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# Influence of Extraction Techniques on the Physicochemical Properties of *Agave decipiens* Fibers

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## ABSTRACT

Natural fiber extraction techniques are important for determining the physicochemical properties and reinforcing potential of plant fibers for sustainable polymer composites. Comparing fiber extraction techniques is essential for identifying suitable processing routes that enhance the properties and reinforcement potential of renewable natural fibers for sustainable composite applications. This study comparatively evaluated the effects of water retting and mechanical decortication on the characteristics of *Agave decipiens* fibers. The extracted fibers were characterized using single-fiber tensile testing, chemical composition analysis, X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM) to determine fiber structure–property relationships of the fibers. The mechanically decorticated fibers exhibited higher tensile strength (477.72 MPa), higher cellulose content (60.78%), and a higher crystallinity index (47.99%) than the water-retted fibers. Further FTIR and SEM analyses revealed fewer residual amorphous components and comparatively cleaner fiber surfaces after mechanical decortication. These data suggest that mechanical decortication may yield fibers with greater stiffness and suitable surface features that could improve fiber–matrix interactions after appropriate surface modification. The results provide valuable insights into the influence of extraction techniques on the structure–property relationships of *A. decipiens* fibers and contribute to the selection of suitable extraction methods for developing high-performance, sustainable natural fiber-reinforced polymer composites.

**Keywords:** *Agave decipiens*; Water retting; Mechanical decortication; Cellulose; Natural fibers.



## 1. INTRODUCTION

The increased demand for low-weight, sustainable, and environmentally benign engineering materials has spurred the development of natural fiber-reinforced polymer composites (NFRPCs) for automotive, building, packaging, marine, and consumer-product applications. Natural fibers offer several benefits compared with synthetic reinforcements such as glass and carbon fibers. These advantages include low density, renewability, biodegradability, competitive mechanical properties, and less environmental impact during the life cycle (Faruk *et al.* 2012; Pickering *et al.* 2007; Mohammed *et al.* 2015). However, the performance of natural fiber composites is not only influenced by the intrinsic properties of the fiber but also by the extraction method used to separate the fiber from the plant matrix. Fiber extraction controls the preservation of cellulose microfibrils, the removal of non-cellulosic ingredients, surface shape, crystallinity, and, ultimately, the quality of fiber–matrix interfacial interaction in composite systems (Muhammed *et al.* 2015; Jawaid and Abdul, 2011; Satyanarayana *et al.* 2009; Sanjay *et al.* 2009). Therefore, comparative evaluation of fiber extraction techniques is important for identifying processing routes that preserve desirable fiber characteristics while supporting the sustainable utilization of renewable plant resources. Such evaluation can help guide the selection of efficient extraction methods for producing natural fibers suitable for sustainable composite applications.

Among extraction processes, water retting and mechanical decortication are the most widely used because of their simplicity, scalability, and applicability to diverse lignocellulosic plants (Kumar *et al.* 2018). Water retting involves microbial breakdown of pectin and other binding chemicals, which liberates fiber bundles from the surrounding tissue. This biological approach generally preserves fiber continuity and flexibility but may result in variable fiber quality, incomplete removal of non-cellulosic components, and environmental concerns associated with wastewater generated during prolonged immersion (Arthanarieswaran *et al.* 2015; Manimaran *et al.* 2020; Vijay *et al*. 2020; Shaker *et al.* 2020). Mechanical decortication, in contrast, separates fibers through controlled mechanical action, enabling rapid extraction with improved output and better industrial applicability (Reddy and Yang, 2005). However, inadequate control of processing conditions may cause fibrillation, local surface damage, or fiber bundling due to high mechanical loading (Kannan and Thangaraju, 2022). Therefore, no single extraction approach is superior; the choice of a suitable procedure depends on the trade-off between fiber cleanliness, structural integrity, processing efficiency, and the desired composite application. Plant-based fibers require extraction through various methods because natural fibers are abundantly available, but extraction determines the quality and morphology, surface characteristics, and mechanical properties of the extracted fibers. Material characteristics affect the two bonding processes at fiber–matrix interfaces and the composite material's performance (Sivalingam and Thirumalaisamy, 2022). Plant fibers are extracted through three main methods: water retting, dew retting, and mechanical decortication; however, water retting and mechanical decortication are preferred because they offer simple, effective, and adaptable extraction methods for various plant materials (Bledzki and Gassan, 1999).

Earlier experiments have shown that the extraction method significantly changes the physicochemical properties of natural fibers. Changes in extraction conditions alter the relative amounts of cellulose, hemicellulose, lignin, waxes, and pectin, which in turn affect crystallinity, moisture absorption, surface roughness, thermal stability, and mechanical behavior (Ovalle-Serrano *et al.* 2018; Tarabi *et al.* 2016). Fibers with a higher cellulose content and crystallinity are often associated with better tensile strength and stiffness, while a high amount of amorphous elements results in a higher moisture uptake and lower dimensional stability (Gebretsadik *et al.* 2023; Mayandi *et al.* 2018). The surface morphology is as important as residual impurities, and non-cellulosic layers inhibit proper wetting and stress transfer at the fiber–matrix interface. Cleaner fiber surfaces provide better conditions for subsequent surface modification and mechanical interlocking with polymer matrices (Yan *et al.* 2014; Kumar and Sekaran, 2014). Therefore, understanding how extraction procedures alter fiber chemistry and morphology is important for optimizing the performance of natural fiber-reinforced composites. The high cellulose content, comparatively low density, and favorable specific mechanical properties have made *Agave* fibers of growing interest. Most published studies have focused on commercially important species such as *Agave americana, Agave sisalana,* and *Agave angustifolia*, where alternative extraction or chemical treatment procedures have been studied to improve fiber performance (Sivalingam *et al.* 2024; Guo *et al.* 2019). All investigations showed that cleaner fiber surfaces, higher cellulose content, and higher crystallinity lead to better mechanical performance. However, these benefits typically depend on plant species, plant age, ambient conditions, and extraction processes, making direct comparisons across experiments difficult. Furthermore, most studies analyze only one extraction method or combine extraction with chemical surface treatments, making it difficult to isolate the influence of the extraction process itself on fiber quality.

*Agave decipiens* is still somewhat neglected in the fiber research literature. For example, *Agave sisalana* and *Agave americana* have been characterized extensively in terms of their physicochemical and mechanical properties, but *Agave decipiens* has received less attention despite its ready availability and clear potential as a reinforcement material. In particular, there has been no previous work comparing water retting and mechanical decortication on fibers drawn from the same *Agave decipiens* source under matched conditions, with a full evaluation covering tensile behavior, chemical composition, crystallinity, functional group chemistry, and surface morphology. This implies that it is not known how the choice of extraction procedure affects the structure–property connections of these fibers and what this suggests for fiber-matrix bonding in composite applications.

This gap motivates the present investigation. The key hypothesis is that the extraction technique strongly influences the physicochemical characteristics of *Agave decipiens* fibers by altering the amount of residual non-cellulosic constituents, degree of crystallinity, and surface morphology, thereby affecting their suitability as reinforcement for sustainable polymer composites. This was confirmed by characterizing fibers generated by water retting and mechanical decortication by single-fiber tensile testing, chemical composition analysis, X-ray diffraction, FTIR spectroscopy, and SEM imaging. Together, this work relates extraction method to fiber chemistry, microstructure, and mechanical performance, providing new insight into *A. decipiens* as a fiber source, and a practical basis for choosing an extraction route when building high-performance natural-fiber composites.

## 2. MATERIALS AND METHODS

### 2.1 Materials

#### 2.1.1 Collection of *Agave decipiens* Leaves

Fresh leaves of *Agave decipiens* were obtained from naturally grown mature plants from Kondampatti Village, Coimbatore District, Tamil Nadu, India (10.9° N, 76.9° E) during the dry season (January 2026). Plants were chosen from an uncultivated region based on consistent maturity, healthy appearance, and no evident signs of disease, insect damage, or mechanical faults. Based on the field observations and plant morphology, the selected plants were around 4–6 years old, which is the mature vegetative growth stage suited for fiber extraction.

**Fig. 1: *Agave decipiens* plant**

The plants had a nicely formed basal rosette of 35–45 leaves. The outer leaves were chosen for fiber extraction because they are more mature and have a higher degree of fiber growth than the younger inner leaves. The average length, maximum breadth, and average thickness at the mid-section of the harvested leaves were 1.05±0.08 m, 10.8±1.2 cm, and 15.2±1.5 mm, respectively. Immediately after harvesting, the marginal spines and terminal spine were removed, and the leaves were rinsed with clean tap water to remove adherent dust and surface pollutants before fiber extraction.

## 2.2 Fiber Extraction

Two commonly employed fiber extraction techniques, namely water retting and mechanical decortication, were adopted to investigate their influence on the physicochemical properties of *Agave decipiens* fibers.

### 2.2.1 Water Retting

Water retting involved submerging freshly collected *Agave decipiens* leaves in a clean polypropylene tank to promote microbial degradation of pectin and other cementing elements that link the fiber bundles. Retting proceeded for 39 days, during which naturally existing bacteria encouraged gradual separation of the fibers from the surrounding leaf tissues (Yan *et al.* 2014). The retting medium was fresh tap water at a water-to-leaf ratio of around 10:1 (v/w) to fully submerge the leaves. Retting was carried out under ambient laboratory conditions at an average water temperature of 29 ± 2 °C, using natural microbial fermentation without external microbial inoculants or chemical additives. To avoid excessive microbial putrefaction and to set uniform retting conditions, the retting water was changed every seven days. Fig. 2 shows the water retting process used for extracting *A. decipiens* fibers.


**Fig. 2: Stages involved in *A. decipiens* fiber extraction through water retting**

After retting, the fibers were manually separated from the softened leaf tissues and thoroughly washed with clean tap water, then with distilled water to remove residual biological matter, degraded pectin, and other adhered impurities. The cleaned fibers were then dried under controlled laboratory conditions at 30 ± 2 °C and 60 ± 5% relative humidity for 48 h, then stored in sealed polyethylene bags until further characterization.

#### 2.2.2 Mechanical Decortication

Mechanical fiber extraction was carried out using a laboratory-scale roller-type fiber decortication machine (custom-fabricated unit) equipped with two counter-rotating cylindrical steel rollers. Before extraction, the marginal spines and terminal spine of the *A. decipiens* leaves were manually removed. The prepared leaves were continuously fed between the rotating rollers operating at 850 rpm with a feed rate of approximately 0.12 m $s^{-1}$ (7.2 m $min^{-1}$). The rollers exerted compressive and shearing action that efficiently separated the fiber bundles from the adjacent parenchymatous tissues, with minimal fiber breakage and maintained continuity. The extracted fibers were then hand-combed to eliminate weakly adherent pulp and to increase fiber separation. After decortication, the fibers were washed extensively with clean tap water (2–3 washing cycles) and finally rinsed with distilled water to remove residual pulp, sap, and surface impurities. The cleaned fibers were conditioned under laboratory conditions of 30 ± 2 °C and 60 ± 5% relative humidity for 48 h until a consistent weight was attained. The dried fibers were stored in sealed polyethylene bags under ambient laboratory conditions before characterization. Fig. 3 depicts the process of extracting *A. decipiens* fibers using the decortication method.

**Fig. 3: Extraction of *A. decipiens* fibers through decortication**

## 2.3 Characterization Methods

#### 2.3.1 Fiber Diameter Measurement

The fiber diameter was measured using a calibrated digital optical microscope. Because natural fibers exhibit irregular geometry along their longitudinal direction, the diameter of each fiber was measured at multiple locations, and the average value was used for subsequent calculations. Ten fibers were randomly selected from each extraction method for measurement. The results are reported as mean ± standard deviation.

#### 2.3.2 Single-fiber Tensile Test

Single-fiber tensile test was performed according to ASTM D3822-07 using a Zwick/Roell Z010 Universal Testing Machine (Guo *et al.* 2019; Jebadurai *et al.* 2019). Ten randomly selected fibers from each extraction method were tested. The gauge length was maintained at 75 mm, while the crosshead speed was fixed at 5 mm $min^{-1}$. The tensile strength was calculated using Eq. 1:

$$\text{Tensile stress} = \frac{F_{max}}{\frac{1}{4}\pi d^2} \qquad \ldots (1)$$

where $F_{max}$ denotes the fiber failure at maximum load and d indicates the cross-sectional dimension of the fiber.

For calculation purposes, the fiber cross-section was assumed to be circular. Although natural plant fibers possess irregular and often non-circular cross-sections, this assumption is widely adopted in ASTM D3822-based tensile evaluation to facilitate comparison among different natural fibers. This assumption's limitation is acknowledged, as it may introduce slight uncertainty in absolute tensile strength values.

#### 2.3.3 Physicochemical Analysis

The presence and proportion of chemical components in *A. decipiens* fibers were determined by chemical composition analysis (CCA). Based on the survey, a pycnometer was used to measure fiber density, using liquid toluene (known density: 0.866 g/cc) as the immersion liquid (Ding *et al.* 2022). Cellulose was determined using the Kürschner and Hoffer method, and wax content was determined using the Conrad method (Elumalai *et al*. 2022; Moshi *et al*. 2020; Bacci *et al.* 2011). Hemicellulose and lignin were predicted using NFT 12-008 and the Klason method, respectively (Manimaran *et al*. 2018; Khan *et al.* 2021). The final step was to determine the moisture content using a Sartorius MA45 moisture analyzer.

#### 2.3.4 X-Ray Diffraction Analysis

Fiber crystallinity was assessed using a Rigaku Ultima IV XRD, which utilizes Cu as the target element. Intensity of the reflected beam and transmitted beam was measured within a range of 5 to 55°, at a rate of 2° per min and a step size of 0.001°. Eq. 2 represents the Segal empirical method used to calculate the crystallinity index

(CrI) based on the peak intensities observed in the XRD pattern (Amel *et al.* 2013).

$$\% \text{ of CrI} = \left(\frac{I_{200}-I_{am}}{I_{200}}\right) X\ 100 \quad \ldots (2)$$

where $I_{am}$ is the amorphous peak intensity, and $I_{200}$ is the crystalline peak intensity.

Using the Debye–Scherrer formula (Eq. 3), the crystallite size (CrS) of the fiber was calculated (Ganapathy *et al.* 2019; Rajeshkumar, 2021).

$$\text{CrS} = \frac{k\,\lambda}{\beta\ \cos\theta} \quad \ldots (3)$$

where $k$ is a constant 0.89, $\lambda$ is the wavelength (0.154 nm), β is the full width at half maximum (FWHM), and $\theta$ is the Bragg angle.

#### 2.3.5 Fourier Transform Infrared Spectroscopy

Based on stretching vibrations, functional groups were identified in water-retted *A. decipiens* fibers (WR-ADF) and mechanically decorticated *A. decipiens* fibers (MD-ADF) using a Thermo Scientific Nicolet IS10 FT-IR spectrometer. The spectrometer uses attenuated total reflectance (ATR) mode for the analysis of molecules vibrating at specific wavelengths. For this purpose, 2 mg of *A. decipiens* fiber (ADF) was mixed with a ZnSe crystal, converted into pellets, and analyzed between 4000 and 600 $cm^{-1}$.

#### 2.3.6. Scanning Electron Microscope

Surface morphology of the extracted fibers was examined using a ZEISS Sigma Field Emission Scanning Electron Microscope (FESEM) operated at an accelerating voltage of 2 kV. Prior to observation, the non-conductive fiber specimens were sputter-coated with a thin conductive layer to minimize charging during imaging. SEM micrographs were acquired at 250× and 500× magnifications to evaluate surface roughness, fiber separation, residual impurities, fibrillation, and other morphological characteristics resulting from the different extraction techniques.

## 3. RESULTS AND DISCUSSION

### 3.1 Fiber Tensile Test and Diameter Measurement

The extraction method significantly influences the tensile properties of natural fibers because it affects fiber integrity and the removal of non-cellulosic constituents. The average fiber diameter, maximum load, and calculated tensile strengths of WR-ADF and MD-ADF are summarized in Table 1. MD-ADF exhibited a slightly smaller average diameter (120 µm) than WR-ADF (123 µm). The maximum load increased from 4.9 N to 5.4 N, increasing tensile strength from 412.58 MPa to 477.72 MPa (approximately 15.8%). This improvement indicates that mechanical decortication effectively preserved the structural integrity of the fibers while removing a greater proportion of non-fibrous materials.

The tensile strength of MD-ADF is comparable to values reported for other *Agave* fibers and several natural lignocellulosic fibers used for composite reinforcement (Ganapathy *et al*. 2019; Rajeshkumar, 2021). Similar trends have been reported for mechanically extracted *Agave americana* and *Furcraea foetida* fibers, where efficient removal of amorphous constituents contributed to improved mechanical performance (Singh *et al*. 2025). In contrast, prolonged water retting may produce greater variability in fiber properties because microbial degradation can be non-uniform and may partially affect the fiber cell wall (Ding *et al.* 2022; Bacci *et al.* 2011). The higher tensile strength of MD-ADF cannot be attributed solely to its slightly smaller diameter. Subsequent chemical composition, XRD, FTIR, and SEM analyses show that mechanically decorticated fibers have higher cellulose content, higher crystallinity, and comparatively cleaner surfaces, all of which are expected to improve load-bearing capability. However, this study evaluates only fiber properties; therefore, any implications for composite reinforcement should be considered indicative until confirmed through composite mechanical testing. Overall, the results show that the extraction method significantly influences the mechanical performance of *A. decipiens* fibers, with mechanical decortication producing fibers with higher tensile strength while maintaining a comparable fiber diameter.

**Table 1. Tensile properties of ADF**

| Type of Fiber | Fiber Diameter (µm) | Maximum Force (N) | Tensile Strength (MPa) |
|---|---|---|---|
| WR-ADF | 123 | 4.9 | 412.58 |
| MD-ADF | 120 | 5.4 | 477.72 |

### 3.2 Chemical Composition Analysis

The chemical composition of natural fibers significantly influences their mechanical properties, moisture absorption behavior, and potential for composite reinforcement. Table 2 summarizes the concentrations of cellulose, hemicellulose, lignin, moisture, density, and wax of WR-ADF and MD-ADF. Cellulose content was higher in mechanically decorticated fiber (60.78%) than in water-retted fiber (53.24%), but hemicellulose, lignin, wax, and moisture were significantly lower. This demonstrates that mechanical decortication removed a larger proportion of non-cellulosic materials bound to the fiber surface. Similar patterns were also seen for *Agave americana*, kenaf, and *Furcraea foetida* fibers, where successful extraction increased the relative cellulose content and reduced the amorphous elements (Tarabi *et al.* 2016; Prithiviraj and Muralikannan, 2022).

The moisture content reduced from 17.24 % for WR-ADF to 14.71 % for MD-ADF, which is attributable to lower hemicellulose content in mechanically decorticated fibers. Due to the abundance of hydrophilic hydroxyl groups, the reduction of hemicellulose generally results in a decrease in the moisture affinity of natural fibers and helps enhance their dimensional stability (Gebretsadik *et al.* 2023; Babu *et al.* 2022). MD-ADF also had higher cellulose content but lower density (1.22 g $cm^{-3}$) than WR-ADF (1.34 g $cm^{-3}$). This behavior most likely results from better removal of residual parenchymatous tissues, pectin, waxes, and other surface contaminants during mechanical decortication, leading to cleaner fiber bundles with reduced bulk density. Similar observations have been reported for mechanically extracted natural fibers, where measured density depends not only on cellulose content but also on retained non-cellulosic materials and fiber microstructure (Ding *et al.* 2022; Madhu *et al.* 2020). Overall, the chemical composition results demonstrate that the extraction technique substantially influences the physicochemical characteristics of *Agave decipiens* fibers. The higher cellulose content, along with lower proportions of hemicellulose, lignin, wax, and moisture in MD-ADF, indicates a cleaner fiber structure, which is expected to improve mechanical performance and reduce moisture sensitivity.

**Table 2. Chemical composition of WR-ADF and MD-ADF**

| Composition | WR-ADF | MD-ADF |
|---|---|---|
| Cellulose (%) | 53.24 | 60.78 |
| Hemicellulose (%) | 28.66 | 26.83 |
| Lignin (%) | 13.93 | 11.35 |
| Moisture (%) | 17.24 | 14.71 |
| Density (g/$cm^3$) | 1.34 | 1.22 |
| Wax (%) | 0.54 | 0.47 |

### 3.3 X-ray Diffraction Analysis

XRD analysis was performed to evaluate the crystalline structure of *Agave decipiens* fibers extracted by water retting and mechanical decortication. The XRD patterns of WR-ADF and MD-ADF are presented in Fig. 4. Both diffraction patterns exhibit a broad amorphous peak at approximately $2\theta = 16°$ ($I_{am}$) and a prominent crystalline cellulose peak at $2\theta = 22.6°$ ($I_{200}$), which are characteristic of cellulose I in natural lignocellulosic fibers (Rajeshkumar, 2021; Krishnamoorthy *et al.* 2025). The calculated crystallinity index (CrI) was 41.28% for WR-ADF and 47.99% for MD-ADF, indicating that mechanical decortication produced fibers with a higher proportion of crystalline cellulose. This increase is consistent with the higher cellulose content and lower hemicellulose and lignin contents observed in the chemical composition analysis. Similar increases in crystallinity following efficient fiber extraction have been reported for *Agave americana* and other natural fibers, where the partial removal of amorphous constituents increases the relative proportion of crystalline cellulose (Terabi *et al*. 2016).

Also, the crystallite size (CrS) was enhanced from 2.980 nm for WR-ADF to 4.721 nm for MD-ADF. Larger crystallites are often associated with increased structural order in cellulose microfibrils, resulting in increased fiber stiffness and more effective load transmission under tensile loading (Ganapathy *et al.* 2019; Zeng *et al.* 2015). Furthermore, highly crystalline fibers are usually less hygroscopic because crystalline cellulose offers less free space for water passage than amorphous components such as hemicellulose and lignin (Liu *et al.* 2019). These properties help enhance the dimensional stability of natural fiber-based composites. In general, XRD data show that the extraction procedure substantially influences the crystalline structure of *Agave decipiens* fibers. The higher crystallinity index and crystallite size achieved after mechanical decortication indicate a more ordered cellulose structure, which agrees with improved tensile properties and reduced moisture content in MD-ADF.

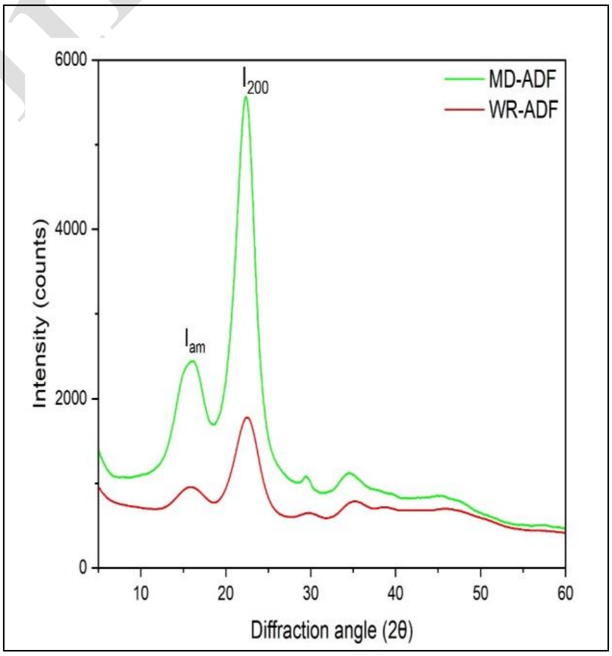



**Fig. 4: XRD patterns of WR-ADF and MD-ADF**

### 3.4 Fourier Transform Infrared Spectroscopy

The FTIR spectra of WR-ADF and MD-ADF are presented in Fig. 5, while the corresponding absorption bands are summarized in Table 3. Both fibers exhibited the characteristic absorption bands of lignocellulosic materials, confirming the presence of cellulose, hemicellulose, lignin, and minor waxy constituents. A broad absorption band between 3700 and 3000 cm⁻¹ corresponds to the stretching vibration of hydroxyl (–OH) groups present in cellulose and hemicellulose. The absorption near 2918 cm⁻¹ is associated with C–H stretching of methyl and methylene groups, whereas the weak bands around 2164 cm⁻¹ and 2092 cm⁻¹ are attributed to wax-related functional groups. The characteristic peak at 1732 cm⁻¹, corresponding to the C=O stretching vibration of acetyl and ester groups in hemicellulose, was more pronounced in WR-ADF than in MD-ADF. Likewise, the absorption band near 1654 cm⁻¹, associated with carbonyl groups, and the lignin-related aromatic vibration around 1510–1517 cm⁻¹ exhibited lower intensity in MD-ADF. These reductions indicate the partial removal of hemicellulose and lignin during mechanical decortication, which agrees well with the chemical composition analysis.

The cellulose-related bands at 1402 cm⁻¹, 1263 cm⁻¹, 1134 cm⁻¹, 1026 cm⁻¹, and 891 cm⁻¹ were observed in both fibers with comparatively greater prominence in MD-ADF, reflecting the relatively higher cellulose content after mechanical extraction. FTIR behavior has been similarly described for *Agave americana* and other natural fibers, where reduced amorphous content increases the relative intensity of absorption bands associated with cellulose (Bezazi *et al.* 2014; El Oudiani *et al.* 2008). Both extraction techniques conserved the basic cellulose structure of *Agave decipiens* fibers as shown by the FTIR study; however, mechanical decortication reduced the relative quantity of hemicellulose, lignin, and waxy components. These spectral variations align with the chemical composition and XRD analysis, showing a cleaner fiber surface and increased cellulose content in MD-ADF.

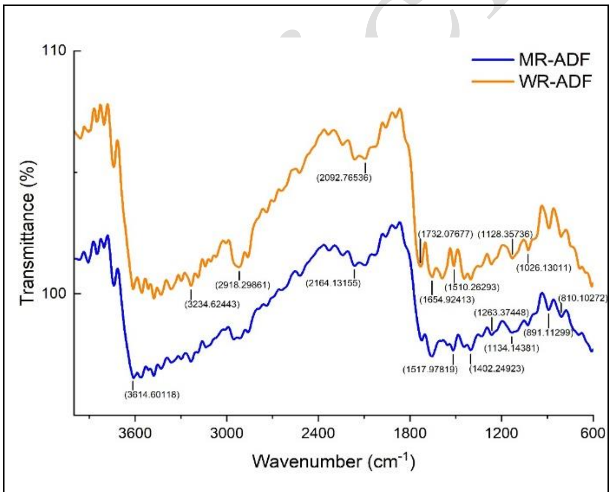
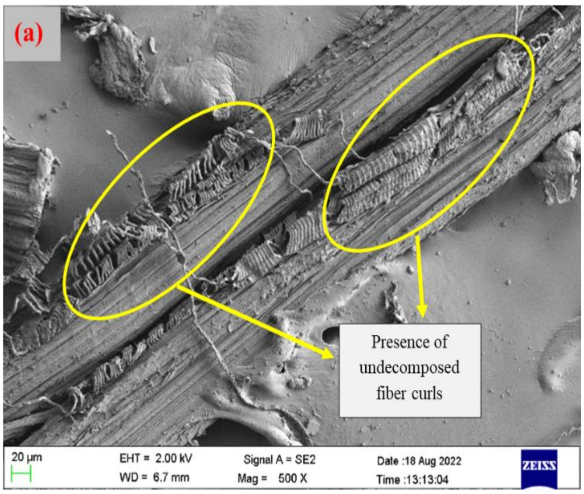



**Fig. 5: FTIR spectra of WR-ADF and MD-ADF**

### 3.5 Scanning Electron Microscope

The surface morphologies of water-retted *Agave decipiens* fiber (WR-ADF) and mechanically decorticated *Agave decipiens* fiber (MD-ADF) are depicted in Figs. 6(a–b). SEM examination provides insight into the efficacy of the extraction process by means of surface cleanliness, residual non-cellulosic components, fiber separation, and morphological flaws. Fig. 6(a) shows that the surface of WR-ADF is rougher and contains visible deposits of residual non-cellulosic materials with partially attached parenchymatous tissues. These traits suggest the water retting method was not effective in removing all amorphous components such as hemicellulose, lignin, pectin, and waxes. The retention of these surface contaminants is compatible with the increased non-cellulosic content, reduced crystallinity, and relatively lower tensile strength found for WR-ADF. Similar surface features have been described for water-retted natural fibers, where partial biological degradation leads to non-uniform fiber surfaces (Kabir *et al*. 2012; Pickering *et al.* 2016).

In comparison, Fig. 6(b) shows that MD-ADF has a much cleaner surface with far fewer residual deposits, indicating that mechanical decortication removes non-cellulosic material more effectively. The elementary fibers remain structurally intact with only slight surface degradation, while some incomplete fiber bundling remains. This morphology aligns with the higher cellulose content, higher crystallinity index, and higher tensile strength found for MD-ADF, indicating that the extraction procedure conserved fiber integrity while minimizing surface contaminants. To summarize, the SEM results show that the surface morphology of *Agave decipiens* fibers depends largely on the extraction process. Mechanical decortication resulted in cleaner fiber surfaces with fewer amorphous deposits. Water retting created more residual surface materials. These morphological differences are well correlated with the chemical composition, XRD, FTIR, and tensile testing results, demonstrating the considerable impact of the extraction procedure on the physicochemical features of the fibers.



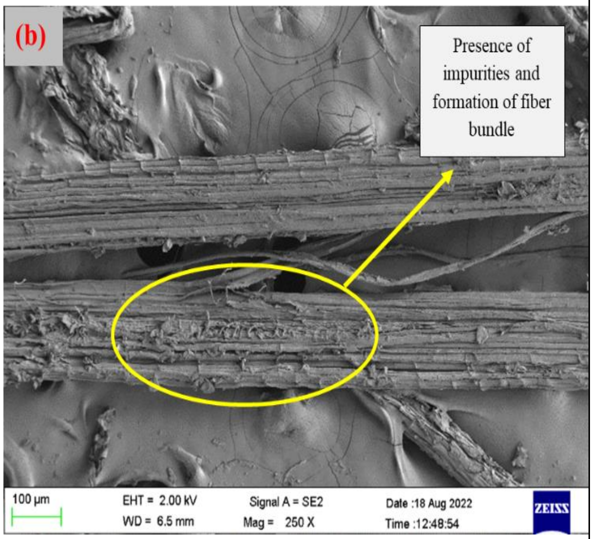



**Fig. 6: SEM images of (a) WR-ADF and (b) MD-ADF**

## 4. CONCLUSION

This study systematically examined the effects of water retting and mechanical decortication on the physicochemical parameters of *Agave decipiens* fibers through mechanical, chemical, structural, and morphological characterization. Under the extraction conditions used in this investigation, mechanical decortication produced fibers with better tensile properties, higher cellulose content and crystallinity, lower moisture content, and cleaner fiber surfaces than water-retted fibers. Combined results from chemical composition, XRD, FTIR, and SEM analyses show that the extraction procedure strongly influences the structural–property relationships of *Agave decipiens* fibers.

These findings provide important guidelines for selecting appropriate fiber extraction procedures for developing sustainable natural fiber-reinforced composites, where fiber quality is a key parameter affecting composite performance. Selecting an effective extraction route can also support the sustainable use of renewable plant resources by enabling the production of natural fibers with desirable characteristics for environmentally responsible material applications. However, the current work measured only the intrinsic properties of the extracted fibers; further experimental validation is needed to assess how the extraction procedure affects fiber–matrix interfacial bonding and composite performance.

Future work could focus on appropriate surface modification of the extracted fibers, followed by composite fabrication, to evaluate their mechanical, thermal, moisture absorption, and long-term durability properties. These investigations will improve understanding of the suitability of *Agave decipiens* fibers for high-performance and sustainable engineering composite applications and further establish their potential as renewable alternatives to conventional synthetic fiber reinforcements.

## DATA AVAILABILITY STATEMENT

The data supporting this study are available from the corresponding author upon reasonable request.

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## CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.



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