombia), preliminary tensile tests conducted on fique fibers from Boyacá, Colombia, at the same span length (25 mm), yielded a comparable tensile strength (455.44 ± 74.63 MPa) to that obtained for the Aranzazu fibers (500.3 ± 78.1 MPa), suggesting that the mechanical properties characterized are not strongly dependent on the specific geographic origin within the studied regions of Colombia.

The results obtained in this research on the physical and mechanical properties of fique fibers demonstrate the importance of using appropriate and validated experimental techniques to obtain accurate values for natural fibers, thereby determining their real potential and expected performance as reinforcement in composite materials.

For future work, it is recommended to evaluate the performance of fique fibers within actual composite materials, assess the effect of surface treatments (such as mercerization) on their mechanical properties, study their behavior under environmental aging conditions, and validate the proposed characterization methodology on other natural fibers of interest.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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