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# Extraction of Natural Fibres from *Agave fourcroydes* Leaves and Multi-Property Evaluation for Potential Textile Applications

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## Abstract

Sustainability concerns, environmental impact, and demand for renewable raw materials have intensified research efforts toward the development of novel natural fibres for textile applications. In this study, fibres extracted from the leaves of *Agave fourcroydes* were systematically investigated to evaluate their suitability as a sustainable textile fibre. Mature leaves were harvested and subjected to a water retting process followed by mechanical separation to extract the fibres, which were subsequently sun-dried. The extracted fibres were characterized for key textile-relevant properties including fibre length, bundle strength, fineness, colour characteristics, density, and thermal stability. In addition, morphological and chemical analyses were performed using scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR), respectively. The results indicate that *Agave fourcroydes* leaf fibres exhibit extra-long staple length, adequate bundle strength, and good thermal stability up to approximately 220 °C, making them suitable for common textile processing conditions. The overall performance of the fibres suggests that they can serve as a viable and eco-friendly alternative to conventional natural fibres, particularly for applications such as packaging textiles and similar functional textile products.

**Keywords:** *Agave fourcroydes*; Characterization; Fibre extraction; Eco-friendly textiles; Natural fibres

## 1. Introduction

~~Research efforts to investigate novel natural fibres that can be successfully applied across a variety of industries have significantly increased in recent years. Natural fibres have been explored for textile applications due to their renewable and biodegradable nature, as well as for automotive components, where they offer lightweight and sustainable alternatives to synthetic materials. In the construction and building materials sector, natural fibres are used to enhance mechanical performance and sustainability of composite materials. Moreover, geotextiles derived from plant fibres are gaining attention for soil reinforcement, filtration, and erosion control applications. Recent research has also investigated the potential of natural fibres in solar-related structures and energy applications, such as eco-friendly substrates and biodegradable components in hybrid systems. These developments are driven by growing environmental awareness, limitations on the use of petroleum-based synthetic materials, and increased demand for sustainable alternatives across diverse technological sectors [1-4].~~

Research efforts to investigate novel natural fibres that can be successfully applied across a variety of industries have significantly increased in recent years. Due to resource scarcity, growing environmental concerns, and the worldwide shift towards circular economies, natural fibres have become sustainable and adaptable materials in various technical and industrial fields. Owing to their superior water absorption, thermal performance, biodegradability, and cost-effectiveness, recent studies have demonstrated that natural fibres have substantial potential for use in solar energy systems [1]. Apart from energy applications, natural fibers are essential to the manufacturing of sustainable textiles. They provide biodegradable and renewable substitutes like cotton, wool, kenaf, ramie, and pineapple, and their qualities can be enhanced with the right extraction and processing methods [2]. In automotive filed, the natural fiber embedded polymers are increasingly adopted to achieve the lightweighting and the reduced emissions, replacing the synthetic fibers with biodegradable options like jute, sisal, flax, and hemp [3]. Similar to these, fibers like hemp, kenaf, mesta, flax, straw, bamboo, and wool help the construction industry achieve green building certifications and lower carbon footprints while also improving thermal and acoustic insulation [4]. In addition to these, fibres include Abaca, coir, jute, pineapple, sisal, etc., have also demonstrated encouraging results in geotextiles uses, where soil strength and durability improvement have been observed with natural fibres inclusion and provide sustainable substitutes for petroleum-based geotextiles [5]. All of these developments demonstrate the growing transdisciplinary significance of natural fibers as essential components for sustainable development.

~~Research efforts to investigate novel natural fibres that can be successfully applied across a variety of industries have significantly increased in recent years. These fibres have demonstrated potential for several uses, such as solar applications, textiles, automotive parts, building materials, and geotextiles. Extensive research into the extraction and application of environmentally friendly materials has been spurred by the growing awareness of environmental issues, limitations on the usage of synthetic materials generated from petroleum, and the financial effects of processing. The natural fibres are used in many different industries, including composites and textiles. However, the majority of the research that is now available, focuses more on the use of natural fibres in composite materials than on their application in textiles [1]~~.

*Taraxacum Sect. Ruderalia* fibres were investigated and characterized in a research work by Köktaş S et al. [6]. It is noteworthy, nonetheless, that their research did not take into account some crucial textile factors, such as defects of fibre/stem skin, density in bulk, and bundle’s strength [7]. Comprehensive data has been gathered in a study by Shinoj S R et al [8] to evaluate oil palm fruit's potential for bio-composite synthesis in various polymeric matrices. However, the viability of using it in textile applications was not investigated. Researchers' interest in investing for properties in new plant-based fibres has grown in a recent past few years, with a focus on assessing their potential for usage in composite applications [9-10]. On the other hand, research on new natural fibres extracted especially for textile applications has been increased in recent years. After thorough analysis, the bark fibre of B. Vahlii was found to be appropriate for yarn production when mixed with other cellulosic fibres [11]. The recent studies on the stem/stalk fibres of the *Cyperus papyrus* plant have showed viable option for conventional textile fibres, particularly in the production of yarn [12]. To comprehend the fibre's spinnability and potential as a raw material for textiles, extensive research has been done on the fibre taken from the E. Elatior plant's main stem part [13]. Additionally, the fibres from *Agave v. cruz* [14], Tellicherry (*piper nigrum*) [15], and *Canna edulis* [16] plants have been thoroughly investigated, with promising results, especially in the area of textile utilization.

*Agave fourcroydes* (henequen) is a perennial, drought-tolerant fibre-yielding plant native to regions of Mexico and Guatemala. It belongs to the Asparagaceae family and exhibits close botanical similarity to the sisal (*Agave sisalana*) crop, particularly in its rosette-type leaf arrangement and bast fibre-bearing structure. The plant develops long, sword-shaped leaves emerging from a robust central stem, with individual leaves reaching lengths of up to approximately 120 cm and widths ranging from 6 to 10 cm. The leaves are greyish-green in colour and relatively rigid compared to conventional sisal mother leaves. Henequen is predominantly propagated vegetatively and thrives in arid to semi-arid environments with low water requirements and well-drained soils, making it suitable for cultivation on marginal lands. Under managed plantation conditions, plants typically attain harvest maturity within 4–6 years and remain productive for more than two decades, with periodic leaf harvesting. Reported fibre yields range from approximately 1 to 2 tons of dry fibre per hectare per year, highlighting the plant's long-standing agronomic importance as a sustainable natural fibre source and supporting its potential for expanded applications beyond traditional uses.

~~The plant known as agave fourcroydes (henequen) is native to parts of Guatemala and Mexico regions. It belongs to the asparagus family and shows a strong botanical kinship with the sisal fibre crop and also grows leaves in rosettes like sisal. With a maximum length of up to 120 cm, these leaves are lengthy and have a sword-like form compared conventional mother leaf sisal plant. Leaves, which grow from a robust stem, are between 6 and 10 cm wide and have a greyish green color.~~

The study conducted by Cazaurang-Martínez et al. [17] presented a detailed evaluation of the chemical, physical, and mechanical properties of *Agave fourcroydes* (henequen) fibre. Chemical composition analysis of the leaf fibres indicated that cellulose was the dominant constituent, accounting for approximately 59% of the total fibre content, followed by hemicellulose at 28% and lignin at about 8%. The mechanical characterization revealed a tensile strength of 570 MPa and a Young's modulus of 14.7 GPa, indicating good stiffness and load-bearing capability. The true density of the fibre was reported to be 1.2 kg/m$^3$. Although the study provided comprehensive insights into the chemical and mechanical characteristics of henequen fibre, it did not explore how these properties could be effectively utilized in textile manufacturing, such as in spinning, weaving, or blending processes. An evaluation of these aspects would be essential to assess the fibre’s suitability and commercial potential for sustainable textile applications beyond its traditional uses.

~~Research presented by Cazaurang-Martinez et al. study. [14] discussed the chemical, physical and mechanical properties of Agave fourcroydes fibre. From chemical analysis of fibres, it has been revealed that the fibre consists of 59% cellulose of the total fibre composition. Analysis also diaplayed hemicellulose were 28% of the sample, and lignin were around 8%. For the mechanical properties of Agave fourcroydes fibre, the tensile strength value of 570 MPa was determined using tensile strength testing. Young’s modulus, which determines the stiffness or elasticity of the material, was also considered to be 14.7 GPa. True density of the fibre reveals t<. But, this study did not examine the potential textile applications for henequen fibre. While this study addressed the chemical and mechanical properties of fibre, it did not address how these properties could be utilized in textile manufacturing. The properties of the fibre in relation to spinning, weaving, or mixing with other fibres for the textile industry would be invaluable in explaining the commercial potential of the fibre. This evaluation is vital in order to evaluate the strength of fibre for sustainable, viable textile products that could expand market opportunities beyond its past uses.~~

Hygrothermal performance of poly butylene succinate (PBS) composites embeded with silk and henequen fibres were researched by

Han So et al. [18]. These biocomposites were manufactured by compression molding and hydrothermal resistance exposure for 1000 hrs at 60 °C and 85% relative humidity. This has shown that the major responsible for declining of mechanical properties in biocomposites is the PBS matrix degradation. One of particular interest is the fact that composites degrade at a lesser rate than the PBS matrix. In both the cases, after 1000 h of exposure, the storage modulus dropped to 50% and 20% for henequen and silk fibres reinforced composites, with respect to the initial value. Water absorption by natural fibres results in a mass increase of the composites, which stabilizes after 50 hours. The capacity of water absorption was higher for silk fibres compared to henequen fibres, which in turn caused the further degradation of the PBS matrix in the composites. Other important observation is that, although drastic, the loss in storage modulus was less pronounced and the silk fibre reinforcement composite still kept its initial storage modulus after 1000 hrs. The henequen fibres on the other hand experienced significant degradation, affecting the performance of the composite. In terms of longevity, choosing natural fibres becomes imperative. While the research emphasizes the role of natural fibres in composite degradation, only its reference to tensile properties is of direct relevance to textile use. This discovery indicates a potential for research in the creation of textiles that exhibit good performance capabilities in high environmental stress situations.

Several works on Henequen fibre were performed by Yasin P et al. [19]. It reports microstructure studies, physicochemical properties, refining extraction of fibres and surface treatments to improve its performance in polymeric composites. This study allowed them to analyze the influence of some treatments to the fibres like alkalinization and heating, individually and mixed, on the mechanical and thermal properties of Henequen/epoxy composites. Tensile and flexural strengths as well as the thermal stability was proved to increase with these treatments. In spite of these advances, the possibilities of Henequen fibre with regards to the textile industry have not been further investigated. Although these contributions are valuable, the latter study primarily examines issue of composite fabrication and application, without specifically addressing the needs and advantages of incorporating Henequen into the textile industry. However, future studies are required in order to determine the viability of Henequen fibres for textile production, which could potentially lead to very sustainable and eco-friendly options to fabric production.

One research the effect of fibre- matrix adhesion on mechanical reinforcement of short Henequen fibres into HDPE-composites was analysed [20]. Use of treatments such as the application alkali, silane coupling agent, and HDPE/xylene pre-impregnation significantly improved the Interfacial Shear Strength (IFSS) with silane and pre-impregnation providing the best tensile, flexural and shear properties. SEM analysis of treated fibres revealed better adhesion and modified failure modes. In a similar manner, another research [21], X-ray photoelectron spectroscopy (XPS) and Fourier transform infrared spectroscopy (FTIR) showed that coupling with silane increased the interaction between fibres and the matrix and reinforced the mechanical performance of the composites. This is important to note that such studies only explored the mechanical and interfacial properties without investigating inherent textile characteristics of henequén fibres, which consist of behaviors in terms of handle, drape, mechanical performance and durability.

Later works [22-26] also investigated henequén fibres in different composites matrices (PP, PA6, PHBV, and epoxy), highlighting mechanical, thermal and structure enhancements through chemical and physical modifications. But there wasn’t any study dealing with the textile performance of these fibres nor of their processability into textile. As a result, the microstructural, physio-mechanical and textile characteristics of henequén fibres, like fineness, bundle strength, and color that might be useful in additive technologies are still to be probed, as most studies have optimized the fibres for the purpose of reinforcement. Fulfilling this gap becomes important to assess A. fourcroydes (Henequén) fibres and as a sustainable option for eco-friendly textiles. Nonetheless, as much as the appeal of these biofibres for such technical purposes has increased, in the literature there have been no previous reports of properties relevant to the manufacture of textiles, such as fineness, strength, flexibility, and spinnability of the fibres extracted from *Agave fourcroydes*, and this represents an important gap in the research addressed through the present study.

Although several studies have investigated *Agave fourcroydes* (henequén) fibres with respect to their chemical composition, mechanical behavior, surface treatments, and performance as reinforcement in polymer composites, systematic evaluation of their textile-relevant characteristics remains largely unexplored. In particular, properties such as fibre fineness, staple length, bundle strength, bulk density, colour characteristics, spinnability-related behavior, and thermal stability under textile processing conditions have not been comprehensively reported. The present study addresses this research gap by providing a detailed textile-oriented characterization of *Agave fourcroydes* leaf fibres, thereby establishing their potential as a sustainable and eco-friendly alternative raw material for textile applications rather than merely as a composite reinforcement.

## 2. Materials and methods

### 2.1 Fibre extraction from leaves

In the present work, healthy *Agave fourcroydes* leaves were harvested from Narapally Reserve Forest Area, Hyderabad, India (Refer Figure 1 (A-F)). The selected and cut leaves had almost equal sizes and colours (Figure 1(B)). The length and width of the leaves were around 65–110 cm and 6–8 cm, respectively. The water retting procedure described by Madival AS et al. [27] and Baskaran PG et al. [28] was used to extract the fibre bundles from plant. The spine at the tip and teeth along edges of the leaves were removed in order to prepare them for pond retting before it was put into water. The leaves were organized into piles as shown in the Figure 1(C). The leaves were water or wet retted under constant water coverage and immersion for 19 days. Retting resulted in the slow, even decay of the soft gum and other non-fibrous content, in which the fibre bundles have been partially exposed but retained their physical structure excluding fibre tissues. The completely retted leaves are shown in figure 1(D). The resulting fibres (Figure 1(E)) were then kept submerged in tap water for an extra two days to help remove any foreign matter that could have remained. The fibres were then carefully removed by gently tapping and sqeezing the leaves with wooden mallet and often rinsed in fresh water resulted for extraction of fibres.the extracted fibres exposed to direct sunlight for a week to speed drying and enhance their quality. The resulting dried *Agave fourcroydes* leaf fibres (AFLFs) shown in Figure 1(F) were then transferred to a fresh plastic bag for storage, preserving them.

Figure 1. (A) *Agave fourcroydes* plant (B) cut and spine-teeth-free leaves (C) Leaves organized into piles (D) Water retting of leaves (E) Extracted fibre (F) Sun-dried fibre

## 2.2 Analysis and evaluation of textile properties

FTIR is an analytical technique that has been used for the identification of functional groups of organic, polymeric, and, in certain cases, inorganic materials. In the present investigation, the FTIR analysis method employs infrared radiation to examine one test samples and determine their chemical characteristics. The Agilent Cary 630 FTIR instrument, which operates at a power requirement of 110-240 VAC and 60/50Hz, was employed in this study. The instrument possesses a spectral resolution that is better to 2 $cm^{-1}$, covering a spectral range from kBr 6300-350 $cm^{-1}$ to ZnSe 5100-600 $cm^{-1}$. Also, it attains a wave number accuracy of 0.05 $cm^{-1}$ and wave number reproducibility of 0.005 $cm^{-1}$, in accordance with the standard ASTM 1921. Instrument utilized for FTIR transmits the infrared radiation into AFLFs sample, where some of which will be absorbed and some of which is going to be transmitted. The radiation that is absorbed by the sample molecules undergoes a process of conversion into rotational and/or vibrational energy. The resulting signal, which is detected and displayed as a spectrum, typically covers a range of 4000 $cm^{-1}$ to 650 $cm^{-1}$. This range effectively captures the molecular fingerprint of the sample and the same has been presented under results and discussion section.

The measurement of fibre length was conducted in accordance with the guidelines outlined in the National Standard 08-1113-1989 for AFLFs Length measurement. In this study, a total of twenty sets of fibre strand samples were utilised, with each set consisting of a minimum of one hundred individual fibres. These fibre strands were carefully spread out in a loose manner on a flat surface, ensuring that they were evenly distributed. The most significant sample from these sets was measured utilising the prescribed methodology.

The *true density* of the AFLF has been measured using an Electronic Weighing balance cum Digital Density instrument was a Deepak Poly Plast Ltd. model, equipped with an LCD-based display unit, a glassware kit, pan straddle and forceps, featuring a highly sensitive flat bar type load cell of 300 gms capacity, providing measurements with a precision of 0.001 gm (1 mg) accuracy and adhering to the reference standard ASTM D 792, operating on 220/230 V AC, 50 Hz Single Phase power. The fibres were meticulously weighed before being cut into tiny pieces varying in length from 3 to 5 mm. Following that, the finely chopped fibre particles were placed in a glass container holding the working liquid (WL). Various working liquids (WLs) were used in this study to accurately measure density, notably toluene and xylene. Each WL was used to determine the density of five AFLFs samples separately. The fibre pieces were carefully introduced into the glass jar filled without and with WL, allowing the Liquid Digital Density Meter (LDDM) to calculate AFLFs density based on specific gravity similar to Pathan Y and GB VK [29].

Although each individual fibre’s appearance can be described in a variety of ways i.e. gradients of grey, creamy pink, ivory, white, cyan, etc.; the most core and visual trait of fibre is its color. The colour analysis of the AFLFs was done as per the color standardization technique set up by the Indian Jute Industries Research Association (IJIRA). The current approach utilizes a whiteness index one complete reed of AFLFs as a measurement tool for determining the percentage of color that lists creamy pink-brownish white (the best quality), brownish- reddish white with faint hints of light grey, brownish-light grey, and grey-dark (lowest quality). In this investigation work, the IJIRA method was applied for the first time to the comprehensive assessment of the color characteristics of the samples of AFLFs. The observed coloration variations were categorized in a systematic way.

This was important to the present study, considering fineness is central as to the parameter of fibre thickness, diameter, breadth or weight per unit length. The testing of ten AFLF samples' fineness were calculated with the help of special air flow instruments, followed BIS Standard IS 271(2020). The experiment consisted in weighing chopped samples of AFLFs and placing them in a two-ended open cylinder chamber in connection with a manometer. These fibres were later compacted to achieve a uniform volume in the chamber. It was also possible to regulate the amount of air in a precise way, because it was injected into the previous chamber with compressed air at fixed pressure levels. A large amount of air in the chamber indicated that there were coarser fibres present. Conversely, instead, it was observed that lower air flow indicates finer fibres. This work was used to set the average character in tex unit for each of the fibres studied. On top of that, fibre diameter and fineness were measured by a process that calculated the fibre diameter based on a ratio between the airflow pressure and the differential pressure.

Strength is an intrinsic property of fibres; it describes their ability to resist forces acting on them, for example the pulling forces. Definition of bundle strength, or fibre tenacity as stated in IS 271 (2020) is the subject of research in this paper. The bundle strength classification adopted in the present study is based on the BIS sub-group scoring system for the strength parameter, evaluated using both hand-and-eye assessment and instrumental measurements in accordance with IS 271 and IS 7032 standards. Instrumentally, fibre strength is expressed in terms of specific strength (g/tex), and the corresponding classifications are defined as follows: fibres exhibiting strength values ≥ 25 g/tex are classified as excellent and assigned a score of 30; values between 20 and 25 g/tex are categorized as good with a score of 23; values ranging from 15 to 20 g/tex fall under the average category with a score of 13; and fibres with strength values below 15 g/tex are considered poor or weak mixed and assigned a score of 4. These scores contribute to the overall grading of the fibre bundles as prescribed in the BIS grading framework. The test instrument was a tensile strength tester with a load of 100 kgf. Ten tensile tests samples were prepared and carefully inserted into the testing apparatus to capture the results. The machine was convinced to impart a controlled load to the fibre samples up to breaking point. Time of fibre breakage was recorded within the predetermined interval 20 ± 5 seconds. Findings of these tests were analyzed in full in order to quantify and indicate the strength of the AFLFs pack in g $tex^{-1}$. The particular measurement described here is significant because it reveals implications for the focal fibre’s ability to resist externally imposed stresses and thus for the fibre’s resultant overall strength and the durability.

The mass-to-volume ratio was calculated while taking airspaces into consideration in order to calculate *bulk density*, also referred to as the weight or volumetric measure of the fibre. The measurement procedure employed in this study adhered to the guidelines specified in IS 271 (2020), which provided a comprehensive framework for assessing bulk density. The bulk density classification of fibres in the present study follows the qualitative grading framework commonly adopted for bast fibres in accordance with BIS guidelines. Based on the measured bulk density values (g/cc), fibres are categorized as loose and light density when the bulk density is below 0.4 g/cc, medium-bodied when the bulk density ranges between 0.4 and 0.80 g/cc, compact when values lie between 0.80 and 1.2 g/cc, and heavy-bodied dense when the bulk density falls in the range of 1.2 to 1.5 g/cc. Specialised equipment was utilised to accurately evaluate the bulk density of ten AFLF samples. In the current study, five different sets of Ag/LFPs were prepared for analysis. Each sample was weighed to exactly 40g and had a length of 100 mm. The samples were then carefully spaced between aluminum plates in a machine designed to measure bulk density. In this present study a 10 kg weight was used as an external force pushing the fibres. Quantity of fibres was precisely measured and monitored throughout the experiment. Mass to volume ratio was used to determine accurately the bulk density of the AFLFs and expressed in g $cc^{-1}$. Bulk density is one of the classic measures of fibre quality and, in general, the higher values are considered as better fibre properties. The association with weight and compactness implies that fibres that have higher bulk density are heavier and more compacted.

An ideal DSC/TG/DTA experiment was carefully designed to understand the thermal behavior and stability, temperature-induced mass changes and informative DSC analysis of AFLFs. This study has been carried out on one AFLF sample using a highly sensitive Seiko TG/DTA 6200-instrument in an inert nitrogen gas atmosphere. Temperature experimentation was performed over a temperature range of 250 to 1500 °C at a heating rate of 20 °C/min. The use of an aluminium capacity and pan designed to securely hold and measure AFLFs samples helped guarantee the accuracy of the experiment. Interestingly the end result of this was capable of reaching a temperature of 720 °C, with a strong 15 kV power supply.

The SEM analysis of five samples was utilized to discover details regarding the morphology of the outer surface and cross-section of the AFLFs. The AFLF samples were carefully processed, particularly with a thin layer of gold sputter-coated to allow for clear imaging. The images captured by the Hitachi SEM S3700, and the EVO 18 ZEISS SEM both coming from Japan and Germany respectively that have an accelerating voltage ranging from 0.2 to 30 kV, with magnification power between 5-1,000,000x and 5-300,000x were obtained in order to review the sections made individually. A 5-Axes motorised Compu-centric Specimen Stage is included in both instruments, enabling precise sample positioning to assist thorough examination of the AFLF samples. For cross-sectional morphological analysis, single fibres were embedded in Lapox-12 epoxy resin prior to SEM examination. Lapox-12 was selected due to its low viscosity, effective fibre wetting capability, minimal shrinkage upon curing, and good dimensional stability, which facilitated stable specimen mounting and precise cross-sectional polishing. The fibre was positioned vertically in the resin mold, leaving one end exposed for sectioning. After

**Table 1** Extraction duration and average fibre content to leaf weight ratio of few natural fibres

| Fibre/plant name | Retting period - (days) | Fibre-to-leaf weight ratio - (%) |
|---|---|---|
| *A. angustifolia marginata* [29] | 15.0 | 3.9 |
| *A. Sisalina* [32] | - | 4 |
| *Fur. selloa k Koch* [33] | 14.0 | - |
| *A. americana L.* [34] | 21.0 | 2.5-4.5 |
| Jute (*Corchorus olitorus*) [35] | 14.0-15.0 | - |
| *Fur. foetida mediopicta* [36] | 21.0 | - |
| Corn husk [37] | 16.0 | - |
| Napier grass [38] | 7.0 | - |

curing, the embedded specimen was carefully polished to obtain a smooth and well-defined cross-sectional surface. This embedding technique enabled improved handling and structural preservation of the fibre during SEM imaging.

## 3. Results and Discussions

### 3.1 Extraction of AFLFs

The *Agave fourcroydes* plant and extracted fibre is presented in Figure 1. Various techniques, including mechanical processing, retting, decortication, and chemical extraction, can be employed to separate fibres from the non-fibrous cellular tissues and pectin components of leaves. The duration of leaf immersion crucially depends on the chosen extraction method [30]. Each leaf, weighing approximately 300-600 gms, underwent a steep retting in a pond. Within a week of the retting process, noticeable deterioration of the surface layers occurred, attributed to enzymatic activity exposing the fibre bundles [31]. Over the course of 10 days, the watering also caused the Juicing of *Agave fourcroydes* leaves to lose its green-juicing content. Over the following two days, further processing continued with the pounding, rinsing, and several more repeated rounds of retting in attempts to clear any remaining green material. Retting process took 19 days to complete, and produced individual fibre strands with low gum content. These results are consistent with Li Y and Shen YO study [32]. Further the analysis reported that each leaf had 4% weighted fibre content, with an estimated fibre number between 900 and 1000 similar to sisal fibre [32]. Values of extraction times and fibre to leaves weight ratios for different natural fibres are shown on Table 1. In addition to that, AFLFs have extracts in less time than many leaf and grass fibres. The extraction time of fibre has almost been the same for *Furcreo Foetida Mediopicta* [36] and AFLFs. Such differences in extraction times between natural fibres are probably due to structural variations in the source, such as cuticle properties, dry mass content, water percentages. This study's findings in comparison highlight the necessity for more in-depth research in order to understand the variability observed.

## 3.2 Potential of AFLFs for Textile applications

The absorption bands in the FTIR spectrum were used to identify the distinctive functional groups present in the AFLFs (Figure 2 and Table 2). The C-OH and C-H bending

**Table 2** FTIR result of AFLFs: peaks, functional groups and components

| Peak Wavenumber in $cm^{-1}$ | Functional Group | Respective Fibre Component | References |
|---|---|---|---|
| 666 | C-H bending | hemicellulose and lignin | [40] |
| 805.1049 | C-H bending (glucomannan) | Hemicellulose | [40] |
| 1043.6545 | C-O and C-OH stretching | Lignin and/or Cellulose | [41] |
| 1252.3855 | C-O stretching | Lignin or/and cellulose, Protein (Amide III), | [42] |
| 1326.9322 | C-H bending (oop) | Lignin and/or cellulose | [43] |
| 1423.8430 | $CH_2$ bending and C=C stretching | Lignin and/or Wax | [44] |
| 1625.1193 | C=O stretching | Hemicellulose | [45] |
| 1729.4847 | C=O stretching | Hemicellulose, Lignin | [46] |
| 2564.4084 | C≡C stretching | Alkynes | [42] |
| 2758.23 | C-H stretching | Hemicellulose, | [42] |

vibrations that are linked to the peaks at about 666$cm^{-1}$, 805.10497 $cm^{-1}$

and 1326.93227 cm$^{-1}$ indicate the existence of hemicellulose and lignin, respectively. Amorphous polysaccharide hemicellulose is a part of fibres that helps to maintain their structural integrity. The fibres are given rigidity and support by lignin, on the other hand. Cellulose, an essential structural polysaccharide in fibres, is indicative of the peak at 1043.65459 cm$^{-1}$, which corresponds to C-O stretching vibrations. The peak at 1423.84305 cm$^{-1}$, which is associated with $CH_2$ bending vibrations, indicates the presence of wax, which aids in water resistance and protection. The peak at 1625.1193 cm$^{-1}$ denotes C=C stretching vibrations linked to unsaturated lipids, which 0support barrier and lubricant characteristics. Both hemicellulose and lignin can be linked to the peak at 1729.48476 cm$^{-1}$, which is associated with C=O stretching vibrations, emphasising these substances' oxidised functional groups. Although the peaks at 2564.40843 cm$^{-1}$ (C-C stretching) and 3168.23716 cm$^{-1}$ (N-H stretching) are unusual for fibres, they could indicate the presence of unusual elements or impurities. The peaks near 2758.23 cm$^{-1}$ and 2907.32351 cm$^{-1}$, which are both C-H stretching vibrations, show the presence of hydrocarbon moieties in hemicellulose and cellulose, which contribute to their structural characteristics. Both cellulose and water may be seen in the peak at 3462.05873 cm$^{-1}$, which is connected to O-H stretching vibrations. It emphasises the significance of hydrogen bonding as well as the fibre's capacity to take in moisture. The peak at 3548.42562 cm$^{-1}$, ascribed to N-H stretching vibrations, may also be a sign of pollutants like amines or proteinaceous substances. Greater transmission intensity between 3600 and 3900 cm$^{-1}$ indicates the possibility of O-H stretching and the presence of hydrogen bonds [49]. The FTIR spectrum analysis confirms the presence of key components in AFLFs, including cellulose, hemicellulose, lignin, and wax, based on the observed characteristic absorption bands. These functional groups are consistent with the expected chemical composition of the fibres and play a critical role in defining their structural and protective properties. While some peaks indicate potential impurities or unusual elements, the overall spectrum validates that the major components contributing to the fibre's integrity and performance are present.

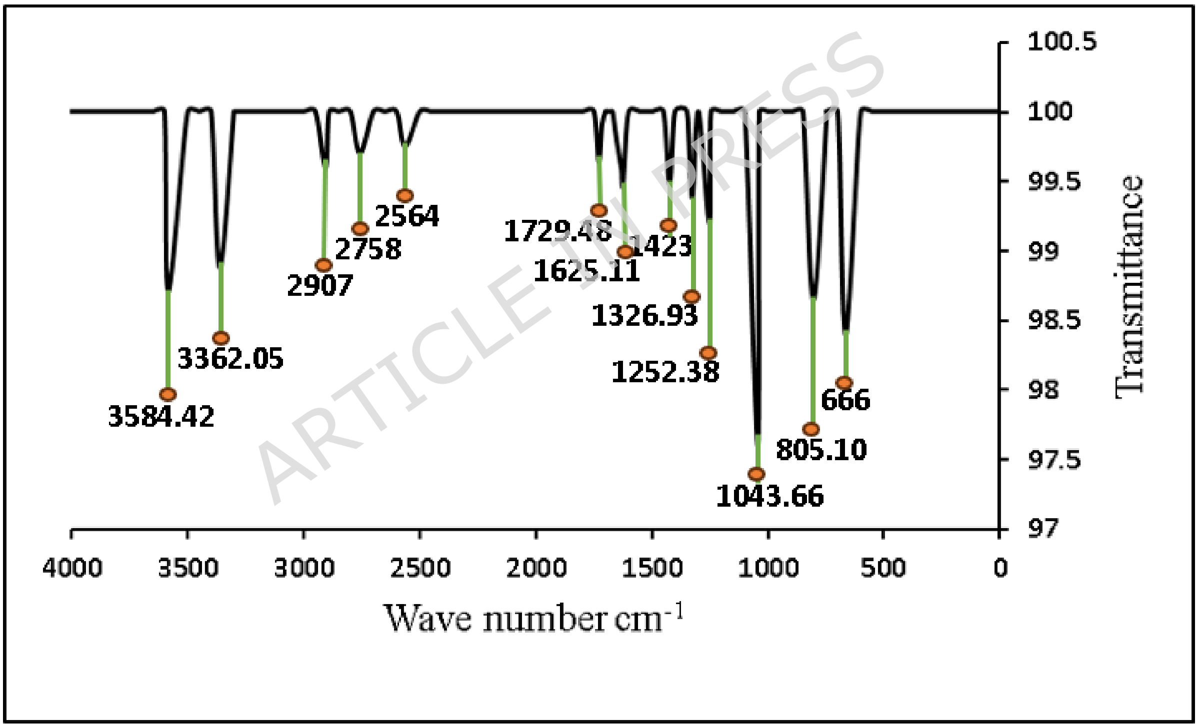

Figure 2. The FTIR spectrum of AFLF

It was determined that the lengths of the AFLFs exhibited a range spanning from 50 to 110 cm. The AFLFs derived from the plant specimens exhibited a close correspondence with the length of the leaves under consideration during the processing phase. The observed similarity in length between fibres implies a potential influence of leaf size on fibre length during the processing stage. The AFLFs can be classified as "extra-long staple fibres" according to their length. In the realm of yarn production, there exists a preference for longer raw fibres as opposed to their shorter counterparts, with the former being deemed superior in

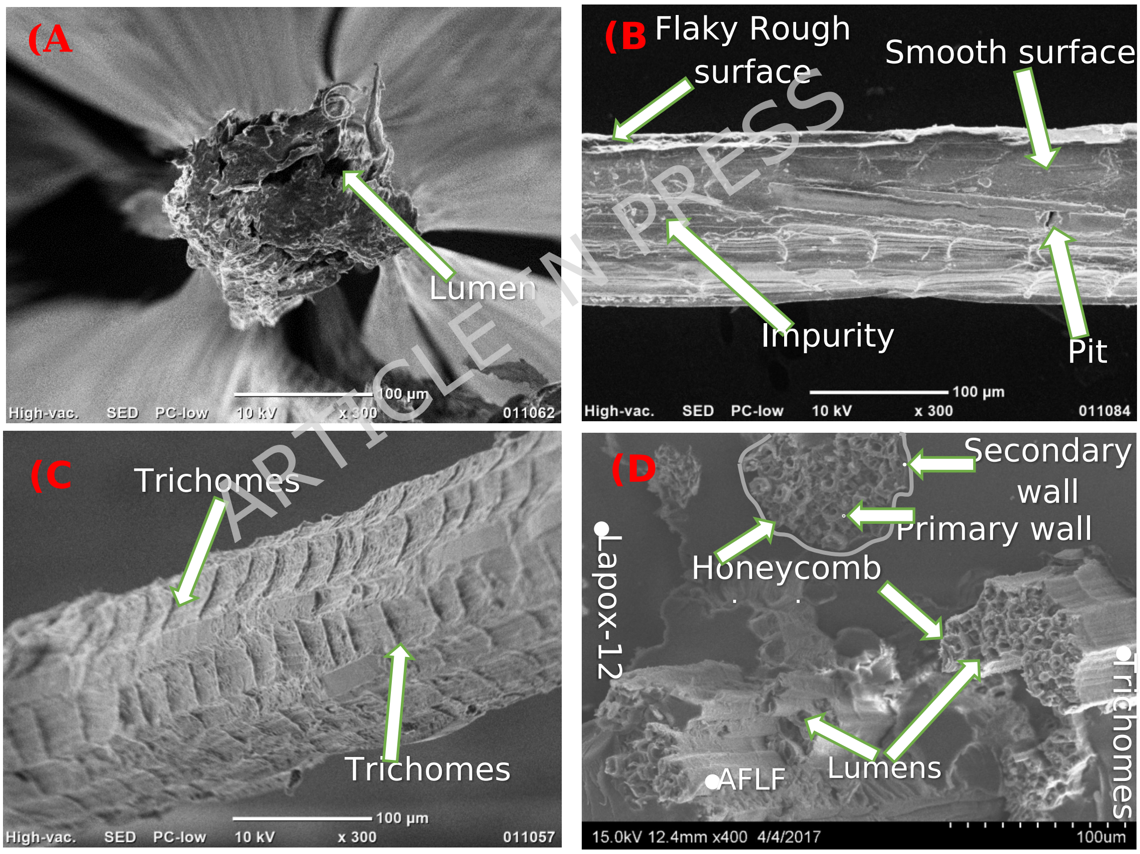

Figure 3. Microstructural analysis of AFLF: (A) Cross sectional view of fibre showing lumens (B) Longitudinal view of fibre showing rough surfaces and impurities (C) fibre captured at angle of $45^0$ showing trichomes and (D) AFLFs reinforced in Lapox-12 Resin for better cross

terms of quality. The preference for longer fibres in the spinning process is based on the recognition of various advantages associated with their use. One notable advantage lies in the augmented surface area of elongated fibres, thereby facilitating enhanced friction and diminished slippage among the fibres [50]. The surface morphology of AFLFs, as depicted in Figure 3 (B-C), clearly demonstrates their rough surface and other characteristics that are advantageous for ensuring adequate friction and preventing slippage during manufacturing and loading scenarios.

**Table 3** Working liquid (WL) and AFLF's true densities in g/cm$^3$

| WL | Density | AFLF sample densities | AFLF mean density (standard deviation) |
|---|---|---|---|
| Toluene | 0.866 | 1.40527<br>1.40731<br>1.39971<br>1.41571<br>1.41535 | 1.40807(±0.005571) |
| Xylene | 0.875 | 1.42561<br>1.41231<br>1.40133<br>1.41737<br>1.40303 | 1.41193(±0.009048) |

According to Murthy H V S [51], the utilisation of long staple yarns in the production of fabrics yields several advantageous outcomes. These fabrics exhibit enhanced strength, smoother texture, and increased functionality, making them more valuable in comparison to fabrics manufactured using short staple yarns. The findings of this study suggest that the utilisation of

**Table 4** True densities of various natural fibres

| Fibre/plant name | True Density in g/cm$^3$ | References |
|---|---|---|
| Jute | 1.3 | [54] |
| Cotton | 1.550 | [55] |
| Bamboo | 0.6-1.1 | [54] |
| Sponge Gourd Outer Skin | 1.344 | [56] |
| Pineapple | 1,440 | [57] |
| Flax | 1.540 | [58] |
| Pigeon Pea | 1.7389 | [59] |
| Hemp | 1.470 | [58] |
| Ramie | 1.5 | [54] |
| Banana | 1.35 | [54] |
| *Agave angustifolia marginata* | 0.983 | [29] |
| Bagasse | 1.25 | [54] |
| *Chloris barbata* | 0.634 | [60] |
| Palm | 0.7-1.55 | [54] |
| Typha | 1.478-1.605 | [61] |

AFLF has the potential to yield yarn of superior quality. According to existing literature, it is advised that the minimum length of the fibre employed in yarn production should be no less than 5 mm. This recommendation is based on the need for a significant length-to-diameter ratio, which is crucial for ensuring the preservation of individual fibre integrity during the manufacturing process [51]. The configuration factor of spinning machines utilised in fibre treatment is subject to the influence of fibre length, which holds significant importance in determining the appropriateness of the spinning process. The ease of spinnability exhibited by AFLFs is a contributing factor to this phenomenon. The industrial handling of textile fibres plays a pivotal role in the overall processing of these fibres for the production of a wide range of products. The role of fibre length in the spinning system is of considerable importance, as it influences the positioning of rollers and aids in mitigating excessive twisting during the processing stage. The minimum length requirement for jute fibre, as specified by the Bureau of Indian Standards (BIS) in their systems IS 271 (2003) and IS 271 (2020), is approximately 100 cm. The optimal length of a card is determined by its ability to facilitate efficient feeding on breaker cards and minimise handling operations [52]. Also, the band at 3548.42562 cm-1, due to N-H stretching vibrations, could be indicative of impurities such as amines or proteinaceous materials. Higher intensity of transmission from 3600 to 3900 cm-1 can suggest the stretching vibrations of O-H bonds and the existence of hydrogen bonds. The identification of cellulose, hemicellulose, lignin, and wax as major components of AFLFs is also supported by the characteristic absorption bands listed in the FTIR spectral information. Because they are likely molecular groups that can be found in the fibres, these functional groups are also relevant in elucidating the structure and protective capabilities of the fibres. A few of the peaks may signify impurities or anomalies, but the spectrum as a whole confirms the presence of the major components that would impart strength and toughness to the fibre. It was defined that the AFLFs obtained lengths ranging from 50 to 110 cm. The leaf size was similar to the length referred of the leaves during the processing stage on the specimens for plant size. The observed not statistically significant size of the fibres could suggest that leaf size has an effect on fibre length also at the processing stage. According to their length, the AFLFs can be considered ‘extra-long staple fibres’. When raw fibres are concerned, the long fibres are more valued; long fibres are considered good fibres for spinning yarn. The spinning process prefers longer fibres for several reasons that make it evident that they are advantageous to be used. An advantage, if only for reduced slippage between fibres would be through an increased surface area provided by elongated fibres. The surface morphology of AFLFs, as observed in Figure 3(B–C), indicates enhanced external friction and improved anti-slip characteristics during manufacturing and loading conditions, which can be attributed to the rough surface texture of the fibres. ~~The surface morphology of AFLFs, observe in Figure 3B-)C), has also showed outstanding external friction properties and anti-slip capabilities during manufacturing and loading situations due to their rough surface.~~ Advantages of using long staple yarns for fabric manufacturing as put by Murthy H V S are: These fabrics are more valuable than fabrics made from short staple yarns because they are stronger, smoother, and more useful. This research also supports that the use of AFLF can result in better quality yarn. The recommended minimum fibre length for use in spinning, according to this literature, is 5 mm. This suggestion is made due to the requirement of a very high length/diameter aspect ratio that is fundamental for the conservation of attainment of fibre integrity at each step of the production process, particularly at spinning stage. Spinning is the preparation facility that, combined with the other two, has a characteristic that can be significantly influenced from the fibre length, because fibre length is of crucial, vital for spinning purposes. The fact that AFLFs can spin is a part of that. The processing of textile fibres is an important first step in the production of countless items and its industrial handling and processing is especially crucial. Fibre length is indeed one of the more relevant parameters in the spinning system, it influences roller arrangements and it helps to prevent a too high amount of twisting during processing. The BIS in their standards IS 271(2003) and IS 271 (2020) state that the jute fibre in question, should have approximately this length, as a minimum. The ultimate card’s length is given by the possibility to have a fast feeding on breaker card and by the operations’ handling that must be minimized. The effect of a low stiffness of fibres is important for the properties of fabrics. Nano-pill meaning small filaments also indicates that nanotechnology in the case of textiles produces much finer fibres that give soft textiles. This also can produce yarn with higher count of threads, further improving fabric quality. Density of a material is related to the molecular interact opportunities of the fluid being a working liquid (WL) and its chemical composition. When a natural fibre is immersed in a liquid, the liquid provides an apparent thermal buoyant force on the fibre, and the density of the fibre can be determined. It must be kept in mind that each of these different liquids imply different density and interactions with the fibre sample, thus, a modification in the measured density. Using the LDDM the real density of the AFLFs was found to be 1.410 g/cm$^3$ (mean value for this study), which represents the mass per unit volume of the AFLFs (see Table 3). The achieved σ (±0.005571 and ±0.009048 g/cm3) shows that measuring results are highly repetitive. These differences in the values undoubtedly can be caused by differences in the physico-chemical characteristics of the region, or may be caused by some experimental bias. The observed value of AFLFs exhibits a higher magnitude when compared to the majority of reported densities found within the existing body of literature pertaining to natural fibres including Jute, bamboo, banana bagasse and palm fibres (refer Table 4). The density of the AFLFs is almost close to sisal and pineapple fibres (Table 3). The variation of densities across different natural fibres can be attributed to the factors such as chemical composition, ageing, internal structure, lumen spaces, microfibril angle, cell dimensions, defects, and other relevant parameters [54]. According to

IS 271 (2003) standards, the higher density value of the natural fibre, the better the quality of fibre, indicating AFLFs one of the quality fibre.

In Figure 3 (A-D), the SEM images of AFLFs reveal various features, including lumens, rough and smooth sections, micro-cracks, impurities, and micro-holes (pits). Figure 3(A-C) show three views of the fibres: cross-sections, longitudinal views, and 45- degree angle views, which clearly show the colored microparticles and trichomes. These microparticles are probably related to amorphous fractions like hemicellulose, cellulose and lignin in concordance with FTIR results [63].

**Table 5** Few AFLFs properties compared to other natural fibres

| Fibre/plant name | Fineness in tex | Bundle strength in g/tex |
|---|---|---|
| Furcraea foetida [50] | 8.3 | 21.0 |
| Cotton [50] | 0.1-0.3 | 26.6-28.7 |
| Jute [65] | 2.9-3.27 | 15.73-17.8 |
| Pineapple leaf [50] | 3.5-4.3 | 23.0-30.0 |
| Sisal [70] | 30.0-32.0 | 28.0-30.0 |
| Abaca [71] | 20.0-35.0 | 20.0-35.0 |
| Ramie [71] | 0.4-0.8 | 28.0-40.0 |
| Coconut fruit [70,71] | 50.0-55.0 | 11.0-12.0 |
| Banana [71] | 3.0-25.0 | 20.0-30.0 |
| AFLF [present study] | 34.44 | 19.0 |

The cross-sectional morphology of the AFLF exhibits a distinct honeycomb-like architecture composed of multiple polygonal cellular cavities (lumens) enclosed by well-defined primary and secondary cell walls (Figure 3 (D)), which is the characteristic feature of lignocellulosic fibres and plays a crucial role in determining various textile-related properties of AFLF. The presence of lumens in AFLF contributes to the hollowness of fibre (low density), good air permeability, and potential thermal insulation, while the porous internal structure of AFLF facilitates the effective moisture absorption and the capillary transport, thereby improving breathability and the comfort performance in textile applications. The cells structure of the AFLFs are inherently complex and can be regarded as a kind of natural composite, wherein the rigid and the highly crystal-cellulose microfibrils in AFLF are embedded within a relatively softer lignin and hemi-cellulose matrix. These microfibrils in AFLF are helically oriented along the AFLF axis to form an ultimate hollow cells, and during the tensile loading of AFLF, the gradual uncoiling and the reorientation of these spirally wound microfibrils absorbs significant energy, which contributes to the strength and the toughness, of AFLF by delaying the structural failure. For detailed morphological examination, the AFLF was embedded in Lapox-12 epoxy resin, which is commonly adopted in composite fabrication to evaluate fibre–matrix interaction and reinforcement potential of AFLF; however, in the present study, epoxy embedding of AFLF was primarily carried out to obtain a stable and damage-free cross-section suitable for clear and accurate SEM imaging. The SEM image of epoxy-embedded AFLF clearly highlights the honeycomb morphology of AFLF along with distinct lumens, trichomes, and primary and secondary cell wall layers, thereby confirming the hierarchical organisation of AFLF, which strongly influences the mechanical performance and composite reinforcement capability of AFLF

(Figure 3 (D)). According to Alzarieni KZ et al. [64], it can be assumed that locally high or low density of any natural fibre must be due to the presence of a large hollow lumen within the structure of the fibre. Figure 3 (A) and (D) both show the presence of lumens in cross-section of AFLFs and correlate with the high density of AFLFs.

The fineness of AFLFs was evaluated in accordance with the IS 271 (2020) standard for jute fibre, which categorizes fibres into four classes: extremely fine, fine, well-separated, and separated fibres. Table 5 displays few properties of AFLFs compared to other natural fibres. Based on this criterion, the AFLFs analysed exhibited an average tex value of 34.44, placing them within the “separated fibres” category. This classification indicates that AFLFs are considerably coarser than typical jute fibres, whose fineness usually lies in the range of 1.3–4.0 tex for conventional jute bast fibres reported in the literature. Such values correspond to much finer textile fibres (on the order of ~15–25 µm in diameter) typical in textile applications. This divergence in fineness becomes particularly evident when AFLFs are compared against not only standard jute fibres but also other lignocellulosic fibres (e.g., flax, cotton, hemp). In many natural fibres, finer linear densities contribute to improved yarn quality by increasing the number of fibres across a given cross-section, thereby enhancing inter-fibre contact and cohesion. The observed higher tex value of AFLFs implies a larger fibre diameter and a consequent reduction in specific surface area per unit mass. According to fundamental textile science principles, larger fibre diameters yield increased stiffness and torsional rigidity, which in turn affects the ease of spinning and the behaviour of fibres in yarn structures. Specifically, coarser fibres typically exhibit higher flexural and torsional rigidity, leading to less flexibility and lower cohesiveness. This can reduce the intimate contact between fibres during spinning, thereby complicating twist insertion and fibre binding. Murthy H. V. S. [51] previously emphasized that fibre fineness plays a significant role in determining key yarn properties, including packing and flexural rigidity. Larger fibres, as observed for AFLFs, are known to contribute to higher rigidity in fibre assemblies, requiring increased twist levels to achieve comparable cohesion relative to finer fibres. However, excessive twist or rigidity can also promote spontaneous kink and snarl formation in relaxed yarn structures due to differential fibre bending stresses and reduced alignment. The reduction in surface area associated with coarser AFLFs also impacts capillary activity within the yarn. A lower specific surface area limits the liquid capillary action intrinsic to finer fibre assemblies, which may affect both moisture transport and binder penetration in downstream processing factors known to influence dye uptake, finishing quality, and mechanical behaviour in textiles. It should also be noted that while coarser fibres tend to store higher strain energy prior to twisting (due to their increased cross-sectional moment of inertia), this is a distinct phenomenon from the energy storage capacity after a yarn has been twisted. In practice, insufficient cohesion and high rigidity can lead to irregular yarn consolidation, surface irregularities, and processing challenges during weaving and knitting. In fabric structures, these characteristics translate into tangible effects on yarn stability, appearance, and handle. Controlled incorporation of bulkier fibres has been shown to enhance cover factor and bulk, which may be advantageous for specific end-uses such as packaging or coarse textiles. However, the same characteristics can also result in surface irregularities, reduced smoothness, and increased yarn hairiness when excessive or improperly managed. Therefore, while AFLFs' coarse nature situates them outside conventional textile fineness regimes, this property may be advantageous in niche applications requiring bulk or rigidity, provided that appropriate adjustments in spinning and fabric formation processes are implemented [51, 72-75].

~~The fineness of AFLFs was determined according to the IS 271 (2020) standard for jute fibre which classifies the fineness in four categories of extremely fine, fine, well separated, and separated fibres. Results from the analysis of the AFLFs show a tex value of the average of 34.44, and they fall amongst "separated fibres". Such categorization is much coarser than the tex value commonly known for jute fibres. This distinction is clearer when comparing AFLFs with other lignocellulosic fibres, and from Table 5's data show that AFLFs have a very high fineness than the others. In this regard, Murthy H V S [51] pointed out that fibre fineness becomes relevant in the determination of relevant yarn properties such as packing and flexural rigidity. The reduction in specific surface area caused by larger fibres observed herein also was reported to occur in yarn structure. It has been reported that this reduction in surface area has a direct effect on the fibre cohesion of the yarn and on the capillary activity of the same yarn. Plus, one should remember that a reduction in the yarn count may tend to increase the torsional resistance of the fibre. The~~

~~twisting process is somewhat problematic, due to these coarser fibres. Nevertheless, twisted yarns can store more strain energy than finer fibres, so that it is relevant only before twisting. This rise in strain energy could eventually give rise to spontaneous kinks and snarls on the relaxed yarn. In fabrics, such kinks and snarls can influence yarn stability, fabric appearance, and handle, contributing to increased bulk and cover when controlled, but causing processing difficulties and surface irregularities when excessive.~~

The performance of a textile product has much to do with its mechanical properties, defined as “the characteristics that determine how a fibre will transmit and react to external forces and deformations”. Fibre strength depends on the plant species and the growth direction among others. All of these things play a role in the tensile strength of the fibres. Tenacity or bundle strength is an important criterion to show the ability of the fibre to bear stresses and it also is directly connected to grading tests [52]. The International Standard 271 (2003) defines the various classifications of bundle strength as follows down six distinct classifications. These are weak mixed, average, fair average, fairly good, excellent and very good. In the work regarding the obtention of AFLFs, bundle strength was measured in 16.2 g tex$^{-1}$ (or 1.79 g den $^{-1}$). This study clearly indicates that AFLFs are also characterized by possessing more than average physical strength. The AFLFs strength and durability (Table 5.) can be seen as an indicator of a strong bundle, indicating its suitability for many applications, a moderately strong, long-lasting “fibre for most applications. In particular, it was also found that the bundle tenacity of

AFLFs is higher than 1 g den$^{-1}$, which is the minimum requested if the textile characteristics are to be exploited and optimized [50, 51]. These fibres have the possibility to be used as clothing and in other domestic applications, and are in accordance with an optimum strength of 3-7 g den$^{-1}$ [50, 51]. The properties of tensile strength of AFLFs are attractive for a variety of textile products which would guarantee their usability and efficacy in apparel as well as in household items.

According to IS 271:2003 bulk density is categorized as follows: heavy-bodied dense, compact and heavy density; medium-bodied, for that of loose and light density. This background is important, as the study presented here specifically deals with AFLFs that are extracted from leaf material. Bulk density of AFLFs, a crucial parameter investigated in this study, is 0.37 g cc$^{-1}$. This value reflects that AFLFs are medium bodied. The bulk density of common jute fibre is 0.45 g cc$^{-1}$ as reported in the literature [66], indicating their low value as opposed to AFLF, which shows a maximum reduction with 0.37 g cc$^{-1}$. The fact that most of these light and less-structured fibres are indeed of AFLF family is indicative of the lightness and frequency of fibres in the AFLF family. It is to be noted here that the most recent BIS Standards, particularly IS 271(2020) have relieved some pressure by making bulk density not a categorization criterion for mother jute fibre [67].

The capacity of a fibre to perceive and recognize various colours i.e., its ability to interact with visible light such as red, white, yellow, and blue is a critical attribute influencing the visual appeal and aesthetic quality of textile materials. In this study, colour measurements of AFLFs were obtained using a portable colour meter calibrated according to BIS standards. The quantified colour response of AFLFs indicated a 36% colour measurement, suggesting a visual profile ranging from grey to dark grey. This measurement reflects the inherent pigmentation of the plant-derived fibres rather than external colouring treatments, and it represents positive colour perception within the context of natural fibres. The observation of AFLFs' inherent colouration emphasizes their high plasticity and affinity for pigmentation, likely originating from natural biochemical constituents such as lignin, tannins, and chlorophylls commonly found in plant fibres. Natural pigmentation in cellulosic fibres has been reported to produce a variety of hues including browns, greens, and tans without the need for appended dyes, a phenomenon similarly noted in naturally coloured cotton varieties where pigments are associated with cell lumen or biochemical compounds inherent to the plant structure. This inherent colouration carries significant implications for sustainability and cost efficiency in textile manufacturing. Traditional dyeing processes represent one of the most resource-intensive and environmentally impactful steps in textile production, consuming substantial amounts of water and energy, and generating dye-laden effluents that contribute markedly to industrial water pollution. Globally, the dyeing stage accounts for a large fraction of the textile industry's water footprint and effluent discharge, with synthetic dyes often containing recalcitrant compounds that persist in water bodies and contribute to ecosystem degradation. By contrast, naturally pigmented fibres such as AFLFs can bypass the dyeing process entirely, offering both economic and environmental advantages. Eliminating the dyeing step reduces the need for chemical inputs and the associated wastewater treatment burden, thereby lowering manufacturing costs and ecological impacts. This aligns with broader efforts in sustainable textiles, where naturally coloured fibres are increasingly recognised for their reduced environmental footprint compared to conventionally dyed materials. However, while inherent colour offers clear sustainability benefits, certain technical limitations should be considered. In the broader context of natural fibre colouration and dyeing, the reproducibility of specific shades and long-term colourfastness remain challenges, particularly for natural dyes and pigmented fibres, which may exhibit greater variability due to biological source differences and weaker bonding compared to synthetic dyes. Nonetheless, the significant reduction in water, energy, and chemical usage associated with dyeing processes coupled with rising consumer preference for eco-friendly textiles reinforces the potential of AFLFs as a low-impact alternative for producing visually appealing and functionally sustainable textile materials. In summary, the positive colour perception and natural pigmentation of AFLFs not only contribute to their aesthetic appeal but also suggest a substantial opportunity for cost savings and environmental benefits in textile applications by obviating or minimizing conventional dyeing requirements [76-78].

~~The capacity of a fibre to perceive and recognize various colors, i.e. red, white, yellow, blue etc., is defined to be perceived, will be called its color perception. This aspect has a great impact on the visual appeal of the~~

~~fibre. Color measurements in AFLFs was done effectively using a portable color meter that has suitable indicators. The AFLFs showed a 36% color measurement according to the BIS method. Such value argues for positive color – it ranges from grey to dark grey. This observation, as well as the one above, stresses the high level of plasticity of AFLFs and their capability to even get coloration by means of the inherent pigmentation of the plant. As a result, these fibres are of the range of colors from a variety of shades of brown to several shades of green. A positive feature of AFLFs is that they could be used for different purposes, such as textiles, clothing and crafts. This low-impact approach suggests the significant potential for cost saving that would come with not dying naturally colored fibres. The high cost of producing textiles is due in large part to the expense of the dyeing process. Dyeing is particularly water and energy-intensive, even yielding the most wastewater and pollution. As a result, the advantage is, that manufacturers can save on the costs and eliminate all the environmental problems related to this specific step of the production of textiles, because it is no longer necessary to dye the fabric. A flute furcatus produce a highly vibrant coloration naturally, and can be utilized in the textile industry. Because AFLFs already have a good color, they do not have to be dyed, and this is also beneficial.~~

According to recent research on ramie fibre [52] and banana fibre [79], grading any new or potential natural fibre is critical for predicting how it will behave during the manufacturing process, determining its best use in the development of various types of yarns, and determining its blending compatibility with other commercial natural fibres. Since AFLFs is a novel natural fibre, there are no recognized grading criteria. The current study investigated the criteria of AFLFs' fineness, bundle strength, bulk density, and color which are a few of the parameters used to assess the grade of jute fibre (BIS system) has been utilized for AFLFs (see Table 6). The remaining two variables as per the BIS system are root content and defects. Because AFLF is a leaf fibre, this BIS system was not considered appropriate to determine root content or defects as they vary from bast fibre to leaf fibre. If root content and defects are eliminated, AFLFs evaluated according to BIS method IS 271 (2020) will yield at least W-4 grade fibres. This type of grade evaluation could certainly aid in blending of jute fibre and AFLFs [80].

Table 6 also presents an assessment of natural fibre quality with respect to various grading systems. The parameters evaluated include Length, where the measurements fall within the range of 60-90 cm for most systems, except for IS 271 (2020), which has a slightly narrower range of 60-89 cm. Fineness for AFLF is graded as coarse with 5 marks in the BIS system, while other systems do not assign a specific grade. Bundle Strength is categorized as Average with 13 marks in the BIS system, whereas other systems do not provide weightage. Bulk Density of AFLF does not receive grading in any of the systems. The color of parameter is uniquely described in terms of its Grey to dark grey appearance with some light grey, scoring 5 marks in the BIS system and is marked as GDG in all other systems. Defects, foreign matter, root content, and harsh fibre are assessed differently in each system, with some marked as Not Appropriate (¥), No Weightage (▯), and others needing further investigation labelled as

Need to Be Investigated (?). Finally, in the classification of the general quality of the fibre the Estimated Grade is also variable among systems, in some cases it is rated with Grade W-3, Grade 3S, Grade R, Type 3, and No.2.

**Table 6** Assessing AFLF Quality in Alignment with Appropriate Natural Fibre Standards

| Name of the Grading system | Parameters and their weightages per grading system | | | | | | | | | Estimated grade designation |
|---|---|---|---|---|---|---|---|---|---|---|
| | Length (70-100 cm) | Fineness (34.44 tex) | Bundle strength (19.0 g tex$^{-1}$) | Bulk density (0.37 g cc$^{-1}$) | Colour (36%) | Defects / other features (16.75%) | Foreign matter/ impurities (-) | Root content (1.52%) | Harsh fibre (-) | |
| BIS system IS 271 (2020) [6] | ▯ | 5 Marks | 13 Marks | ▯ | 5 Marks (GDG) | ¥ - 17 Marks | ? | 20 Marks | ? | Grade W-4 |
| East African sisal fibre grading system [81] | Good quality (>60-89cm) | ▯ | ▯ | ▯ | Poor quality (GDG) | ? | ▯ | ¥ | ▯ | Grade 3S |
| Madagascar sisal fibre grading system [81] | Good quality (>60-90cm) | ▯ | ▯ | ▯ | Poor quality (GDG) | ? | ▯ | ¥ | ▯ | Grade R |
| Brazil sisal fibre grading system [81] | ▯ | ▯ | ▯ | ▯ | Poor quality (GDG) | ? | ? | ¥ | ▯ | Type 3 |
| Aloe grading system [81] | Good quality (> min. 60cm) | ▯ | ▯ | ▯ | Poor quality (GDG) | ? | ? | ¥ | ? | No. 2 |

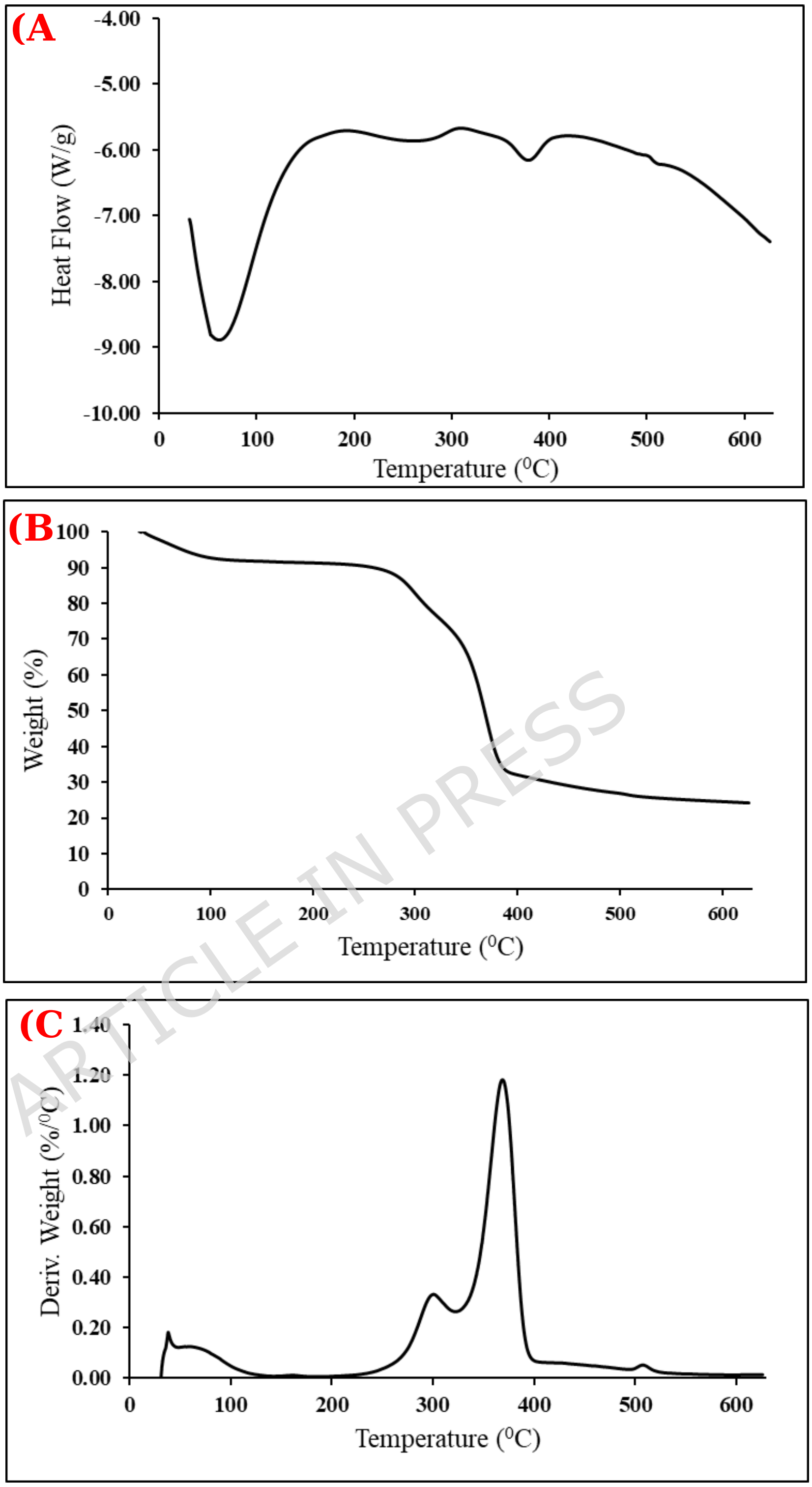

Figure 4. Thermal analysis of AFLFs: (A) DSC curve (B) TG curve and (C) DTG curve

**Table 7** Thermal stability of recently explored natural fibres

| Plant/fibre name | Thermal stability in ºC | References |
|---|---|---|
| *Tithonla Diversifolia* | 237 | [91] |
| *Ficus carcia* | 225 | [92] |
| *Hibiscus Vitifolius* | 260 | [93] |
| *Ageratina adenophora* | 244 | [94] |
| *Albizia Saman* | 306.19 | [95] |
| *Cissus quadrangularis* | 294 | [96] |
| *Celosia argentea* | 280 | [97] |
| *Coccinia Indica* | 204 | [98] |
| *Albizia amara* | 330.6 | [99] |
| *Acacia Concinna* | 280 | [100] |
| *Pithecellobium dulce* | 170 | [97] |
| *Agave angustifolia marginata* | 240 | [29] |
| *Albizia lebbeck* | 250 | [94] |
| *Celosia argentea* | 280 | [97] |

The thermal behavior of *Agave fourcroydes* leaf fibres (AFLFs) was evaluated to assess their suitability for textile processing and end-use applications. The TGA/DTG/DSC results reveal a three-stage thermal degradation mechanism, including initial moisture evaporation, followed by decomposition of hemicellulose and cellulose, and finally lignin degradation. AFLFs exhibit good thermal stability up to approximately 220 °C, with minimal weight loss in the intermediate temperature range, indicating their ability to withstand common textile processing and ironing conditions without significant thermal degradation. The study of thermal properties of the new natural fibres, and therefore also of their thermal stability, is important because it may be crucial to evaluate their applicability as reinforcing agents in the production of new textiles or bio-composites. One interesting detailed analysis performed in the present work, is the study of the degradation behaviour caused by temperature in powder form AFLF's. The synergic effect of the above- mentioned degradation phenomena were determined via DSC, Thermogravimetric (TG) and DTA, and synthetized in an appealing way in Figure 4.

The DSC curve in Fig.9 (A) describes the main thermal properties of AFLFs. A peak corresponding to an endothermic reaction with a maximum at temperatures between 50 and 100 °C is well defined and it is associated to the heat absorbed during the evaporation of free water located in the fibre intercellular spaces [82]. "Linked water" is also strongly associated with the cellulose structure and is removed only at higher temperatures. This can be appreciated in the change of slope of the curve at about 100 °C. It is important to note that the DSC analysis reveals a feature at 64.30 °C, being this temperature the one that corresponds to the lower endothermic peak.

The TGA curve of the AFLFs shows three distinct phases of degradation with temperature. These two little endothermic peaks occur in the DTG curve for the first degradation step at 39.51°C and 143.61°C. This finding may be an effect caused by the evaporation of moisture and liberation of water molecules in the structure of AFLFs. The obtained experimental values show this reduction at a temperature of 143.61 °C and is of 8.25%. Thermal stability tests showed that AFLFs exhibit a high thermal stability in a temperature interval between 143.61 and 220 °C. One indication of this is the very small weight loss of only 0.71%. This gives an indication of the temperature range in which textile items produced from AFLFs can be effectively processed or ironed. This is the second phase of decomposition and the temperature of the onset is 220 °C. At this point there is a notable weight loss of 57.37%. It can be weighted this weight loss to the decomposition of hemicellulose, hemicellulose glycosidic linkages, cellulose I and α-cellulose. The noticeable endothermic peak at 367.32 °C is relevant since it describes a faster decomposition. A final step (step three) takes place in the range 387.20-625.27 ºC with 9.38% weight loss. It is during this stage the residual cellulose, lignin and aromatics in AFLFs are decomposed. The endothermic peak observed at 507.59 °C represents the maximum level of lignin degradation as well as the thermal depolymerization of wax. Lignin decomposition is the slowest of the three processes cellulose, and hemicellulose being faster. This is presumably due to the high variety of functional groups available in the fibre lignin, each presenting different thermal stability. The percentage of char is measured at 22.80 % at 705.70°C. Table 7 also shows the comparison of thermal stability of AFLFs with different natural fibres. It is important to note that the thermal stability of AFLFs is higher than that of several natural fibres, such as *Pithecellobium dulce* and *Coccinia indica*, but is generally lower than that of most other natural fibres [83-90].

## 4. Conclusion

This study systematically investigated the textile-relevant characteristics of *Agave fourcroydes* leaf fibres (AFLFs) to assess their potential as a sustainable natural fibre for textile applications. Fibres were successfully extracted from leaves using a water retting process, and their physical, geometrical, mechanical, thermal, and morphological properties were comprehensively evaluated.

The extracted AFLFs were found to possess extra-long staple length, moderate fineness, and adequate bundle strength, which are favourable attributes for yarn formation and textile processing. The natural grey colour of the fibres offers an additional advantage by reducing the need for dyeing, thereby contributing to environmentally friendly textile production. Thermal analysis revealed that AFLFs exhibit good thermal stability up to approximately 220 °C, indicating their suitability for common textile processing and finishing operations. Morphological observations confirmed the fibrous structure, supporting the measured geometrical and mechanical behaviour.

Although advanced structural parameters such as crystallinity index and crystallite size were not investigated in the present work, the obtained results demonstrate that AFLFs exhibit a balanced combination of mechanical performance, thermal resistance, and aesthetic natural appearance. These characteristics highlight their potential as an alternative natural fibre for sustainable textile applications. Future studies will focus on detailed structural analysis and processing optimization to further enhance their applicability in textile products.

## Declarations

**Ethics approval and consent to participate:** Not applicable

**Consent for publication:** Not applicable

**Availability of data and material:** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Competing interests:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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