Journal of Natural Fibers

ISSN: 1544-0478 (Print) 1544-046X (Online) Journal homepage: www.tandfonline.com/journals/wjnf20

Comparative Analysis of Polyester Composites Reinforced with Local Plant Fibers: *Stipa tenacissima* Vs. *Agave americana*

Mostefa Meddah, Salah Amroune, Mansour Rokbi, Ahmed Belaadi, Nourelimane Bouaziz, Saber Achour, Mahmood M. S. Abdullah, Hamad A. Al-Lohedan, Amar Al-Khawlani & Herbert Mukalazi

To cite this article: Mostefa Meddah, Salah Amroune, Mansour Rokbi, Ahmed Belaadi, Nourelimane Bouaziz, Saber Achour, Mahmood M. S. Abdullah, Hamad A. Al-Lohedan, Amar Al-Khawlani & Herbert Mukalazi (2026) Comparative Analysis of Polyester Composites Reinforced with Local Plant Fibers: *Stipa tenacissima* Vs. *Agave americana*, Journal of Natural Fibers, 23:1, 2646163, DOI: 10.1080/15440478.2026.2646163

To link to this article: https://doi.org/10.1080/15440478.2026.2646163

Published online: 26 Mar 2026.

JOURNAL OF NATURAL FIBERS
2026, VOL. 23, NO. 1, 2646163
https://doi.org/10.1080/15440478.2026.2646163

Taylor & Francis
Taylor & Francis Group

Comparative Analysis of Polyester Composites Reinforced with Local Plant Fibers: *Stipa tenacissima* Vs. *Agave americana*

Mostefa Meddah[a], Salah Amroune[a,b], Mansour Rokbi[a], Ahmed Belaadi[c], Nourelimane Bouaziz[a], Saber Achour[a], Mahmood M. S. Abdullah[d], Hamad A. Al-Lohedan[d], Amar Al-Khawlani[e], and Herbert Mukalazi[f]

[a]Mechanical Department, Faculty of Technology, University of Msila, Msila, Algeria; [b]Materials and Structural Mechanics Laboratory (LMMS), University of Msila, Msila, Algeria; [c]Department of Mechanical Engineering, Faculty of Technology, University 20 Août 1955, Skikda, Algeria; [d]Department of Chemistry, College of Science, King Saud University, Riyadh, Saudi Arabia; [e]Jiangsu Optoelectronic Functional Materials and Engineering Research Centre, School of Chemistry and Chemical Engineering, Southeast University, Nanjing, China; [f]Department of Mathematics and Statistics, Kyambogo University, Kampala, Uganda

ABSTRACT

This work presents a comparative investigation of unsaturated polyester composites reinforced with two local Algerian lignocellulosic fibers: Stipa Tenacissima and Agave americana. These fibers were harvested, water-retted, and subsequently characterized using Fourier Transform Infrared Spectroscopy (FTIR) and X-ray Diffraction (XRD). Single-fiber tensile testing, supported by Weibull statistical analysis, showed that Stipa Tenacissima fibers exhibit a higher Young's modulus (~15.5 GPa) and lower elongation at break, whereas Agave fibers display lower stiffness (~6.7 GPa) but significantly greater ductility. Two unidirectional composites, unsaturated polyester/ Stipa Tenacissima and unsaturated polyester/ Agave Americana, containing each approximately 25 wt% fiber were fabricated using the vacuum-bagging process and cured at 70 °C for 2 h. Mechanical testing revealed substantial improvements compared to neat polyester. Stipa Tenacissima fiber composites achieved an increase of about 120% in tensile modulus and nearly 110% in flexural modulus. In contrast, Agave Americana fiber composites exhibited lower stiffness but superior strain-to-failure and toughness, with an enhancement of ~95% in flexural strength. Overall, the results confirm that both Stipa Tenacissima and Agave Americana are effective reinforcements for polymeric matrices: Stipa Tenacissima fibers primarily improve stiffness and strength, while Agave fibers enhance ductility and energy-absorption capability.

摘要

这项工作对用两种阿尔及利亚当地木质纤维素纤维增强的不饱和聚酯复合材料进行了比较研究: Stipa Tenacissima和Agave americana. 收集这些纤维，用水脱胶，随后使用傅里叶变换红外光谱 (FTIR)和X射线衍射 (XRD)对其进行表征. Weibull统计分析支持的单纤维拉伸试验表明，Stipa Tenacissima纤维具有更高的杨氏模量 (~15.5 GPa)和更低的断裂伸长率，而龙舌兰纤维的刚度较低 (~6.7 GPa)，但延展性明显更高. 使用真空装袋工艺制备了两种单向复合材料，不饱和聚酯/Tenacissima针茅和不饱和聚酯/Pagave Americana，每种复合材料含有约25重量%的纤维，并在70℃下固化2小时. 机械测试显示，与纯聚酯相比，有了实质性的改进. Stipa Tenacissima纤维复合材料的拉伸模量提高了约120%，弯曲模量提高了近110%. 相比之下，龙舌兰纤维复合材料的刚度较低，但断裂应变和韧性较好，抗弯强度提高了约95%. 总体而言，研究结果证实，Stipa Tenacissima和Agave Americana都是聚合物基体的有效增强材料: Stipa Tenaciossima纤维主要提高刚度和强度，而Agave纤维则提高延展性和能量吸收能力. 这些发现突显了当地可用的天然纤维作为结构和半结构复合材料应用的可持续替代品的潜力.

KEYWORDS

Stipa tenacissima; *Agave americana*; natural fiber composites; polyester resin; tensile and flexural properties; Weibull statistics

关键词

限制性规定; 美国龙舌兰; 天然纤维复合材料; 聚酯树脂; 拉伸和弯曲性能; 统计

CONTACT Ahmed Belaadi ahmedbelaadi1@gmail.com Department of Mechanical Engineering, Faculty of Technology, University 20 Août 1955, BP 26, Route d'El Hadaiek, Skikda 21000, Algeria; Herbert Mukalazi hmukalazi@kyu.ac.ug Department of Mathematics and Statistics, Kyambogo University, P.O. Box 1, Kyambogo, Kampala, Uganda

Introduction

Today, research on new high-performance composites (HPCs) focuses on advanced materials (B. X. Chai et al. 2023; Chai et al., 2024a; Chai, Eisenbart, Nikzad, Fox, Blythe, et al. 2023; Wang et al. 2024), which are lightweight and ultra-resistant. These materials are produced by combining two different synthetic reinforcements (such as carbon, aramid, or glass fibers) with a matrix (epoxy or ceramic) in order to achieve superior properties, including an excellent strength-to-weight ratio, high durability, and good fatigue resistance (Blythe et al. 2024; B. Chai et al. 2024; B. X. Chai et al. 2024; Shevtsov et al. 2024).

In response to the growing global environmental concerns associated with the use of conventional plastic materials, interest in sustainable and renewable materials continues to rise. Natural plant fibers have emerged as promising alternatives for reinforcing polymer composites, combining light weight, biodegradability, and local availability while reducing the environmental footprint of conventional composite materials (Abdollahiparsa et al. 2023; B. X. Chai et al. 2023; Elfaleh et al. 2023; Kir et al. 2024; Nouri et al. 2025; Saha et al. 2025). Recent studies on wood fiber reinforced geopolymer composites demonstrate natural fibers' versatility across matrices, achieving enhanced mechanical properties (compressive ‹ flexural with 5–35 wt% fibers) despite different chemistry from polyester (Furtos et al. 2021, 2022). Our polyester/Alfa-Agave system complements this‹ highlighting local Algerian fibers' potential

Among natural fibers, those derived from endemic plants of the Mediterranean basin – particularly *Stipa tenacissima* (named Alfa) and American Agave (named Agave) – stand out due to their remarkable mechanical properties and wide availability in Algeria and the Maghreb region (Abdollahiparsa et al. 2023; Elfaleh et al. 2023; Gheribi et al. 2024; Nouri et al. 2025; Saha et al. 2025).

Alfa fiber, known for centuries in North African regions, is a long cellulosic fiber traditionally used for producing coarse fabrics and insulating materials. Its high cellulose content, combined with good mechanical stiffness, makes it an ideal candidate for composite reinforcement, with an industrial potential that remains underexploited. On the other hand, Agave fiber offers an interesting combination of stiffness and elongation at break, providing a more ductile mechanical behavior to composites reinforced with this fiber (Idres et al. 2022; Msahli et al. 2015).

One of the major challenges associated with integrating natural fibers into polymer matrices is the poor chemical compatibility between the hydrophilic nature of plant fibers and the hydrophobic character of polymer matrices. This incompatibility can lead to weak interfacial adhesion and premature degradation of mechanical properties, particularly in the presence of moisture (Lee, Khalina, and Lee 2021; Sathish et al. 2021). This study stands out by using environmentally friendly fiber extraction methods – specifically water retting – without resorting to chemical treatments, in order to preserve the natural structure of the fibers while minimizing environmental impact (Gheribi et al. 2024; Sanjay et al. 2019; Tahir et al. 2011).

The selected manufacturing technique, *vacuum bagging*, allows the production of unidirectional composites with good impregnation of the fibers by the unsaturated polyester matrix, thereby promoting improved overall mechanical performance (Rayyaan et al. 2021). The evaluation of mechanical properties is based on tensile and three-point bending tests, conducted in accordance with ASTM standards, as well as statistical analysis of the data using Weibull distribution, which makes it possible to assess the reliability and homogeneity of the properties of the fibers and composites (Benarab et al. 2025; Torres et al. 2017).

Although several studies have separately explored the use of Alfa or Agave fibers in polymeric composites, none, to our knowledge, has proposed a direct comparison within a unified experimental protocol.

For instance, Alfa has already been studied for its structural and mechanical properties after chemical treatments, notably through FTIR and XRD analyses, as well as in hybrid composites (Atoui et al. 2024; Bouchareb et al. 2025). Furthermore, several recent reviews on natural-fiber composites highlight advances in surface treatments, manufacturing techniques, and applications; however, these studies remain general and do not address an integrated comparison of two local fibers under identical conditions (Islam et al. 2024; Meddah, Rokbi, and Zaoui 2023). In the same context, recent works have reported the extraction and characterization of lignocellulosic fibers from local plants such as *Malva sylvestris* L. and *Centaurea hyalolepis*, opening new perspectives for their use as composite reinforcements (Makri et al. 2023; Meddah, Rokbi, and Zaoui 2023).

The absence of a comparative study combining structural characterization (FTIR, XRD), tensile testing with Weibull analysis, and the fabrication of polymeric composites using vacuum bagging represents a major scientific gap.

Our work aims to fill this gap by proposing, for the first time, a comprehensive methodological evaluation, from isolated fibers to the mechanical performance of composites, applied under strictly identical conditions for Alfa and Agave fibers. This research provides an original contribution through the detailed comparison of two local natural fibers in the formulation of unsaturated polyester-reinforced composites, highlighting the distinct effects of Alfa and Agave fibers on mechanical performance, as well as their potential to partially replace synthetic fibers in structural and semi-structural applications, with a strong emphasis on sustainability and the valorization of local resources.

Material and methods

Harvesting, extraction, and preparation of Alfa and Agave fibers

Alfa (*Stipa tenacissima*) and *Agave americana* fibers were harvested in the Boussaâda region (M'Sila, Algeria), selecting only mature and healthy leaves with a light-green to green coloration and free from any visible defects (Figure 1a). This rigorous selection was adopted to ensure morphological homogeneity and consistent mechanical properties of the extracted fibers.

Fiber extraction was carried out through *biological water retting*. This environmentally friendly method consists of immersing the leaves in water at ambient temperature (25–30°C) for *30 to 45 days* in closed containers (Mansour, Abdelaziz, and Fatima Zohra 2018). Retting promotes enzymatic degradation of non-fibrous components (pectin, hemicelluloses, waxes), allowing efficient release of fiber bundles without the use of harmful chemical agents (Banik et al. 2003). After retting, the extracted fibers were thoroughly washed with running water until no visible pith, cuticle fragments, or mucilaginous residues remained on the bundles. This combination of controlled water retting followed by intensive washing is in line with

Figure 1. Sequential fiber extraction process: (a) *Stipa tenacissima* (Alfa) plant used as raw material; (b) *Stipa tenacissima* fibers after water retting, washing, and drying; (c) *Agave americana* plant used as raw material; (d) *Agave americana* fibers after water retting, washing, and drying.

standard extraction protocols for natural fibers, where fibers are washed thoroughly with water after retting to remove residual non-cellulosic components and degradation products before drying (Meddah, Rokbi, and Zaoui 2023).

Fibers were air-dried in shade, then oven-dried at 70°C for 5 h to achieve low, stable moisture content – essential for matrix wettability and dimensional stability. Final fiber morphology shown in Figure 1(b,e).

The dried fibers were then manually combed, sorted according to length, and stored in moisture-proof sealed bags until their use in physicochemical analysis, mechanical testing, and composite fabrication.

The matrix used for composite manufacturing was an *orthophthalic polyester resin*, widely employed in industry due to its ease of processing, good adhesion to natural fibers, and moderate cost. Resin curing was initiated by incorporating *1.5% by volume of methyl ethyl ketone peroxide (MEKP)* as a catalyst.

This methodology effectively valorizes local plant resources through environmentally responsible processes while ensuring optimal reproducibility and reliability of the produced composite materials.

X-ray diffraction (XRD)

The dried Alfa and Agavefibers were ground and analyzed by XRD (Cu Kα, λ = 1.5406 Å) in θ–2θ mode, over the range 2θ = 5–40°, with a step size of 0.02° and a scanning speed of approximately 1°·min^{-1}. The crystallinity index (CI) was estimated using the Segal method (Segal et al. 1959):

$$CI\% = \left(\frac{I_{002} - I_{Am}}{I_{002}}\right) \times 100 \quad (1)$$

where I_{002} is the maximum intensity (corresponding to the (200) plane of cellulose I) around 22–22.8° (2θ), and I_a is the minimum intensity of the amorphous region near 18° (2θ). This method, widely used for lignocellulosic materials, allows a relative comparison between Alfa and Agave; however, its metrological limitations, discussed in recent literature, must be kept in mind.

ATR-FTIR spectroscopy

Infrared spectra were recorded using Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) spectroscopy in the range 4000–400 cm^{-1}, with a spectral resolution of 4 cm^{-1} and 32 scans per sample. This technique was selected to identify the chemical functional groups present on the fiber surfaces through direct contact with the ATR crystal, providing qualitative information on cellulose, hemicellulose, and lignin content essential for understanding fiber-matrix compatibility.

Tensile testing of single fibers

The tensile mechanical behavior of individual fibers was evaluated using a universal testing machine (Zwick/Roell Z100, Germany) equipped with a 2.5 kN load cell. Each fiber was carefully mounted on a rectangular paper frame to ensure proper axial alignment and prevent slippage, in accordance with the preparation procedures described in ASTM D3822-01 (International 2007) (Figure 2). The lateral sides of the frame were cut just before the test to release the fiber and eliminate any possible pre-tension.

Tensile tests were carried out under quasi-static conditions with a crosshead speed of 2.5 mm·min^{-1} and a gauge length of 40 mm. For each fiber type, at least 30 valid specimens were tested to ensure sufficient statistical significance. The tensile strength (σ_u) was calculated using the following equation:

$$\sigma = F/A \quad (2)$$

where σ (MPa) is the ultimate tensile stress, F (N) is the maximum applied load, and A (m^2) is the mean cross-sectional area of the fiber, determined from optical micrographs using digital image analysis.

All tests were performed under ambient laboratory conditions (22 ± 2°C, 50 ± 5% RH). The resulting stress – strain curves allowed the identification of the elastic and failure regions and were used for statistical dispersion analysis of the data using the Weibull distribution (Bouchareb et al. 2025).

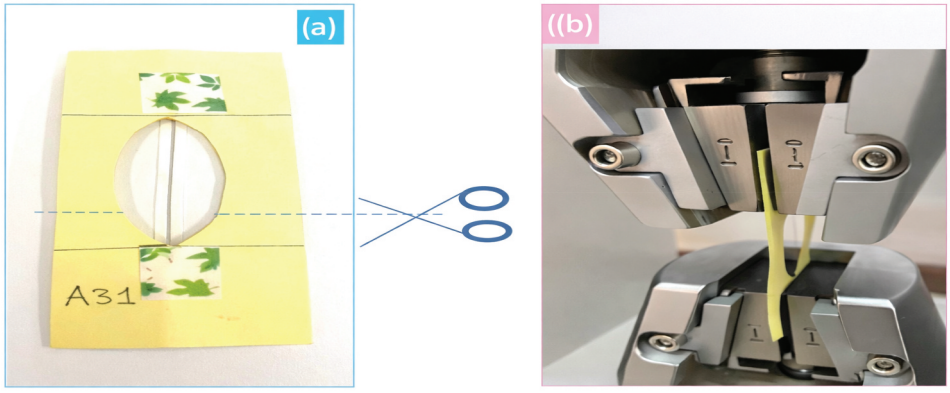

Figure 2. Tensile test: (a) preparation of tensile specimens; (b) test specimens loaded in tension until failure.

Weibull statistical analysis

The dispersion of the tensile failure stresses was analyzed by applying the two-parameter Weibull distribution. The cumulative probability of failure was estimated using (Bedjaoui et al. 2019; Belaadi et al. 2022; Saaidia et al. 2015):

$$(\sigma) = \frac{\mathrm{i} - 0.3}{\mathrm{N} + 0.4} \tag{3}$$

where **i** is the rank of the specimen and **N** is the total number of samples. The linearized form:

$$\ln(\ln(\frac{1}{1-(F(\sigma)}))) - \ln(\frac{L}{L_0}) = m(\ln\sigma - \ln\sigma_0) \tag{4}$$

allows the determination of the Weibull modulus (m) and the characteristic strength σ_0. This approach is widely used to evaluate the reliability and homogeneity of natural fibers (Amroune, Belaadi, Bourchak, et al. 2022; Belaadi, Amroune, and Bourchak 2020; Benarioua et al. 2025).

Manufacturing of unidirectional composites

The fabrication of the polyester-matrix composites was carried out following a rigorous methodology inspired by recently validated protocols in the scientific literature (Amroune, Belaadi, Dalmis, et al. 2022; Grisin, Carosella, and Middendorf 2024; Phiri et al. 2024). After extraction and drying, each fiber type was processed separately to avoid cross-contamination and to ensure the comparability of results.

The fibers were manually aligned in a strictly parallel configuration to form unidirectional mats with dimensions of 250 × 150 mm. To ensure homogeneous orientation and stability during handling, the ends of the fiber bundles were fixed using double-sided adhesive tape on the longitudinal edges of a rigid cardboard frame, forming a regular mat ready for impregnation (Figure 3(a-e)). Four unidirectional plies were then prepared for each fiber type of fibers and stacked in a flat rigid mold coated with a release agent. The Ortho-phthalic polyester resin was carefully degassed under vacuum for several minutes to eliminate microbubbles that could compromise interfacial cohesion. The mold was then covered with an airtight nylon film, an absorbent sheet, and a drainage fabric, and sealed hermetically using sealing tape.

Impregnation of the fibers by the resin was optimized through the application of a controlled vacuum of −0.8 bar, in accordance with the recommendations reported for the vacuum bagging process (Ashrith, Jeevan, and Xu 2023; Grisin, Carosella, and Middendorf 2024). This step promotes uniform matrix distribution and reduces internal porosity (Figure 3c). After impregnation, the laminate was left at room temperature for 24 h to allow initial polymerization, followed by a post-curing treatment at 70°C for 2 h in a ventilated oven to ensure complete curing and improved dimensional stability (Figure 3d). This methodology enabled the production of homogeneous unidirectional composites characterized by efficient

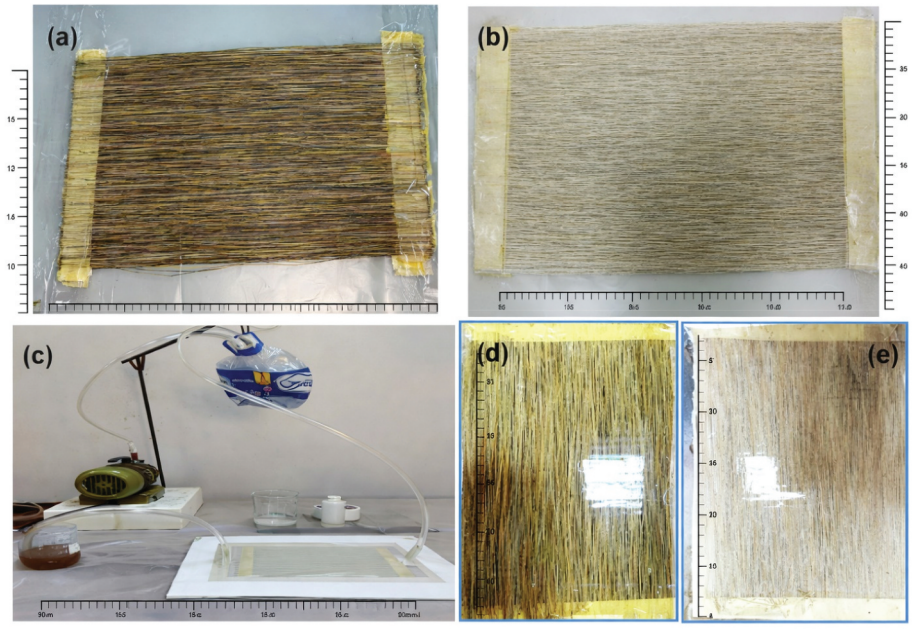

Figure 3. Unidirectional plies of: (a,b) Alfa and Agave plies, (c) vacuum bagging setup used for composite manufacturing; (d, e) bio-composite plates.

impregnation, uniform fiber distribution, and optimized structural quality, thus making the materials suitable for mechanical characterization and for comparing the performances of the two fiber types.

Mechanical characterization of the composites and the resin

Mechanical tests were conducted to evaluate the performance of the Ortho-phthalic polyester resin alone as well as the composites. The Tensile tests were carried out in accordance with ASTM D3039 on specimens with dimensions of $100 \times 10 \times 2\ mm^3$ (Figure 4). Six samples were tested for each configuration (pure resin and Alfa/polyester composite). The crosshead speed was set to 2 mm/min. In addition, the flexural tests were performed according to ASTM D790-10 using a tensile testing machine equipped with a 2.5 kN load cell. The span length between supports was fixed at 32 mm, corresponding to a ratio of L/h = 16, which complies with the standard recommendations (Figure 5). The mechanical properties (maximum stress, flexural modulus, and corresponding strain) were calculated using the standard equations for three-point bending.

Results and discussion

X-ray diffraction (XRD)

X-ray diffraction (XRD) analysis was carried out to characterize the crystalline structure of Alfa and *Agave* fibers. Based on the corresponding diffractograms (Figure 6(a,b)) and using the empirical Segal method, a crystallinity index (CI) of ≈47% was obtained for Alfa fibers and ≈41% for Agave fibers. This difference is attributed to the better organization of cellulose chains in Alfa, which generally results in a more ordered structure and a higher cellulose content – both known factors that increase the stiffness and mechanical strength of reinforcing fibers. Indeed, high crystallinity is frequently correlated with a higher Young's modulus and improved tensile performance (Salem et al. 2023). In contrast, Agave fibers exhibit a lower CI, indicating a higher proportion of amorphous components (lignin, hemicelluloses) and reduced crystalline organization. Such a less rigid structure may promote greater ductility and elongation at break, which is consistent with applications requiring higher energy absorption. Chemical pretreatments such as alkali or enzymatic treatments, as reviewed in (Antony et al. 2025; Cherian et al. 2023; Chirayil, Joy, et al. 2014;

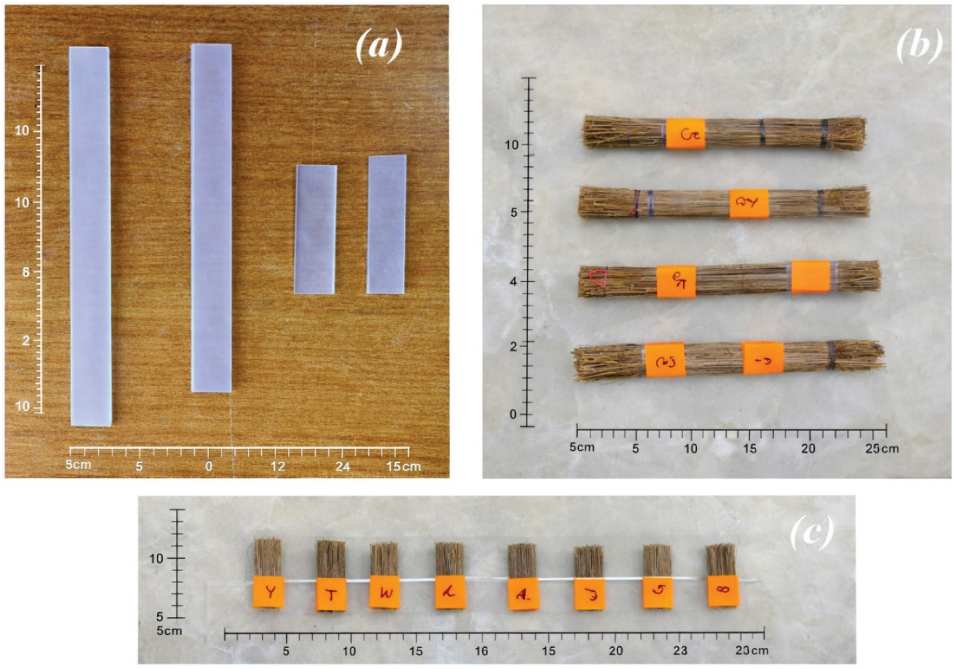

Figure 4. Of specimens obtained: (a) tensile and three-point bending specimens of resin, (b) tensile specimens of bio-composites, and (c) three-point bending specimens of bio-composites.

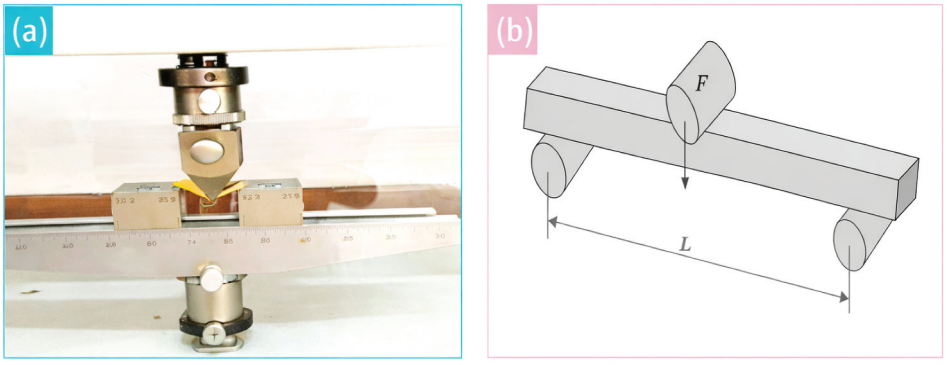

Figure 5. Experimental setup for three-point bending: (a) experimental configuration; (b) diagram of a flexural test specimen.

Chirayil, Mathew, et al. 2014; Varghese et al. 2024), can further enhance crystallinity by 10–20% through selective removal of amorphous components (hemicellulose, lignin, pectin), offering potential for additional stiffness and compatibility optimization in future Alfa and Agave fiber applications. In summary, the XRD results (Figures 6a and 7b) and the obtained CI values help explain, in part, the mechanical performance differences between the two fiber types and guide their potential use in different composite reinforcement applications. These observations confirm the XRD results and help clarify the structural and mechanical differences between the two fibers within composite materials.

ATR-FTIR analysis

ATR-FTIR analysis allowed the identification of the main functional groups present in Alfa and *Agave* fibers (Table 1). The spectra shown in Figure 7(a,b) reveal characteristic bands of lignocellulosic fibers, similar to those reported for several other local plant fibers such as *Hyphaene thebaica*, *Lygeum spartum*, *Juncus*

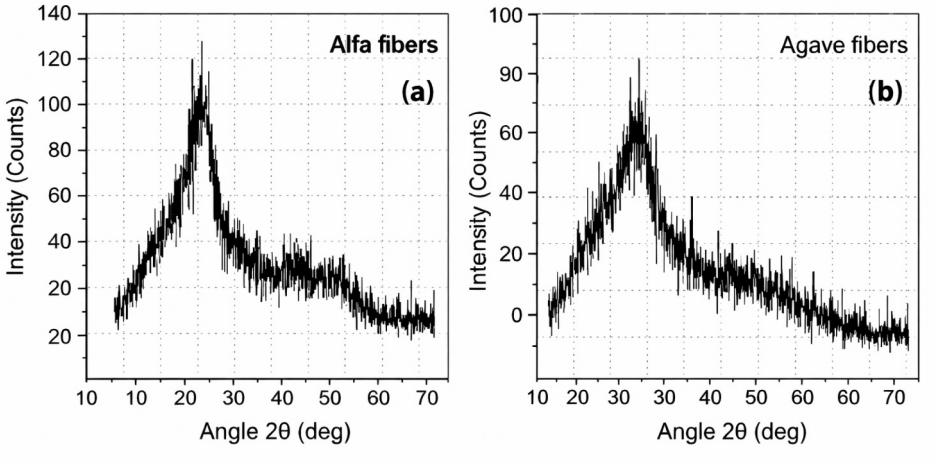

Figure 6. X-ray diffraction (XRD) patterns of Alfa and Agave fibers.

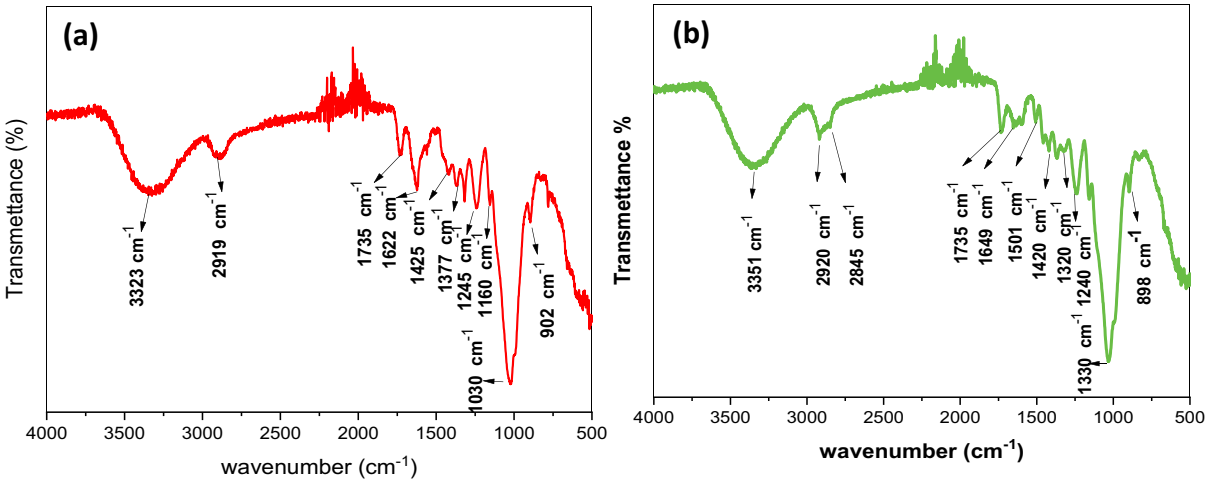

Figure 7. ATR-FTIR spectra of Agave (a) and Alfa fibers (b).

effusus, *Silybum marianum*, or *Inula viscosa* (Belouadah, Ati, and Rokbi 2015; Laifa et al. 2022; Lemita et al. 2022; Maache et al. 2017; Mansour, Abdelaziz, and Fatima Zohra 2018; Moussaoui et al. 2021). The broad band around 3330–3350 cm^{-1} corresponds to O – H stretching vibrations, indicating the presence of cellulose and hemicelluloses. Similar peaks have been reported for *Hyphaene thebaica* (Mansour, Abdelaziz, and Fatima Zohra 2018) and *Juncus effusus* (Maache et al. 2017). The band observed around ≈2900 cm^{-1}, attributed to C – H stretching vibrations of aliphatic structures, also appears in all lignocellulosic fibers described in the literature. In the 1730–1740 cm^{-1} region, Agave fibers exhibit a more intense carbonyl (C = O) band, indicative of a higher content of hemicelluloses and pectic compounds. A similar intensity of this band has been reported for *Silybum marianum* (Laifa et al. 2022) and *Inula viscosa* mouss (Moussaoui et al. 2021). The band around 1510–1520 cm^{-1}, characteristic of aromatic C = C vibrations of lignin, is visible in both fiber types but appears slightly more pronounced in Agave fibers. This behavior is consistent with observations reported for *Strelitzia reginae* fibers (Lemita et al. 2022), known for their higher lignin content. Finally, the bands located between 1030 and 1050 cm^{-1}, attributed to C – O – C vibrations of the polysaccharide cellulose backbone, are more intense in Alfa fibers. This result aligns with the characteristics of cellulose-rich fibers such as *Lygeum spartum* (Belouadah, Ati, and Rokbi 2015) and *Juncus effusus* (Maache et al. 2017), suggesting a higher cellulose content in Alfa fibers. These FTIR signatures confirm higher cellulose content in Alfa fibers versus hemicellulose/lignin-rich Agave. Chemical pretreatments documented in (Antony et al. 2025; Cherian et al. 2023; Chirayil, Mathew, et al. 2014; Varghese et al.

Table 1. Identification of the most significant peaks in the ATR-FTIR spectra of the two fibers.

Wavenumber (cm^{-1})	Band positions (cm^{-1})		Functional group	Source
	Agave	Alfa		
3600–3100	3323	3351	O–H stretching	Cellulose, Hemicellulose
2950 and 2854	2919	2920 and 2845	CH_2	Cellulose, Hemicellulose
1740–1600	1735 and 1622	1735 and 1649	C = O	Cellulose, Hemicellulose
1460	–	1501	C = C	Lignin, Hemicellulose
1430	1425	1420	CH_2	Lignin, Hemicellulose
1377	1377	1330	C–H	Lignin
1320	–	1320	CH_2 and CH_3	Cellulose
1243	1245	1240	–COO	Hemicellulose
1055	1030	1030	C–O	Cellulose
1160	1160	–	C–O–C	Cellulose, Hemicellulose
894	902	898	Glycosidic bond	Cellulose, Hemicellulose

2024) demonstrate that alkali and enzymatic methods can further reduce non-cellulosic impurities (C = O 1730 cm^{-1}, lignin 1500 cm^{-1}), potentially enhancing fiber-matrix compatibility for future composite optimization. Overall, the ATR-FTIR analysis shows that: (i) Alfa fibers possess a higher cellulose content and a more ordered structure; (ii) Agave fibers contain a higher amount of lignin and amorphous components, which explains their more ductile mechanical behavior.

Tensile analysis of both single fibers

The tensile tests performed on Alfa and *Agave* fibers highlight clearly distinct mechanical behaviors (Figure 8(a,b)). Alfa fibers exhibit a well-defined linear elastic behavior followed by a sudden failure, characteristic of a brittle and highly crystalline material. This failure mode has already been reported for Alfa fibers by (Bessadok et al. 2009; Rokbi, Herbelot, and Imad 2013), who emphasized that the high cellulose content and compact microfibrillar organization promote abrupt failure under tensile loading. In contrast, Agave fibers show a much more ductile and multi-stage behavior, similar to the observations reported by (Fiore et al. 2016). The stress – strain curves of Agave typically exhibit: (i) an initial linear elastic phase; (ii) a non-linear transition zone marked by the occurrence of micro-fractures within the microfibrils, a phenomenon previously described by (Satyanarayana, Arizaga, and Wypych 2009); (iii) a final quasi-linear phase leading to failure. This ductile behavior is attributed to a higher lignin and hemicellulose content, giving Agave fibers a less ordered structure that is more capable of elongation, as explained by (Hidalgo-Reyes et al. 2015; Satyanarayana, Arizaga, and Wypych 2009). The average mechanical values obtained (Table 2) confirm these trends: (i) Alfa fibers exhibit a higher tensile strength (269.17 ± 70.32 MPa), a higher Young's modulus (14.875 ± 8.60 GPa), and a low elongation at break (1.77 ± 0.52%). These values are consistent with those reported in the literature (Rokbi, Herbelot, and Imad 2013). (ii) Agave fibers display slightly lower tensile strength (228.97 ± 47.76 MPa) and a lower modulus (4.83 ± 1.027 GPa), but a significantly higher elongation at break (≈20%), in agreement with the results published by (Fiore et al.

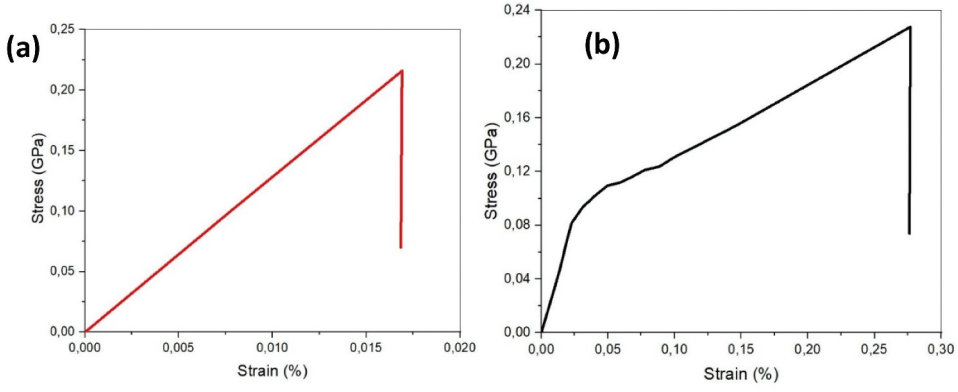

Figure 8. Typical stress–strain (σ , ε) curve of Alfa fiber. and, (b) Agave fiber.

Table 2. Mechanical properties of Alfa and Agave fibers.

Fibers	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
Alfa	269.17 ± 70.32	14.875 ± 8.60	1.77 ± 0.52
Agave	228.97 ± 47.76	4.83 ± 1.027	20.26 ± 5.32

2016). The observed differences are directly related to the microstructure of the fibers: (i) Alfa possesses a more crystalline microfibrillar organization, resulting in higher stiffness and strength. (ii) Agave presents a more amorphous and lignin-rich structure, promoting energy absorption, plasticity, and deformation before failure. Finally, the values obtained are comparable to those reported for other natural fibers such as sisal, kenaf, and certain date palm fibers, further supporting the reliability and consistency of the results.

Weibull statistical analysis

The mechanical properties of Alfa and *Agave* fibers were estimated using the two-parameter Weibull distribution. This method is commonly employed to describe the variability of brittle materials and the dispersion of natural fiber properties (Bourahli 2018; Cândido et al. 2014; Dooley, Creasy, and Cuellar 2000; Hashim and Oleiwi 2016). This approach enables the estimation of the shape parameter (m), which reflects data dispersion, as well as the characteristic value (σ_0, E_0, or ε_0) associated with a 63.2% probability of failure. Figure 9(a–f) show the Weibull distributions for tensile strength, Young's modulus, and strain at break, respectively. The nearly linear alignment of the experimental points demonstrates good agreement with the Weibull model, confirming its relevance for the statistical analysis of fibers. For tensile strength, the obtained parameters indicate that Agave fibers exhibit slightly lower dispersion than Alfa fibers, reflecting a more homogeneous mechanical behavior. This result is consistent with the more amorphous nature of Agave fibers, as previously reported in the literature (Lalaymia et al. 2024). For Young's modulus, Alfa fibers show a higher shape parameter (m), indicating lower variability. This behavior is expected for fibers with a more crystalline and better-organized structure, as demonstrated in several studies such as (El-Abbassi et al. 2020). Regarding strain at break, Agave fibers present significantly higher characteristic values, confirming their ductility and superior elongation capacity. This trend is directly related to their higher lignin and hemicellulose content (Nasri, Loranger, and Toubal 2023; Ye et al. 2018). All Weibull and experimental results are summarized in Table 3, which compiles the statistical parameters associated with each mechanical property. In conclusion, the two-parameter Weibull distribution proves to be an effective tool for modeling the variability of natural fibers. It highlights the difference between the brittle and stiff behavior of Alfa fibers and the more ductile and dispersed response of Agave fibers, providing essential information for their use in composite materials.

Tensile test of both composites

The results of the tensile tests show clear differences between the neat polyester resin and the composites. The pure resin exhibits a typically brittle behavior, characterized by a linear elastic phase followed by an abrupt fracture, which is consistent with the classical behavior reported for thermoset polyester matrices (Abbasnejadfard, Bastami, and Hashemi 2022; Hemadi, Al-Ahmady, and Sulyman 2024). The incorporation of natural fibers significantly enhances the mechanical response of the materials. The polyester/Alfa composite shows an increase in Young's modulus (≈2.99 GPa) compared to the neat resin, reflecting the contribution of a rigid reinforcement (Figure 10). This result agrees with the findings of (Brahim and Cheikh 2007) on Alfa – polyester composites, who reported a significant increase in stiffness due to the crystalline microfibrillar organization of Alfa fibers. However, the ultimate tensile strength remains moderate, and the maximum strain is low, suggesting limited fiber – matrix interfacial adhesion, leading to brittle failure and imperfect load transfer. In contrast, the polyester/Agave composite exhibits a more ductile mechanical behavior and a higher strain at break (1.55%). This behavior can be attributed to the more amorphous lignocellulosic structure of Agave fibers and to a more efficient fiber – matrix interface, enabling greater energy dissipation before fracture. Similar trends have been reported in sisal – polyester composites (Oksman et al. 2002) and in Agavere inforced polyester composites, where woven Agave fiber

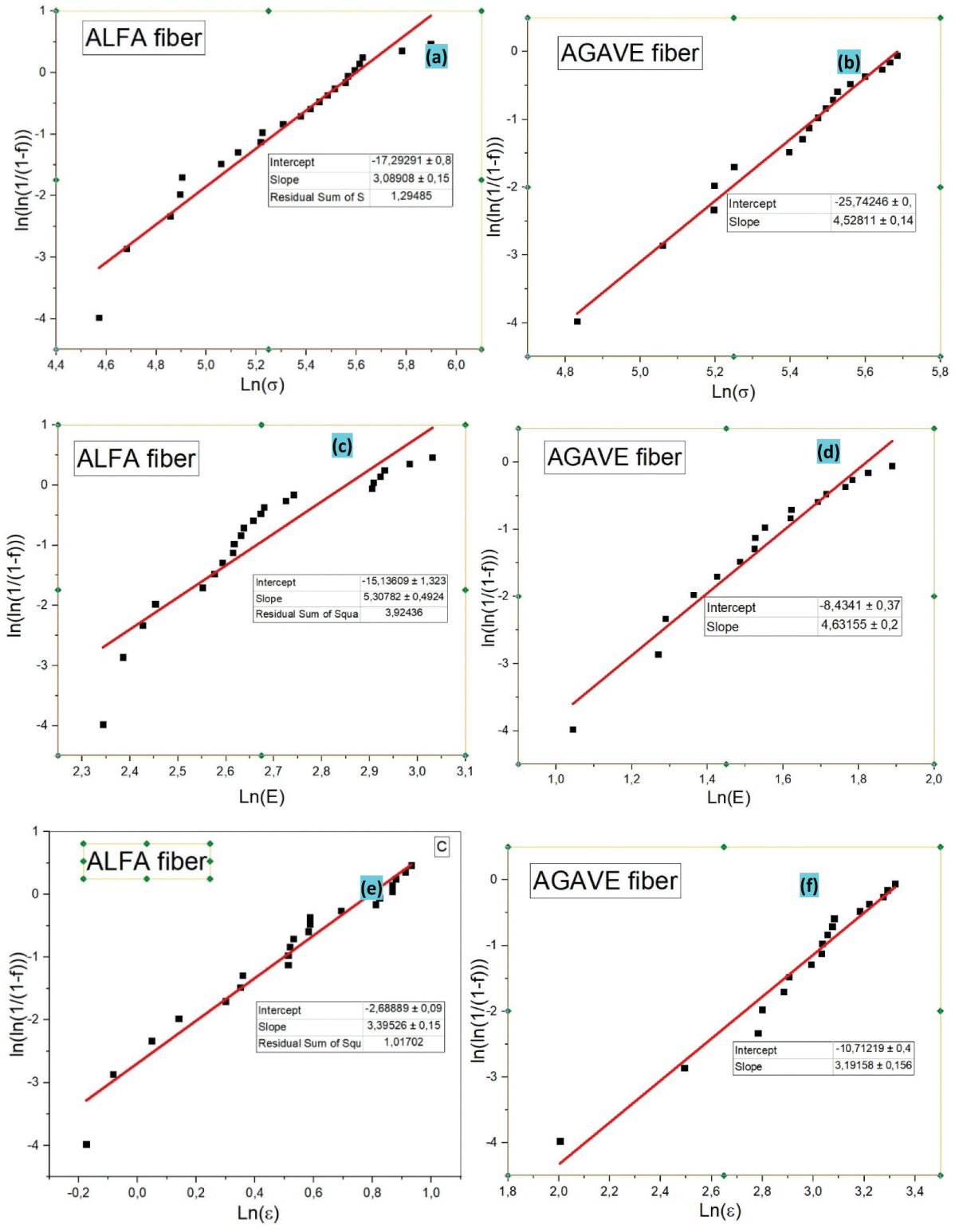

Figure 9. Two-parameter Weibull distribution for tensile properties (a,b) strength, (c,d) Young's modulus, (e,f) strain at break for Alfa and Agave fibers.

reinforcements led to improved tensile properties and interfacial bonding in polyester matrices (Balaji et al. 2025) (Table 4). The maximum tensile strength obtained for the Agave composite (≈30.97 MPa) slightly exceeds that of the Alfa composite (≈25.12 MPa), confirming better mechanical and interfacial compatibility of Agave fibers with the polyester matrix. This finding is consistent with the performances reported

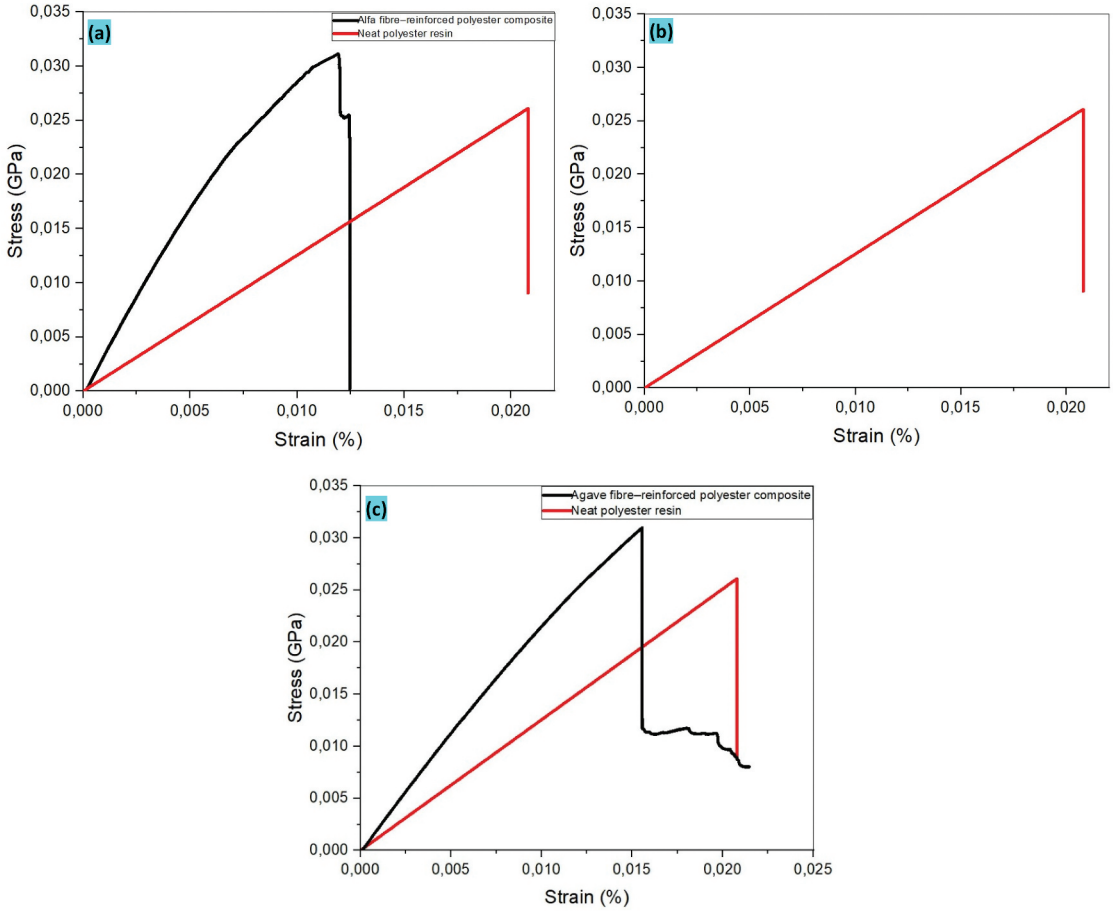

Figure 10. Typical stress–strain (σ –ε) curve under tensile loading for (a) polyester resin, (b) Alfa-fiber-reinforced composite (c) e neat resin and the Agave-fiber-reinforced composite.

Table 3. Weibull distribution results (two-parameter model) for the mechanical properties of Alfa and *Agave americana* fibers.

Plants fiber	Tensile strength (MPa)		Young's modulus (GPa)		Strain (µm)	
	Weibull	*exp*	*Weibull*	*exp*	*Weibull*	*exp*
Agave	m = 4.52	σ_0 = 293.93	σ = 228.97	m = 4.63	E_0 = 6.17	E = 4.83
Alfa	m = 3.89	σ_0 = 269.90	σ = 213.17	m = 5.30	E_0 = 17.36	E = 14.87

Table 4. Comparison of tensile properties of unidirectional natural fiber composites.

Composite UD	Fiber content (%)	Tensile strength (MPa)	Young's modulus (GPa)	Strain (%)	Reference
Polyester/Alfa	21	25.12 ± 6.52	2.99 ± 0.85	0.88 ± 0.92	Present study
Polyester/*Agave*	21	30.97 ± 9.88	2.13 ± 0.51	1.55 ± 0.83	
Epoxy/Sisal (UD)	46	211	19.7	1.9	Oksman et al. (2002)
Epoxy/Flax (UD)	26 ± 0.4	234 ± 12	16.0 ± 1.0	1.7 ± 0.1	Martin, Davies, and Baley (2014)
Epoxy/Jute (UD)	32	122 ± 15	10 ± 0.5	1.7 0.25	Hasan et al. (2021)
Epoxy/Harakeke (UD)	55	223	16.8	1.44	Le and Pickering (2015)
Polyester/Banana (UD)	37.4	60.9	1.08		Rao, Rao, and Prasad (2010)
Polyester/Vakka (UD)	37	66	1.79	1.70	Rao, Rao, and Prasad (2010)
Polyester/Elephant grass (UD)	31.28	80.55 26	1.52	—	Rao et al. (2007)
Epoxy/Lygeum (UD)	23.41 ± 0.14	88.38 ± 11.24	7.17 ± 0.34	1.41 ± 0.11	Belouadah, Rokbi, and Ati (2022)

by (Fiore et al. 2016) for sisal/polyester composites, where interfacial adhesion strongly influences strength and deformation. Overall, these results show that: (i) Alfa fibers, being more crystalline and rigid, provide a higher modulus but lead to a brittle fracture; (ii) Agave fibers, being more ductile, enhance toughness and result in a more progressive mechanical behavior; (ii) The reinforcement effect is consistent with classical observations for unidirectional natural fibres and is comparable to composites reinforced with sisal, elephant grass, or flax fibers, where the nature of the reinforcement and fiber – matrix interfacial characteristics strongly influence tensile performance (Martin, Davies, and Baley 2014; Oksman et al. 2002; Rao et al. 2007). These observations highlight the importance of fiber microstructure and interfacial adhesion in determining the overall behavior of the composites, and confirm that both natural reinforcements investigated offer promising potential for lightweight structural applications.

From an interfacial point of view, several studies have demonstrated that the tensile behavior of unsaturated polyester composites reinforced with natural fibers is strongly governed by the quality of fiber–matrix adhesion. George, Sreekala, and Thomas (2001) provided a comprehensive review highlighting that efficient interfacial bonding is essential for effective stress transfer and improved mechanical performance in natural fiber reinforced polymer composites. This interfacial quality has often been indirectly assessed through dynamic mechanical analysis (DMA) and the associated glass transition temperature (Tg). In this context, Pothan, Oommen, and Thomas (2003) reported that improved interfacial bonding in banana fiber reinforced polyester composites restricts polymer chain mobility near the fiber surface, leading to enhanced stress transfer and higher tensile efficiency. Similarly, Idicula et al. (2005) showed that variations in viscoelastic response and damping behavior are directly related to the quality of the interphase in natural fiber–polyester systems. Although DMA measurements were not performed in the present study, the higher tensile strength and strain at break observed for the Polyester/Agave composite are consistent with these literature findings, suggesting more effective fiber–matrix interaction compared to the Polyester/Alfa composite.

Three-point bending behavior of both composites

Figures 11 show the three-point bending stress–strain curves of the neat polyester resin and the unidirectional composites reinforced with Alfa and Agave fibers. The neat polyester resin exhibits a brittle behavior typical of thermosetting polymers, with a maximum stress of 82.31 ± 12.3 MPa and a flexural modulus of 1.79 ± 0.32 GPa (Table 5).

The incorporation of natural fibers significantly modifies the mechanical response of the matrix. The Polyester/Alfa composite reaches a maximum stress of 95.47 ± 10.14 MPa with a modulus of 2.45 ± 0.52 GPa, whereas the Polyester/Agave composite shows the highest value, 108.7 ± 15.2 MPa, with a modulus of

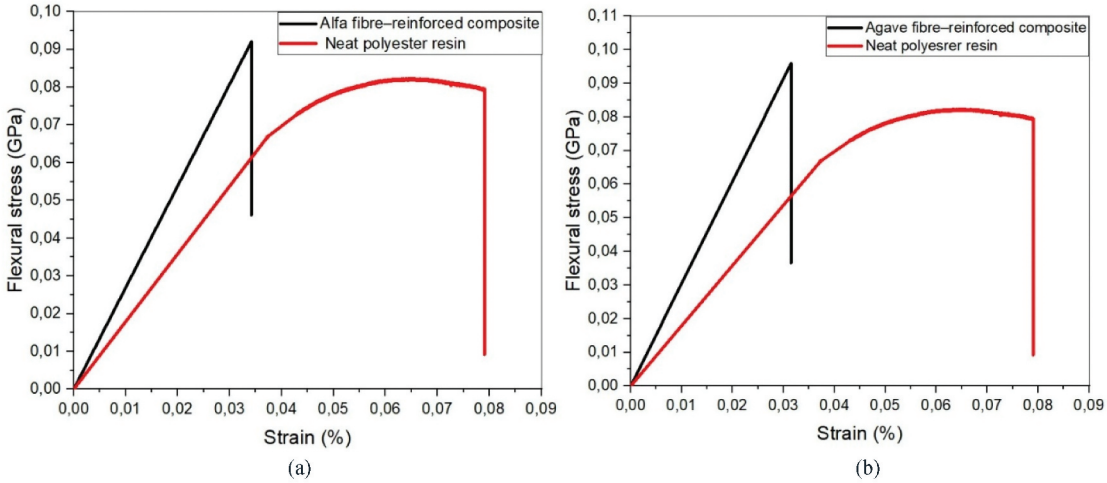

Figure 11. Stress–strain curves obtained from three-point bending tests (a) neat polyester resin and the polyester/Alfa composite, (b) neat polyester resin and the polyester/*Agave americana* composite.

Table 5. Comparison of flexural properties of polyester composites reinforced with Alfa and *Agave americana* fibers versus literature data on unidirectional natural fiber composites.

Composite	Fiber content (%)	Flexural strength (MPa)	Flexural modulus (GPa)	Strain at break (%)	Ref
Polyester	0	82.31 ± 12.3	1.79 ± 0,32	6.49 ± 2.31	current work
Polyester/Alfa	21	95.47 ± 2.32	2.45 ± 0,52	2.45 ± 0.52	
Polyester/Agave	23	108.7 ± 9.88	2.98 ± 0,32	2.89 ± 0.32	
Polyester/Vakka	39.7	93.79	3.32	15 ± 1--2.7 ± 0.4	(Rao, Rao, and Prasad 2010)
Epoxy/Jute	32	52 ± 9	6.5 ± 1	2.57 ± 0.3	(Hasan et al. 2021)
Epoxy/Harakeke	49	223	13.72.17		(Le and Pickering 2015)
Polyester/Kenaf	48	235.13 ± 27	5.572 ± 0.8		(Yousif et al. 2012)
Polyester/Fique	40	168 ± 11 118.99 ±	8.0 ± 0.7		(Hoyos and Vázquez 2012)
Epoxy/Lygeum spartum	23.41 ± 0.14	11.8	6.02 ± 0.3		(Belouadah, Rokbi, and Ati 2022)

2.98 ± 0.32 GPa (Amrane et al. 2019). Both composites retain an overall brittle behavior but exhibit a much higher load-bearing capacity compared to the neat resin.

In terms of relative improvements, flexural strength increases by +25.09% for Polyester/Alfa and +32.05% for Polyester/Agave, while the modulus increases by +71% (Alfa) and +73% (Agave). Conversely, the strain at failure decreases substantially, with a reduction of approximately 71% for Polyester/Alfa and approximately 55% for Polyester/Agave, reflecting the intrinsic brittleness of natural fibers and the limited interfacial plasticity under flexural loading (Sugiman et al. 2020).

The Polyester/Alfa composite exhibits a mechanically stiff response followed by an abrupt fracture. Such behavior is typical of highly crystalline fibers, as previously reported for unidirectional Alfa/polyester composites (Baley 2002; Brahim and Cheikh 2007). In contrast, the Polyester/Agave composite shows a more progressive response, with a higher maximum load and greater deflection before fracture. This behavior is associated with the microstructure of Agave fibers, which are rich in lignin and hemicelluloses, providing enhanced ductility.

Table 5 compares the obtained values with those of other unidirectional natural-fiber composites. The results show that even with only 23% fiber content, the Polyester/Agave composite achieves flexural properties superior to some highly loaded natural-fiber composites, such as Polyester/Fique (40%) (Suarez and Cordoba 2022) and Polyester/Treated Bamboo (48%) (Sugiman et al. 2020). Leaf fibers (Agave, henequen) are known for their high stiffness and excellent flexural performance due to their thick cell walls and low microfibril angle, whereas bast fibers (flax, hemp) generally excel in tensile behavior owing to their high crystallinity (Baley 2002).

These observations confirm that Agave is a particularly effective reinforcement for polyester composites, offering an advantageous balance between stiffness and ductility even at low fiber content.

Alfa reinforcement is particularly suited for applications where stiffness is the primary requirement, whereas Agave offers a more versatile reinforcement, providing a favorable combination of strength, modulus, and deformation capacity. This makes it suitable for structures requiring improved energy absorption and better crack-tolerance.

In the context of flexural loading, interfacial adhesion also plays a critical role in determining the stiffness and load-bearing capacity of natural fiber reinforced polyester composites. Previous DMA studies by George, Sreekala, and Thomas (2001) and Pothan, Oommen, and Thomas (2003) have shown that improved fiber – matrix interaction leads to higher storage modulus and shifts in the glass transition temperature, reflecting restricted molecular mobility at the interphase. Idicula et al. (2005) further demonstrated that such interfacial effects significantly influence bending performance by enhancing stress transfer efficiency under flexural deformation. Although DMA analysis was not conducted in this work, the superior flexural strength and modulus exhibited by the Polyester/Agave composite are in good agreement with these reported trends, indicating a more efficient interfacial stress transfer compared to the Polyester/Alfa system.

Alfa/Agave polyester composites (flexural 108 MPa‹ +73% modulus) compare favorably with wood fiber geo-polymers (Furtos et al. 2021, 2022) demonstrating natural fibers' broad matrix compatibility while leveraging polyester's industrial scalability.

Conclusion

This study investigated the mechanical performance of polyester composites reinforced with locally available plant fibers, namely *Stipa tenacissima* and *Agave americana*. The results demonstrated that fiber type significantly influences the mechanical behavior of the composites, with *Stipa tenacissima*–reinforced composites exhibiting superior tensile and flexural properties compared to those reinforced with *Agave americana*. These differences are mainly attributed to the intrinsic characteristics of the fibers and their interaction with the polyester matrix. Overall, the findings highlight the potential of local plant fibers, particularly *Stipa tenacissima*, as sustainable and effective reinforcements for polyester-based composites in lightweight structural applications.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The authors acknowledge the financial support through Ongoing Research Funding program [ORF-2026-688], King Saud University, Riyadh, Saudi Arabia.

ORCID

Salah Amroune http://orcid.org/0000-0002-9565-1935

References

Abbasnejadfard, M., M. Bastami, and S.-A. Hashemi. 2022. "Experimental Investigation on the Stress-Strain Behavior of Unsaturated Polyester Polymer Concrete Subjected to Monotonic and Cyclic Loadings." *Journal of Building Engineering* 48:103966. https://doi.org/10.1016/j.jobe.2021.103966.

Abdollahiparsa, H., A. Shahmirzaloo, P. Teuffel, and R. Blok. 2023. "A Review of Recent Developments in Structural Applications of Natural Fiber-Reinforced Composites (NFRCs)." *Composites and Advanced Materials* 32:26349833221147540. https://doi.org/10.1177/26349833221147540.

Amrane, A., Z. Sereir, C. Poilâne, and A. Vivet. 2019. "Effet du Facteur de Forme et de la Fraction Massique des Fibres Courtes d
'Alfa sur le Comportement Mécanique d'un Bio-Composite Alfa/Greenpoxy." *Journal of Composite & Advanced Materials/Revue des Composites et des Matériaux Avancés* 29 (4): 185–191. https://doi.org/10.18280/rcma.290401.

Amroune, S., A. Belaadi, M. Bourchak, A. Makhlouf, and H. Satha. 2022. "Statistical and Experimental Analysis of the Mechanical Properties of Flax Fibers." *Journal of Natural Fibers* 19 (4): 1387–1401. https://doi.org/10.1080/15440478.2020.1775751.

Amroune, S., A. Belaadi, R. Dalmis, Y. Seki, A. Makhlouf, and H. Satha. 2022. "Quantitatively Investigating the Effects of Fiber Parameters on Tensile and Flexural Response of Flax/Epoxy Biocomposites." *Journal of Natural Fibers* 19 (6): 2366–2381. https://doi.org/10.1080/15440478.2020.1817831.

Antony, T., R. M. Cherian, R. T. Varghese, A. Malhotra, S. R. Chauhan, A. Chauhan, H. Kargarzadeh, C. J. Chirayil, and S. Thomas. 2025. "Harvesting nature's Treasure from Agricultural Biomass: Spatholobus parviflorus Unveiled as a Source of Nano-Scaled Crystalline Cellulose." *Biomass Conversion and Biorefinery* 15 (8): 12501–12514. https://doi.org/10.1007/s13399-024-06155-3.

Ashrith, H., T. Jeevan, and J. Xu. 2023. "A Review on the Fabrication and Mechanical Characterization of Fibrous Composites for Engineering Applications." *Journal of Composites Science* 7 (6): 252. https://doi.org/10.3390/jcs7060252.

Atoui, S., A. Belaadi, B. X. Chai, M. M. Abdullah, A. Al-Khawlani, and D. Ghernaout. 2024. "Extracting and Characterizing Novel Cellulose Fibers from Chamaerops humilis Rachis for Textiles' Sustainable and Cleaner Production as Reinforcement for Potential Applications." *International Journal of Biological Macromolecules* 276:134029. https://doi.org/10.1016/j.ijbiomac.2024.134029.

Balaji, A. N., M. K. V. Karthikeyan, V. Vignesh, A. B. Madhavan, N. Ayrilmis, K.-H. Ryu, and H.-J. Kim. 2025. "Properties and Prototype Applications of Polyester Composites Reinforced with Woven Fabric of Agave vera-cruz Fiber." *Journal of Wood Science* 71 (1): 30. https://doi.org/10.1186/s10086-025-02207-y.

Baley, C. 2002. "Analysis of the Flax Fibres Tensile Behaviour and Analysis of the Tensile Stiffness Increase." *Composites Part A: Applied Science and Manufacturing* 33 (7): 939–948. https://doi.org/10.1016/S1359-835X(02)00040-4.

Banik, S., M. Basak, D. Paul, P. Nayak, D. Sardar, S. Sil, B. Sanpui, and A. Ghosh. 2003. "Ribbon Retting of Jute—A Prospective and Eco-Friendly Method for Improvement of Fibre Quality." *Industrial Crops and Products* 17 (3): 183–190. https://doi.org/10.1016/S0926-6690(02)00097-3.

Bedjaoui, A., A. Belaadi, S. Amroune, and B. Madi. 2019. "Impact of Surface Treatment of Flax Fibers on Tensile Mechanical Properties Accompanied by a Statistical Study." *International Journal of Integrated Engineering* 11 (6): 10–17. https://doi.org/10.30880/ijie.2019.11.06.002.

Belaadi, A., S. Amroune, and M. Bourchak. 2020. "Effect of Eco-Friendly Chemical Sodium Bicarbonate Treatment on the Mechanical Properties of Flax Fibres: Weibull Statistics." *International Journal of Advanced Manufacturing Technology* 106 (5–6): 1753–1774. https://doi.org/10.1007/s00170-019-04628-8.

Belaadi, A., S. Amroune, Y. Seki, O. Y. Keskin, S. Köktaş, M. Bourchak, A. Dufresne, H. Fouad, and M. Jawaid. 2022. "Extraction and Characterization of a New Lignocellulosic Fiber from Yucca treculeana L. Leaf as Potential Reinforcement for Industrial Biocomposites." *Journal of Natural Fibers* 19 (15): 12235–12250. https://doi.org/10.1080/15440478.2022.2054895.

Belouadah, Z., A. Ati, and M. Rokbi. 2015. "Characterization of New Natural Cellulosic Fiber from Lygeum spartum L." *Carbohydrate Polymers* 134:429–437. https://doi.org/10.1016/j.carbpol.2015.08.024.

Belouadah, Z., M. Rokbi, and A. Ati. 2022. "Manufacturing and Characterization of New Composite Based on Epoxy Resin and Lygeum spartum L. Plant." *Journal of Natural Fibers* 19 (11): 4236–4248. https://doi.org/10.1080/15440478.2020.1856273.

Benarab, M., A. Belaadi, A. Bedjaoui, M. Boumaaza, and D. Ghernaout. 2025. "Characterizing Novel Cellulosic Fibers Extracted from Vicia faba Plant Waste Stems as a Promising Reinforcement for Applications in Sustainable Textile and Lightweight Biocomposites." *International Journal of Biological Macromolecules* 307:141940. https://doi.org/10.1016/j.ijbiomac.2025.141940.

Benarioua, M., S. Amroune, H. Alshahrani, A. Belaadi, A. Hachaichi, I. M. H. Alshaikh, M. Barhm, and K. Saada. 2025. "Statistical Normalization of Mechanical Properties of Natural Date Palm Biofibers Using the Box-Cox Transformation." *Journal of Natural Fibers* 22 (1): 2544176. https://doi.org/10.1080/15440478.2025.2544176.

Bessadok, A., S. Roudesli, S. Marais, N. Follain, and L. Lebrun. 2009. "Alfa Fibres for Unsaturated Polyester Composites Reinforcement: Effects of Chemical Treatments on Mechanical and Permeation Properties." *Composites Part A: Applied Science and Manufacturing* 40 (2): 184–195. https://doi.org/10.1016/j.compositesa.2008.10.018.

Blythe, A., B. Fox, M. Nikzad, B. Eisenbart, and B. X. Chai. 2024. "Stiffness Retention in Cyclic-Loaded CFRP Composites Produced via Novel Automatic Tape Laying." *Journal of Composites Science* 8 (3): 9. https://doi.org/10.3390/jcs8030092.

Bouchareb, S., M. Rokbi, M. Benhamida, S. Mekideche, N. Belayachi, M. Meddah, B. Boucherit, and D. Kouidri. 2025. "Effect of Chemical Treatment on the Mechanical Properties of Intra-Layer Hybrid Alfa/Jute Fabric Composites." *Journal of Composite Materials* 59 (13): 1651–1677. https://doi.org/10.1177/00219983251316336.

Bourahli, M. 2018. "Uni-And Bimodal Weibull Distribution for Analyzing the Tensile Strength of Diss Fibers." *Journal of Natural Fibers* 15 (6): 843–852. https://doi.org/10.1080/15440478.2017.1371094.

Brahim, S. B., and R. B. Cheikh. 2007. "Influence of Fibre Orientation and Volume Fraction on the Tensile Properties of Unidirectional Alfa-Polyester Composite." *Composites Science and Technology* 67 (1): 140–147. https://doi.org/10.1016/j.compscitech.2005.10.006.

Cândido, V. S., M. P. Oliveira, R. D. A. Gouvêa, A. L. B. S. Martins, and S. N. Monteiro. 2014. "Weibull Analysis to Characterize the Diameter Dependence of Tensile Strength in Sugarcane Bagasse Fibers." In *Materials Science Forum*, 80–85. Vol. 775. Trans Tech Publ. https://doi.org/10.4028/www.scientific.net/MSF.775-776.80.

Chai, B., Eisenbart, B., and Nikzad, M 2024a. "Review of Approaches to Minimise the Cost of Simulation-Based Optimisation for Liquid Composite Moulding Processes." *Materials* 16 (24). https://doi.org/10.3390/ma16247580.

Chai, B., B. Eisenbart, M. Nikzad, B. Fox, A. Blythe, P. Blanchard, and J. Dahl. 2023. "A Novel Heuristic Optimisation Framework for Radial Injection Configuration for the Resin Transfer Moulding Process." *Composites Part A: Applied Science and Manufacturing* 165:107352. https://doi.org/10.1016/j.compositesa.2022.107352.

Chai, B., J. Wang, T. Dang, M. Nikzad, B. Eisenbart, and B. Fox. 2024. "Comprehensive Composite Mould Filling Pattern Dataset for Process Modelling and Prediction." *Journal of Composites Science* 8 (4): 15. https://doi.org/10.3390/jcs8040153.

Chai, B. X., B. Eisenbart, M. Nikzad, B. Fox, A. Blythe, K. H. Bwar, J. Wang, Y. Du, and S. Shevtsov. 2023. "Application of KNN and ANN Metamodeling for RTM Filling Process Prediction." *Materials* 16 (18): 6115. https://doi.org/10.3390/ma16186115.

Chai, B. X., M. Gunaratne, M. Ravandi, J. Wang, T. Dharmawickrema, A. Di Pietro, J. Jin, and D. Georgakopoulos. 2024. "Smart Industrial Internet of Things Framework for Composites Manufacturing." *Sensors* 24 (15): 4852. https://doi.org/10.3390/s24154852.

Cherian, R. M., R. T. Varghese, T. Antony, A. Malhotra, H. Kargarzadeh, S. R. Chauhan, A. Chauhan, C. J. Chirayil, and S. Thomas. 2023. "Non-Cytotoxic, Highly Functionalized Cellulose Nanocrystals with High Crystallinity and Thermal Stability Derived from a Novel Agromass of Elettaria cardamomum, Using a Soft and Benign Mild

Oxalic Acid Hydrolysis." *International Journal of Biological Macromolecules* 253:126571. https://doi.org/10.1016/j.ijbiomac.2023.126571.

Chirayil, C. J., J. Joy, L. Mathew, J. Koetz, and S. Thomas. 2014. "Nanofibril Reinforced Unsaturated Polyester Nanocomposites: Morphology, Mechanical and Barrier Properties, Viscoelastic Behavior and Polymer Chain Confinement." *Industrial Crops and Products* 56:246–254. https://doi.org/10.1016/j.indcrop.2014.03.005.

Chirayil, C. J., L. Mathew, P. Hassan, M. Mozetic, and S. Thomas. 2014. "Rheological Behaviour of Nanocellulose Reinforced Unsaturated Polyester Nanocomposites." *International Journal of Biological Macromolecules* 69:274–281. https://doi.org/10.1016/j.ijbiomac.2014.05.055.

Dooley, T., T. Creasy, and A. Cuellar. 2000. "Extraction of Weibull Parameters from Fiber Bundle Experiments Through Fourier Deconvolution." *Composites Part A: Applied Science and Manufacturing* 31 (11): 1255–1260. https://doi.org/10.1016/S1359-835X(00)00092-0.

El-Abbassi, F. E., M. Assarar, R. Ayad, A. Bourmaud, and C. Baley. 2020. "A Review on Alfa Fibre (Stipa tenacissima L.): From the Plant Architecture to the Reinforcement of Polymer Composites." *Composites Part A: Applied Science and Manufacturing* 128:105677. https://doi.org/10.1016/j.compositesa.2019.105677.

Elfaleh, I., F. Abbassi, M. Habibi, F. Ahmad, M. Guedri, M. Nasri, and C. Garnier. 2023. "A Comprehensive Review of Natural Fibers and Their Composites: An Eco-Friendly Alternative to Conventional Materials." *Results in Engineering* 19:101271. https://doi.org/10.1016/j.rineng.2023.101271.

Fiore, V., T. Scalici, F. Nicoletti, G. Vitale, M. Prestipino, and A. Valenza. 2016. "A New Eco-Friendly Chemical Treatment of Natural Fibres: Effect of Sodium Bicarbonate on Properties of Sisal Fibre and Its Epoxy Composites." *Composites Part B Engineering* 85:150–160. https://doi.org/10.1016/j.compositesb.2015.09.028.

Furtos, G., L. Molnar, L. Silaghi-Dumitrescu, P. Pascuta, and K. Korniejenko. 2022. "Mechanical and Thermal Properties of Wood Fiber Reinforced Geopolymer Composites." *Journal of Natural Fibers* 19 (13): 6676–6691. https://doi.org/10.1080/15440478.2021.1929655.

Furtos, G., L. Silaghi-Dumitrescu, P. Pascuta, C. Sarosi, and K. Korniejenko. 2021. "Mechanical Properties of Wood Fiber Reinforced Geopolymer Composites with Sand Addition." *Journal of Natural Fibers* 18 (2): 285–296. https://doi.org/10.1080/15440478.2019.1621792.

George, J., M. Sreekala, and S. Thomas. 2001. "A Review on Interface Modification and Characterization of Natural Fiber Reinforced Plastic Composites." *Polymer Engineering & Science* 41 (9): 1471–1485. https://doi.org/10.1002/pen.10846.

Gheribi, H., S. Teyar, M. Boumaaza, A. Belaadi, B. X. Chai, M. M. Abdullah, A. A. Gelgelu, and I. Klimkina. 2024. "Statistical Study of the Mechanical Behavior of the New Fiber from the Strelitzia juncea Plant Fibers: Application in Ecological Yarns." *Journal of Natural Fibers* 21 (1): 2396905. https://doi.org/10.1080/15440478.2024.2396905.

Grisin, B., S. Carosella, and P. Middendorf. 2024. "Vacuum Chamber Infusion for Fiber-Reinforced Composites." *Polymers* 16 (19): 2763. https://doi.org/10.3390/polym16192763.

Hasan, M., A. Saifullah, H. N. Dhakal, S. Khandaker, and F. Sarker. 2021. "Improved Mechanical Performances of Unidirectional Jute Fibre Composites Developed with New Fibre Architectures." *RSC Advances* 11 (37): 23010–23022. https://doi.org/10.1039/D1RA03515K.

Hashim, A. M., and J. K. Oleiwi. 2016. "Tensile Properties Distribution of Coir Natural Fiber Using Weibull Statistics." *Engineering and Technology Journal* 34:1080–1087.

Hemadi, A. E. K., K. K. Al-Ahmady, and E. Z. Sulyman. 2024. "Improving Mechanical and Thermal Properties of Unsaturated Polyester Resin by Adding Automotive Glass Waste." *Ochrona Przed Korozją* 1 (10): 294–305. https://doi.org/10.15199/40.2024.10.2.

Hidalgo-Reyes, M., M. Caballero-Caballero, L. H. Hernández-Gómez, and G. Urriolagoitia-Calderón. 2015. "Chemical and Morphological Characterization of Agave angustifolia Bagasse Fibers." *Botanical Sciences* 93 (4): 807–817. https://doi.org/10.17129/botsci.250.

Hoyos, C. G., and A. Vázquez. 2012. "Flexural Properties Loss of Unidirectional Epoxy/Fique Composites Immersed in Water and Alkaline Medium for Construction Application." *Composites Part B Engineering* 43 (8): 3120–3130. https://doi.org/10.1016/j.compositesb.2012.04.027.

Idicula, M., S. Malhotra, K. Joseph, and S. Thomas. 2005. "Dynamic Mechanical Analysis of Randomly Oriented Intimately Mixed Short Banana/Sisal Hybrid Fibre Reinforced Polyester Composites." *Composites Science and Technology* 65 (7–8): 1077–1087. https://doi.org/10.1016/j.compscitech.2004.10.023.

Idres, C., M. Kaci, N. Dehouche, C. Lainé, and S. Bruzaud. 2022. "Effect of Agave americana Fibers Content on Morphology and Mechanical, Rheological, and Thermal Properties of Poly (3-Hydroxybutyrate-Co -3-Hydroxyhexanoate) Biocomposites." *Polymers from Renewable Resources* 13 (4): 191–205. https://doi.org/10.1177/20412479221128962.

International, A. 2007. *Standrd Test Method for Tensile Properties of Single Textile Fibers1*. ASTM International.

Islam, T., M. H. Chaion, M. A. Jalil, A. S. Rafi, F. Mushtari, A. K. Dhar, and S. Hossain. 2024. "Advancements and Challenges in Natural Fiber-Reinforced Hybrid Composites: A Comprehensive Review." *SPE Polymers* 5 (4): 481–506. https://doi.org/10.1002/pls2.10145.

Kir, M., M. Boudiaf, A. Belaadi, M. Boumaaza, M. Bourchak, and D. Ghernaout. 2024. "Extracting and Characterizing of a New Vegetable Lignocellulosic Fiber Produced from C. humilis Palm Trunk for Renewable and Sustainable

Applications." *International Journal of Biological Macromolecules* 281:136495. https://doi.org/10.1016/j.ijbiomac.2024.136495.
Laifa, F., M. Rokbi, S. Amroune, M. Zaoui, and Y. Seki. 2022. "Investigation of Mechanical, Physicochemical, and Thermal Properties of New Fiber from Silybum marianum Bark Fiber." *Journal of Composite Materials* 56 (14): 2227–2238. https://doi.org/10.1177/00219983221090020.
Lalaymia, I., A. Belaadi, M. Boumaaza, H. Alshahrani, M. K. Khan, and A. Dib. 2024. "Weibull Statistic and Artificial Neural Network Analysis of the Mechanical Performances of Fibers from the Flower Agave Plant for Eco-Friendly Green Composites." *Journal of Natural Fibers* 21 (1): 2305228. https://doi.org/10.1080/15440478.2024.2305228.
Le, T. M., and K. L. Pickering. 2015. "The Potential of Harakeke Fibre as Reinforcement in Polymer Matrix Composites Including Modelling of Long Harakeke Fibre Composite Strength." *Composites Part A: Applied Science and Manufacturing* 76:44–53. https://doi.org/10.1016/j.compositesa.2015.05.005.
Lee, C. H., A. Khalina, and S. H. Lee. 2021. "Importance of Interfacial Adhesion Condition on Characterization of Plant-Fiber-Reinforced Polymer Composites: A Review." *Polymers* 13 (3): 438. https://doi.org/10.3390/polym13030438.
Lemita, N., S. Deghboudj, M. Rokbi, F. M. L. Rekbi, and R. Halimi. 2022. "Characterization and Analysis of Novel Natural Cellulosic Fiber Extracted from Strelitzia reginae Plant." *Journal of Composite Materials* 56 (1): 99–114. https://doi.org/10.1177/00219983211049285.
Maache, M., A. Bezazi, S. Amroune, F. Scarpa, and A. Dufresne. 2017. "Characterization of a Novel Natural Cellulosic Fiber from Juncus effusus L." *Carbohydrate Polymers* 171:163–172. https://doi.org/10.1016/j.carbpol.2017.04.096.
Makri, H., M. Rokbi, M. Meddah, N. Belayachi, and A. Khaldoune. 2023. "Extraction and Characterization of Novel Lignocellulosic Fibers from Centaurea hyalolepis Plant as a Potential Reinforcement for Composite Materials." *Journal of Composite Materials* 57 (21): 3317–3330. https://doi.org/10.1177/00219983231184020.
Mansour, R., A. Abdelaziz, and A. Fatima Zohra. 2018. "Characterization of Long Lignocellulosic Fibers Extracted from Hyphaene thebaica L. Leaves." *Research Journal of Textile and Apparel* 22 (3): 195–211. https://doi.org/10.1108/RJTA-02-2018-0009.
Martin, N., P. Davies, and C. Baley. 2014. "Comparison of the Properties of Scutched Flax and Flax Tow for Composite Material Reinforcement." *Industrial Crops and Products* 61:284–292. https://doi.org/10.1016/j.indcrop.2014.07.015.
Meddah, M., M. Rokbi, and M. Zaoui. 2023. "Extraction and Characterization of Novel Natural Lignocellulosic Fibers from Malva sylvestris L." *Journal of Composite Materials* 57 (5): 897–912. https://doi.org/10.1177/00219983221146355.
Moussaoui, N., M. Rokbi, H. Osmani, M. Jawaid, A. Atiqah, M. Asim, and L. Benhamadouche. 2021. "Extraction and Characterization of Fiber Treatment Inula viscosa Fibers as Potential Polymer Composite Reinforcement." *Journal of Polymers and the Environment* 29 (11): 3779–3793. https://doi.org/10.1007/s10924-021-02147-w.
Msahli, S., M. Jaouadi, F. Sakli, and J.-Y. Drean. 2015. "Study of the Mechanical Properties of Fibers Extracted from Tunisian Agave americana L." *Journal of Natural Fibers* 12 (6): 552–560. https://doi.org/10.1080/15440478.2014.984046.
Nasri, K., E. Loranger, and L. Toubal. 2023. "Effect of Cellulose and Lignin Content on the Mechanical Properties and Drop-Weight Impact Damage of Injection-Molded Polypropylene-Flax and-Pine Fiber Composites." *Journal of Composite Materials* 57 (21): 3347–3364. https://doi.org/10.1177/00219983231186208.
Nouri, L., B. Azzedine, D. Nadir, M. Azzedine, and A. Yakout. 2025. "Study of the Mechanical Behavior of a Composite Material Reinforced with Stipa tenacissima Fibers." *International Journal of Professional Business Review* 10 (2): 4. https://doi.org/10.26668/businessreview/2025.v10i2.5316.
Oksman, K., L. Wallström, L. A. Berglund, and R. D. T. Filho. 2002. "Morphology and Mechanical Properties of Unidirectional Sisal–Epoxy Composites." *Journal of Applied Polymer Science* 84 (13): 2358–2365. https://doi.org/10.1002/app.10475.
Phiri, R., S. M. Rangappa, S. Siengchin, O. P. Oladijo, and T. Ozbakkaloglu. 2024. "Advances in Lightweight Composite Structures and Manufacturing Technologies: A Comprehensive Review." *Heliyon* 10 (21): e39661. https://doi.org/10.1016/j.heliyon.2024.e39661.
Pothan, L. A., Z. Oommen, and S. Thomas. 2003. "Dynamic Mechanical Analysis of Banana Fiber Reinforced Polyester Composites." *Composites Science and Technology* 63 (2): 283–293. https://doi.org/10.1016/S0266-3538(02)00254-3.
Rao, K. M. M., A. R. Prasad, M. R. Babu, K. M. Rao, and A. Gupta. 2007. "Tensile Properties of Elephant Grass Fiber Reinforced Polyester Composites." *Journal of Materials Science* 42 (9): 3266–3272. https://doi.org/10.1007/s10853-006-0657-8.
Rao, K. M. M., K. M. Rao, and A. R. Prasad. 2010. "Fabrication and Testing of Natural Fibre Composites: Vakka, Sisal, Bamboo and Banana." *Materials and Design* 31 (1): 508–513. https://doi.org/10.1016/j.matdes.2009.06.023.
Rayyaan, R., Z. Yousaf, W. Kennon, and P. Potluri. 2021. "Compaction Behaviour of Various Flax Fabric Structures During Composite Manufacturing: Mechanical Characterisation and Microstructural Analysis." ArXiv Preprint arXiv:2110.06110.
Rokbi, M., C. Herbelot, and A. Imad. 2013. "Influence du traitement chimique sur le comportement à la rupture du polyester orthophtalique renforcée par des fibres Alfa." In *CFM 2013-21ème Congrès Français De Mécanique*, Maison de la Mécanique: AFM.

Saaidia, A., A. Bezazi, A. Belbah, S. Amroune, and F. Scarpa. 2015. "Evaluation of Mechanical Properties of Jute Yarns by Two-and Three-Parameters Weibull Method Procena Mehaničkih Svojstava Prediva Konoplje Primenom Dvo-i Tro-Parametarskog Vejbulovom Metoda."

Saha, M., H. Singh, M. K. Singh, S. M. Rangappa, and S. Siengchin. 2025. "Advancements in Natural Fiber Composites: Market Insights, Surface Modifications, Advanced Fabrication Techniques and Applications." *Sustainable Chemistry for Climate Action* 6:100081. https://doi.org/10.1016/j.scca.2025.100081.

Salem, K. S., N. K. Kasera, M. A. Rahman, H. Jameel, Y. Habibi, S. J. Eichhorn, A. D. French, L. Pal, and L. A. Lucia. 2023. "Comparison and Assessment of Methods for Cellulose Crystallinity Determination." *Chemical Society Reviews* 52 (18): 6417–6446. https://doi.org/10.1039/D2CS00569G.

Sanjay, M., S. Siengchin, J. Parameswaranpillai, M. Jawaid, C. I. Pruncu, and A. Khan. 2019. "A Comprehensive Review of Techniques for Natural Fibers as Reinforcement in Composites: Preparation, Processing and Characterization." *Carbohydrate Polymers* 207:108–121. https://doi.org/10.1016/j.carbpol.2018.11.083.

Sathish, S., L. Prabhu, S. Gokulkumar, N. Karthi, D. Balaji, and N. Vigneshkumar. 2021. "Extraction, Treatment and Applications of Natural Fibers for Bio-Composites–a Critical Review." *International Polymer Processing* 36 (2): 114–130. https://doi.org/10.1515/ipp-2020-4004.

Satyanarayana, K. G., G. G. Arizaga, and F. Wypych. 2009. "Biodegradable Composites Based on Lignocellulosic Fibers —An Overview." *Progress in Polymer Science* 34 (9): 982–1021. https://doi.org/10.1016/j.progpolymsci.2008.12.002 .

Segal, L., J. J. Creely, A. Martin Jr, and C. Conrad. 1959. "An Empirical Method for Estimating the Degree of Crystallinity of Native Cellulose Using the X-Ray Diffractometer." *Textile Research Journal* 29 (10): 786–794. https://doi.org/10.1177/004051755902901003.

Shevtsov, S., S. H. Chang, I. Zhilyaev, B. X. Chai, and N. Snezhina. 2024. "Numerical Study of Thin-Walled Polymer Composite Part Quality When Manufactured Using Vacuum Infusion with Various External Pressure Controls." *Polymers* 16 (5): 654. https://doi.org/10.3390/polym16050654.

Suarez, S. A. G., and E. Cordoba. 2022. "Composite Materials Reinforced with Fique Fibers–A Review." *Revista UIS Ingenierías* 21 (1): 163–178. https://doi.org/10.18273/revuin.v21n1-2022013.

Sugiman, S., A. Martino, P. D. Setyawan, and B. Anshari. 2020. "Tensile, Flexural and Water Absorption Properties of Bamboo Fiber/Unsaturated Polyester Composites: Effect of Calcium Carbonate Content." *Key Engineering Materials* 867:68–74. https://doi.org/10.4028/www.scientific.net/KEM.867.68.

Tahir, P. M., A. B. Ahmed, S. O. SaifulAzry, and Z. Ahmed. 2011. "Retting Process of Some Bast Plant Fibres and Its Effect on Fibre Quality: A Review." *BioResources* 6 (4): 5260–5281. https://doi.org/10.15376/biores.6.4.5260-5281.

Torres, J., L.-J. Vandi, M. Veidt, and M. Heiztmann. 2017. "Statistical Data for the Tensile Properties of Natural Fibre Composites." *Data in Brief* 12:222–226. https://doi.org/10.1016/j.dib.2017.03.043.

Varghese, R. T., R. M. Cherian, T. Antony, C. J. Chirayil, H. Kargarzadeh, A. Malhotra, A. Chauhan, and S. Thomas. 2024. "Thermally Stable, Highly Crystalline Cellulose Nanofibrils Isolated from the Lignocellulosic Biomass of G. tiliifolia Plant Barks by a Facile Mild Organic Acid Hydrolysis." *Biomass Conversion and Biorefinery* 14 (24): 31591–31605. https://doi.org/10.1007/s13399-023-05049-0.

Wang, Y., S. Xu, K. Bwar, B. Eisenbart, G. Lu, A. Belaadi, B. Fox, and B. Chai. 2024. "Application of Machine Learning for Composite Moulding Process Modelling." *Composites Communications* 48:101960. https://doi.org/10.1016/j.coco.2024.101960.

Ye, H., Y. Zhang, Z. Yu, and J. Mu. 2018. "Effects of Cellulose, Hemicellulose, and Lignin on the Morphology and Mechanical Properties of Metakaolin-Based Geopolymer." *Construction and Building Materials* 173:10–16. https://doi.org/10.1016/j.conbuildmat.2018.04.028.

Yousif, B., A. Shalwan, C. W. Chin, and K. Ming. 2012. "Flexural Properties of Treated and Untreated Kenaf/Epoxy Composites." *Materials and Design* 40:378–385. https://doi.org/10.1016/j.matdes.2012.04.017.