RESEARCH ARTICLE

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Assessing Extraction Methods and Mechanical and Physicochemical Properties of Algerian Yucca Fibers for Sustainable Composite Reinforcement

Mohamed Amine Kacem, Moussa Guebailia, Nassila Sabba, Said Abdi, and Mahdi Bodaghi**

The utilization of biofiber in recent years has significantly increased due to its advantages like being environmentally friendly, availability, and low costs. This paper investigates the physicochemical, mechanical, and morphological properties of the yucca fiber extracted by three methods such as water-retting, traditional, and chemical methods. These analyses are designed to evaluate the extraction methodology and the hypothesis of the influence of harvesting location and growth conditions of the fiber. Various technologies are used, such as SEM, FTIR, XRD, and tensile tests. The fiber extracted by water retting is the strongest in the mechanical analysis with a strength of 690.48 MPa, followed by fiber extracted with the traditional method with 685.48 MPa, also 673.06, 657.94, 373.68 MPa for the fiber extracted by the chemical method using 3%, 5%, 10%NaOH respectively. The fiber obtained by the water retting method also has a higher chemical composition with 80.25% cellulose, 10.45% lignin, and 13.75% hemicellulose. The morphological characteristics are examined using Scanning Electron Microscopy. The crystallinity index ranged from 61.75% to 70.77%, and crystallite size from 1.73 to 2.04 nm is calculated from the XRD analysis. All these results confirm that yucca fiber can be a good sustainable choice for composite reinforcement.

1. Introduction

In the new era of materials technology, the availability of polymers can reduce the exploitation and use of environmentally harmful materials. One of the obstacles that prevent the use of these polymers is their low mechanical properties, in order to improve these polymers and make them more cost-effective and more resistant with good mechanical properties. Researchers have found a way to reinforce matrices, using synthetic fibers such as fiberglass and carbon fiber, the combination of polymer (matrices) and fiber (reinforcement), gives rise to a new composite material more resistant than the base polymer. Subsequently, with the advancement of science and the use of several specialties such as materials chemistry, mechanics, and biology, researchers were able to find another solution to reinforce matrices with natural fibers.[1–3]

In this context, the advantages of using this type of fiber are represented in **Figure 1**, such as the availability of these renewable resources, their biodegradability, low environmental impact, recyclability,

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Figure 1. Advantages and applications of natural fibers.

no health danger, accessibility in many countries, and low exploitation and production costs.[1,4,5] All these advantages have made natural fibers an ideal choice for reinforcing a composite matrix to produce a bio-composite material for the manufacture of a wide range of products in the marine industry, automotive, aerospace, and biomedical sectors.[6–9]

Generally, these natural fibers (Banana, Bamboo, Kenaf, Sisal, etc.) are composed of cellulose, pectin, hemicellulose, and lignin.[10,11] The percentages of which can vary depending on the plant species, the part of the plant used, and the growing conditions.[12] The nature and crystallography of the cellulose define the reliability of the reinforcement of these natural resources as cellulose is the major factor in the tensile strength of the natural fiber.[13] The hemicellulose and the lignin represent the amorphous phase of the chemical structure and can obtain the flexibility and rigidity of the bio-fibers respectively.[14,15]

Figure 2 shows all the steps required to benefit these resources, the first important step to benefit these resources is to extract the fiber; actually, there are several methods of extracting fibers from natural plants such as Chemical extraction, Traditional ex-

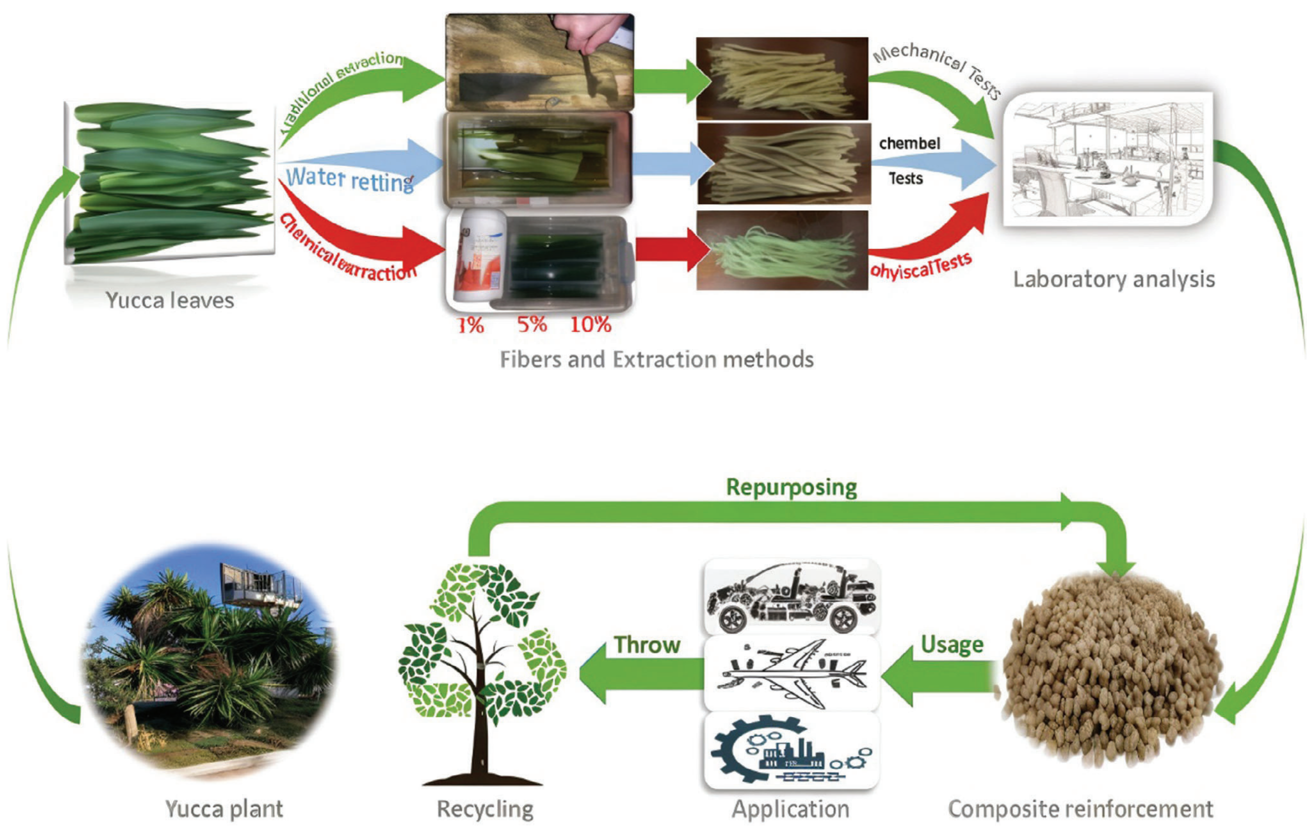

Figure 2. Steps to benefit these natural fibers.

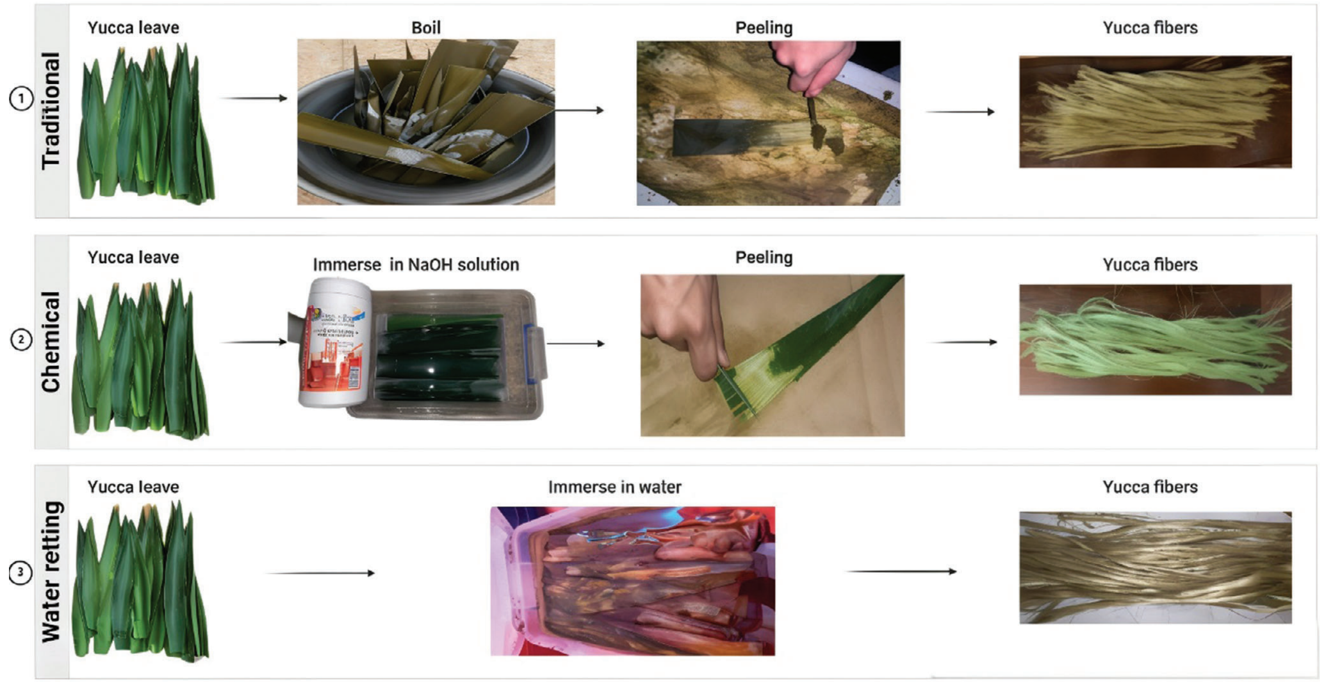

Figure 3. Fiber extraction steps in different methods.

traction, and Biological methods with water retting.[16] Further, several researchers have determined that there are six types of bio-fiber that can be extracted,[17–19] and are classified: seed fiber (cotton, Kapok...), Steam fiber (Ramie, Jute, Kenaf...), leaf fiber (Yucca, Sisal...), Stalk fiber (Bamboo, Wood), and fruit fiber (coir, pineapple...). It is important to note that the specific method of extraction depends on the nature of the plant and the required properties of the fibers. Each method has its specific advantages and disadvantages, and the choice of method will depend on the intended use of the fibers.

The literature shows that the extraction method has a significant effect on the quality of the final fiber, fiber physiology, and chemical constituents, mechanical and thermal properties.[20–22] With this information, the fascinating world of materials will be explored, with a focus on the critical importance of extraction methods in the manufacture of natural fibers. In the chemical method, the NaOH solution is the best chemical agent to use for separating the fiber structural linkages between lignin and cellulose.[23] In another method, water retting, one of the most frequently employed methods, the microorganisms present in water begin to break down pectins and other constituents, helping to separate the fibers from the organic matter.[16] The traditional method is based on the application of a force to remove the non-cellulosic components from the fiber.[24]

As with all natural fibers, the Yucca fiber is a new reinforcing fiber, yucca plant was classified in the Asparagaceae family, mainly from the semi-arid and arid regions of North America, Central America, and the Caribbean. The green leaves are 80 to 120 cm long and 3–5 cm wide. The yucca is an economical plant that can produce ≈60–80 leaves each year.[25]

In recent years, new sustainable plant resources have been discovered and used as reinforcing fibers to make a new eco-friendly material.[26] For instance, a new natural fiber Vakka has been studied.[27] First, the extraction method involved immersing the plant in water for a total period of 18 days, then the fiber was mechanically analyzed to determine the tensile strength as well as the young's modulus and strain of this fiber, which are (549 MPa), (15.85 GPa), and (3.46%), respectively. Another scientific study characterized chemically and mechanically the natural fiber obtained from the yucca plant after using water retting as an extraction method.[28] The results concerning the chemical composition of the fiber are acceptable, with cellulose at (52.54%), hemicellulose at (20.53%) and lignin at (10.03%), however, this fiber has a greater tensile strength rating of (801 MPa). In another similar research, a thermal study was carried out on Ethiopian yucca fiber obtained by the water-retting extraction method. The results showed a weight loss of ≈(70%).[29] The water retting extraction method was shown as one of the most effective extraction methods. It is necessary to characterize and test other extraction methods with different parameters to explore new natural fibers and produce bio-composites based on natural fibers with low cost, low environmental impact, and good mechanical performance.

The extraction and characterization of other natural fibers for application as a bio-composite reinforcement has been extensively studied. However, only one study[29] has been carried out on the different methods of extracting yucca fibers for use in the reinforcement of a new bio-composite based on this fiber.

This research is based on several hypotheses in the areas concerning fiber harvesting location, growth conditions, and fiber extraction method. The main objective is to determine the impact of the fiber extraction methods on the physicochemical, and mechanical properties, in order to determine the difference between the various extraction methods and to identify the Algerian yucca fiber obtained by several methods. Several technologies and methods are used, such as the chemical composition protocol, SEM, FTIR, XRD, and mechanical tensile tests.

2. Experimental Section

2.1. Algerian Yucca Fiber Extraction

The yucca leaves for this research were grown in the Khamisty Al-Arabi Tabsi garden in Hadjout City, Tipaza province, Algeria. With the Geographic Coordinates, 36° 30′ 44.787″ N 2° 24′ 50.859″ E. The Altitude is 98 m. The method used to harvest yucca leaves was by hand, using an agricultural scissor. **Figure 3** demonstrates three extraction methods used to extract Algerian yucca fiber as detailed below.

2.1.1. Traditional Method

It is the simplest and oldest method of extraction. The first step was to slice the yucca leaf into 30 cm pieces to make it easier to handle when elaborating the bio-composite. The second step of this method was to soak the leaf pieces in boiling water (80 °C) for 1 h, after which the fibers were left to cool in the air for 24 h. This step was to make the organic material flexible and therefore to detach the fiber from the organic material. The last step was to recover the fiber through a process of peeling and elimination of the unfibrous parts, after which the fibers were air-dried and characterized.

2.1.2. Chemical Method

The chemical method was based on the use of chemical agents to loosen the lignocellulose material between the fibers and separate the structural links between the cellulose and the lignin.[29] This extraction method might be divided into two different categories: acid extraction methods and alkali extraction methods.[30] Various NaOH concentrations were used (3%, 5%, 10%) for 5 h, at a room temperature of ≈20 °C, in order to extract the yucca fiber. To eliminate Noah residue, stop the chemical reaction, guarantee the purity of the fiber, and reduce cross-contamination, the fibers were cleaned with distilled water. The combing process was used to extract and separate the fiber from the lignocellulose material.

2.1.3. Water Retting

Water retting is a biological extraction method that depends on the activity of the microorganisms living in the body of water. These microorganisms produce enzymes such as pectinases, which break down pectin and other substances that bind the fibers with the lignocellulose material.[31] In this process, yucca leaves were immersed in a water bath for 25–35 days at room temperature (20 °C). The anaerobic bacteria action accelerates the degradation of the leaf and loosens the fiber from the lignocellulose material. The fiber was then cleaned with distilled water to remove residual lignocellulose material before drying in the air.

2.2. Chemical Composition

This part of the study was the most important one for identifying the fiber in relation to other natural fibers. In reality, there are several contents in the fiber such as cellulose, lignin, hemicellulose, pectin, and others. However, the three components have a major influence on morphology, shape, structure, and even mechanical properties. For that, this study only assessed the cellulose, hemicellulose, and lignin content of the extracted fibers with a chemical protocol used by.[29]

2.2.1. Cellulose Content

2 grams of yucca fibers (Ws) underwent a treatment in which they were exposed to a solution consisting of 40 mL of 80% acetic acid and 2 mL of concentrated nitric acid. This mixture was then brought to reflux conditions, allowing a chemical reaction to occur, and this reaction was sustained for a period of 30 min. Following this step, the samples were subjected to centrifugation at 15 000 rpm for 5 min in hot ethanol95, facilitating the separation process, and were subsequently subjected to filtration via suction. The washing process was sequentially conducted in hot Benzene, followed by Ethanol95, and ultimately with Petroleum ether. The sample was subjected to a drying process at 105 °C in an oven for 1 h, during which time its weight was determined within a hermetically sealed container, thus yielding the weight measurement denoted as W2. In the ultimate phase of the process, the sample was introduced into a furnace held at a precisely controlled temperature of 500 °C for a meticulously timed interval of 3 h, ultimately leading to the precise determination of the weight of the resultant ashes, denoted as the weight measurement W1.

The equation for calculating the percentage cellulose content is:

$$\%Cellulose = \frac{W2 - W1}{Ws} \times 100 \tag{1}$$

where:

Ws: The initial mass of the sample.
W1: The weight of the sample's residual ashes after exposure to a temperature of 500 °C.
W2: The mass of the sample post-desiccation at 105 °C.

2.2.2. Hemicellulose Content

2 g of fibers were treated with 5% of Potassium hydroxide (KOH) for 2 h, and then the mixtures were filtered. Ethanol95 was employed to induce the precipitation of hemicellulose from the filtrate, which was subsequently separated by centrifugation for 15 min at 15 000 rpm.

The separated hemicellulose was desiccated in a convection oven at 105 °C for 1 h, and its mass was subsequently determined within a sealed receptacle (W1). The sample's ash content was acquired by exposing the desiccated specimen to a furnace maintained at 500 °C for 3 h. Subsequently, it was cooled, and its mass was measured within a sealed vessel. The assessment of the precipitated hemicellulose's weight (WA) was then conducted. The

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equation for calculating the percentage hemicellulose content is:

$$\%Hemicellulose = \frac{WA}{W1} \times 100 \quad (2)$$

where:

WA: represents the weight of the precipitated hemicellulose.
W1: the dry weight of the fiber sample.

2.2.3. Lignin Content

2 g of fibers (Wa) was used to measure lignin content, following ASTM D1106 standard, the bio-fiber samples were treated with 72% of Sulphuric Acid (H2SO4) for 2 h and then refluxed for 3 h more. The residue after filtering was washed with hot water to eliminate the residual acid. The residue was dried in the oven at 105 °C for 1 h, and then weighed (W1). Subsequently, the residue was then heated in a muffle furnace to 500 C for 3 h, left to cool freely, and weighed in a closed bowl (W2). The equation for calculating the percentage lignin content is:

$$\%Lignin = \frac{W1 - W2}{Wa} \times 100 \quad (3)$$

in which,

W1: weight after drying;
W2: weight after heating;
Wa: the weight of the initial fiber.

2.3. Tests

2.3.1. Scanning Electron Microscope Observation (SEM)

In order to inspect the morphology of the fiber surface as well as the diameter, SEM analyses were carried out on the five categories of Yucca fibers, the tests were performed on the JEOL JSM-7100F machine.

2.3.2. Fourier Transform Infrared Spectroscopy (FTIR)

FTIR was used to characterize the chemical structure of five categories of yucca fiber extracted by different methods. The shape of the fiber during analysis was in the form of a long fiber, the IRAffinity-1S machine was employed in this study with a 4000–600 cm^{-1} scanning range.

2.3.3. X-Ray Diffraction

The fiber structure of Algerian Yucca extracted by several methods was analyzed using the PANalytical machine model Empyrean. The X-ray diffraction (XRD) measurements were carried out at 45 kV and 40 mA using Cu K-Alpha wavenumber ($K\alpha$ = 0.15 425 nm). The scan step size was 0.026 degrees, with data recorded from 5° to 95°. The goals of this analysis are to determine the fiber crystallinity index (C) using Segal Equation (4),[32] The crystallite size (D) using Scherrer Equation (5),[33] and determine the Miller index.

$$C = \frac{I_{cr} - I_{am}}{I_{cr}} \times 100 \quad (4)$$

where C is percentage of crystallinity. Icr and Iam are the intensity of the diffraction peak corresponding to the crystalline and amorphous phase respectively.

$$D = \frac{K\lambda}{\beta \cos(\theta)} \quad (5)$$

in which D is the average crystallite size in a given direction, K is Scherrer's shape constant (0.9), λ is the wavelength of the X-rays used, β is the half-value width of the lattice plane (002) cellulose, and θ is the diffraction angle corresponding to the peak.

2.3.4. Fiber Tensile Tests

The mechanical properties of yucca fiber were determined in accordance with ASTM D 3822-01[34] using a fiber length (GL) of 50 mm. Due to the large variability of the bio fibers, the tests were carried out on 20 fiber samples per category. The results were then processed by the TOPSIS method to determine the best result in the 20 tests.[35] TOPSIS method is a statistical technique used for multi-criteria analysis, designed to rank results according to their importance. This approach is based on the principle that the ideal alternative is the one closest to the positive ideal solution, and the positive ideal solution maximizes the choice criteria. Tensile tests were carried out through the Zwick Universal Testing Machine with a 2.5 KN capacity load cell. **Figure 4a** shows the technique for fixing the fiber between the machine's jaws.

2.3.5. TOPSIS Method

The technique of preference ordering by similarity to the ideal solution (TOPSIS) is a multi-criteria decision-making method that evaluates and ranks various alternatives.[36] According to this method, the best alternative should have the shortest distance to the positive ideal solution.[37] One of the advantages of this method is that it allows trade-offs between various criteria, whereby a low result in one criterion may be improved by a good result in another.[38] The main aim of this method in this study is to classify fibers tested and to facilitate the determination of the most appropriate tensile test result. All the data obtained from the tests were used to start the TOPSIS calculation, five steps, with several equations, were used to classify the fibers in each category.

3. Results and Discussion

3.1. Chemical Contents of Yucca Fiber

Table 1. Presents the chemical contents of Algerian yucca fiber extracted by several extraction methods. The chemical extraction by NaOH with a variety of concentrations of 3%, 5%, and 10% induced a minor cellulose degradation in the fiber, obtaining contents of 73.95%, 73.95%, and 65.85% respectively. On the other

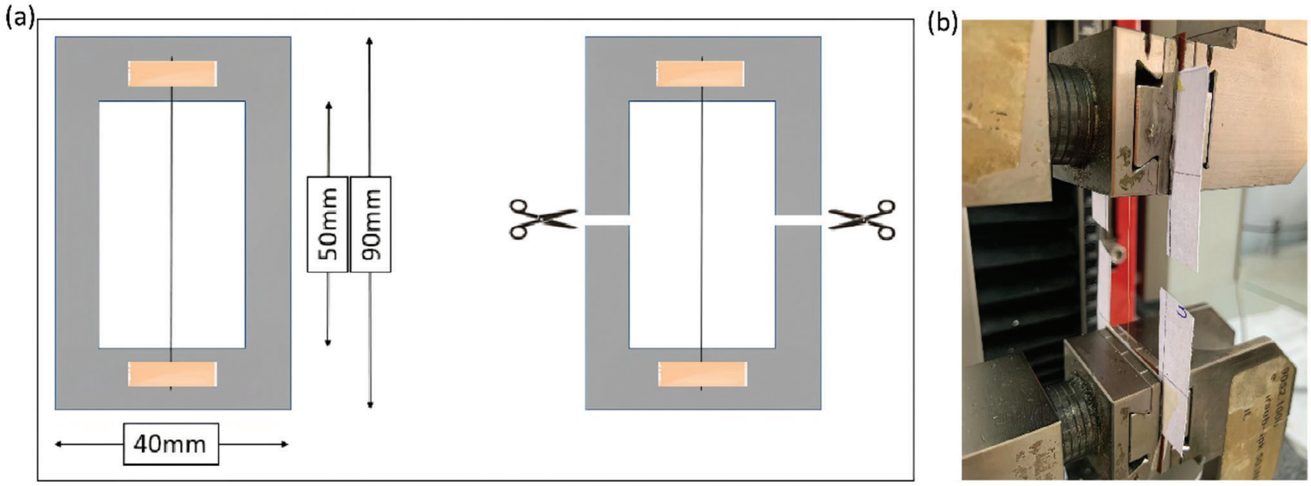

Figure 4. a) Fiber sample, the edges of the paper are completely cut before testing, b) Fiber sample is fixed in the machine for tensile testing.

hand, an improvement in cellulose content with the traditional method is noted with 78.06%. The highest cellulose content is measured for Algerian yucca fiber extracted by the water retting method with a content of 80.25%. This confirms that the highest fiber quality resides within this category. Otherwise, hemicellulose is the component responsible for the fiber's flexibility. The highest result was also recorded for the category of fiber extracted by water retting with a hemicellulose content of 13.75%. Followed by the chemical extraction using 3% and 10% NaOH are recorded with a rate of 13.55% and 12.97% respectively. The hemicellulose content exhibits a decrease through both traditional and chemical using 5% NaOH extraction methods with a content of 12.7% and 11.84% respectively. Ultimately, the lignin content in Algerian yucca fiber extracted by the traditional method ranks highest in this study, reaching 10.95% content. Followed by fibers extracted using the water retting method with a content of 10.45%, the chemical extraction method yields different contents ranging from 7.20%, 10.10% to 10.33% using NaOH concentrations of 3%, 5%, and 10%. These findings contribute to the identification of Algerian yucca fiber in comparison with other natural fibers worldwide shown in **Table 2**, in measure with these references, the Algerian yucca fiber has good chemical properties relative to other natural fibers. This property has a major influence on the fiber's other characteristics and will confirm the high mechanical strength of Algerian yucca fiber presented in the single fiber tensile properties section of this study.

Table 1. Chemical contents of yucca fiber extracted by different methods.

Fiber extraction method	% cellulose	%lignin	%hemicellulose
Water retting	80.25	10.45	13.75
Traditional	78.06	10.95	12.70
Chemical – 3%NaOH	73.95	07.20	13.55
Chemical – 5%NaOH	73.95	10.10	11.84
Chemical – 10%NaOH	65.85	10.33	12.97

3.2. Morphologies Analysis Result (SEM)

SEM analysis was performed to inspect the surface quality of the fiber, and the morphological structure, and to estimate the diameter of each fiber category. The special SEM images of yucca fiber extracted by different methods are presented in **Figure 5–9**. This analysis confirms that the morphological structure of all the fibers is practically identical,[44] with a different impurity content probably due to the effect of the extraction method.

The fiber extracted by the traditional method shown in Figure 5, has numerous impurities on the morphological surface, since the extraction method frees the fiber of organic matter, without limiting all this matter on the surface. Moreover, numerous voids can be found in this category of fibers, probably due to the temperature used in the extraction method. The higher temperature can facilitate the decomposition of non-fibrous components, such as lignin and pectin, making the fibers easier to extract. However, this may also increase the risk of thermal degradation of the fiber, which can increase void development and affect the fiber's mechanical properties. This problem, however, can be solved by using a surface treatment that reduces or eliminates voids by favoring the consolidation of the fiber structure.[45] In contrast, the fiber extracted by the chemical method, represented in Figure 6–8 with a different concentration of NaOH (3%, 5%,

Table 2. Chemical compositions of other natural fibers in comparison with yucca fiber.

Natural fiber	Country	% cellulose	%lignin	%hemicellulose	Reference
Sisal	India	65–78	9.9	10–14	[39]
Jute	United kingdom	72	13	13	[40]
Bamboo	Brazil	54.6	21.7	11.4	[10]
Hemp	Spain	69.4	5.7	13.0	[41]
Pineapple	India	67.3	7.4	16.9	[42]
Yucca	Iran	66.36	6.7	19.74	[43]
Yucca	Algeria	80.25	10.45	13.75	Present study

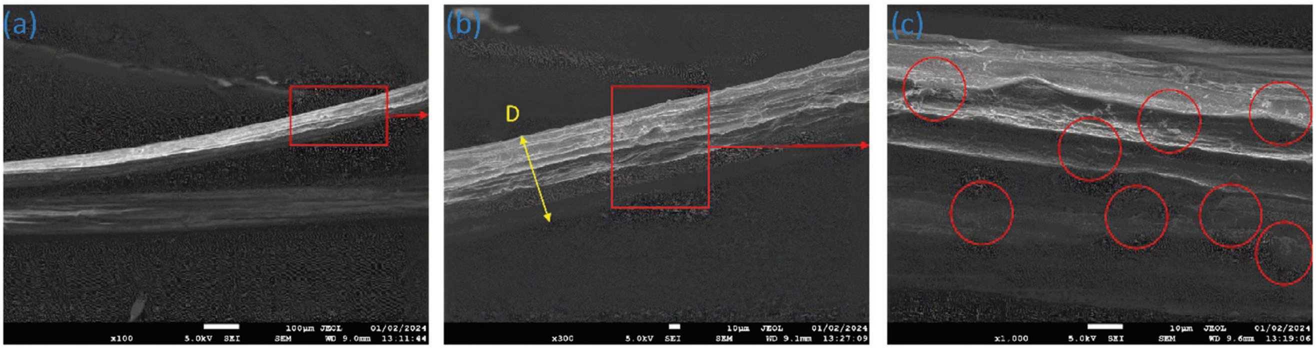

Figure 5. a) SEM images of yucca fiber extracted by the traditional method, b) image of surface zoomed view x300, c) image of surface zoomed view x1000.

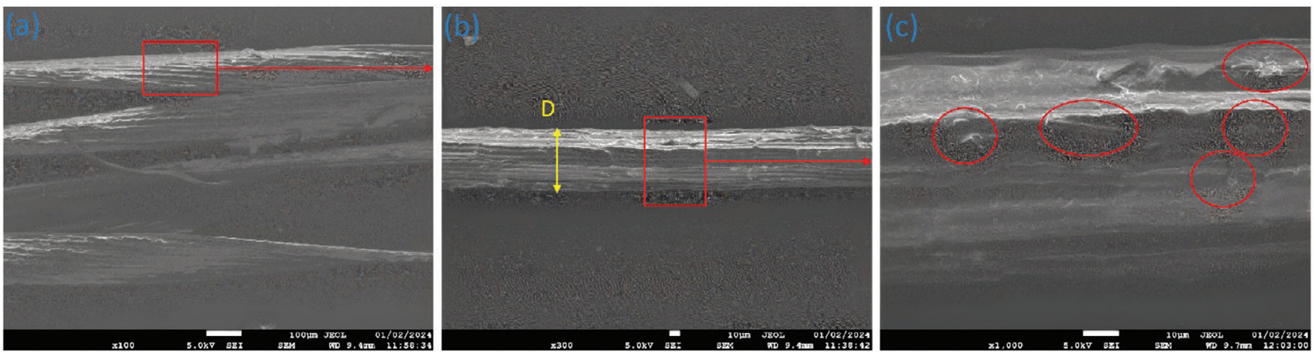

Figure 6. a) SEM images of yucca fiber extracted by the chemical method using 3% NaOH, b) image of surface zoomed view x300, c) image of surface zoomed view x1000.

10%), offers a good surface quality, especially with a high concentration, SEM images confirm that when the concentration is higher, the chemical solution attacks and eliminates these impurities. In comparison with other categories of fiber, the fiber extracted by the water retting method proposes a smoother surface quality; the images shown in Figure 9 confirmed that, possibly due to microorganisms the extraction method is based on attacks and eliminates all the organic matter from the surface final of fiber. It is important to mention the evident existence of these impurities can be an obstacle and reduce the adhesion between the bio-fiber and the matrix. Concerning the adhesion, all images show all categories of yucca fiber have many porosities, this parameter has a major role in the adhesion between the fiber and the matrix in bio-composite.[46]

For another part of this analysis, **Table 3** shows the diameter of each category of fiber after measuring with six different places. The results obtained in this analysis demonstrate that the physical properties precisely on the fiber diameter are influenced by the extraction method used. The diameters varied between 62 um measured in the fiber extracted by the chemical method using 3% NaOH and 90 um measured in the two extraction methods, traditional and chemical with 10% NaOH, the fibers extracted by the

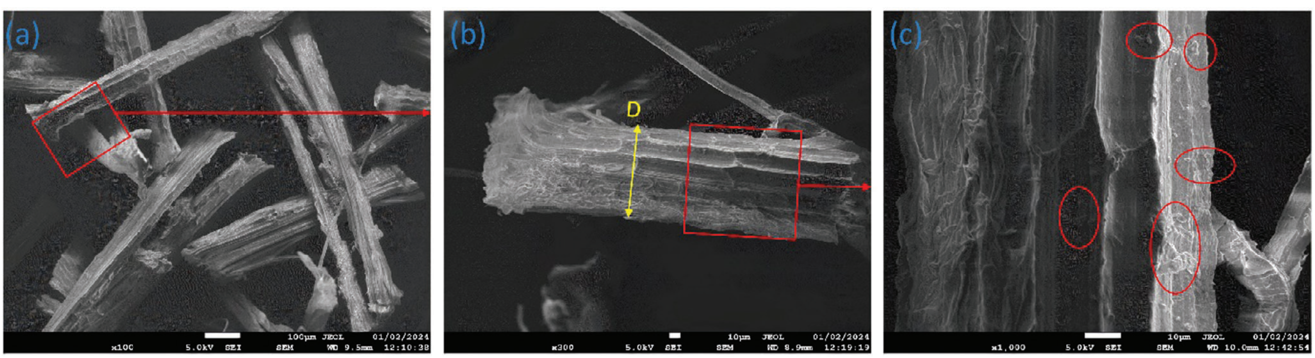

Figure 7. a) SEM images of yucca fiber extracted by the chemical method using 5% NaOH, b) image of surface zoomed view x300, c) image of surface zoomed view x1000.

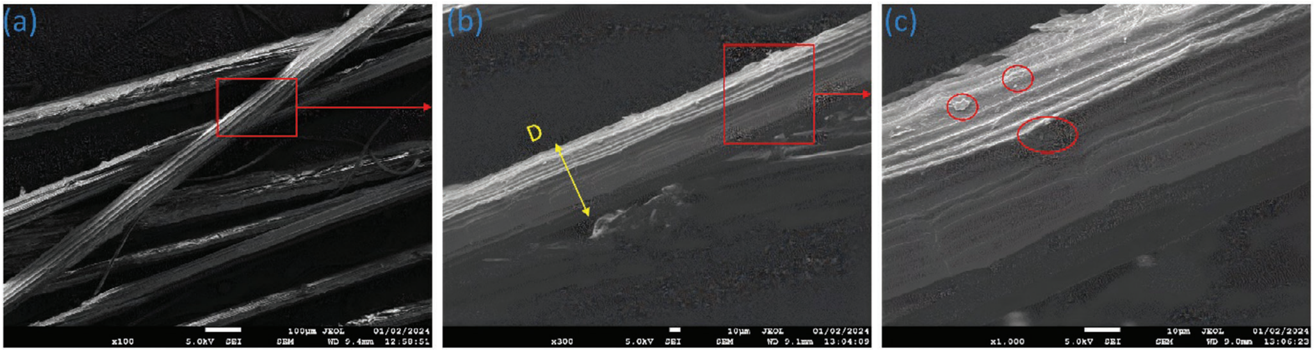

Figure 8. a) SEM images of yucca fiber extracted by the chemical method using 10% NaOH, b) image of surface zoomed view x300, c) image of surface zoomed view x1000.

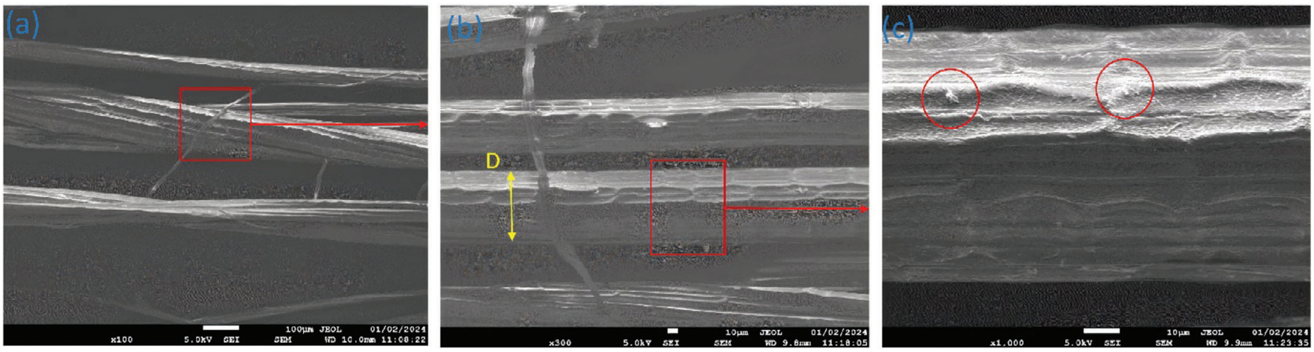

Figure 9. a) SEM images of yucca fiber extracted by the water retting, b) image of surface zoomed view x300, c) image of surface zoomed view x1000.

water retting and chemical method with 5% NaOH offer a good diameter of 75 and 85 um respectively.

3.3. FTIR Analysis

FTIR analysis was performed on the Algerian yucca fiber extracted by various extraction methods. This analysis can be used to characterize the chemical structure by identifying the functional groups present in each fiber category.[47] **Figure 10** shows the FTIR spectra of Algerian yucca fiber, with two absorbance regions for all samples analyzed, the first range is from 1800 to 600, and the second is from 3800 to 2800. The peaks are visible in positions 3794, 2924, 2854, 1743, 1643, and 1041 in all types of extraction methods, and the peak at 1234 is visible for all spectra except the spectra of fiber extracted by the chemical method using 5% and 10% of NaOH. The biggest difference between the spectra is the peak's width, resulting from the difference in chemical composition rates in each fiber category.[48]

Peak visualized in the specified range from 3400 to 3800 in the spectrum, assigned to OH Stretching Vibration of the OH group in cellulose.[4] Therefore, in this zone, a peak of 3794 was observed. The peaks at 2924 and 2854 can be represented by the C—H stretching vibration of CH and CH2 in cellulose and hemicellulose components.[49] The zone between 1600 and 1800 has two peaks 1743 and 1643, which can be due to the existence of C═O the stretching vibration of the C═O bonds in the acetyl groups, and alkene C═C of hemicellulose in the structure of yucca fiber respectively.[50–52] The peak at 1234 present in the spectra of fiber extracted by water retting, traditional and chemical methods using 3% NaOH indicates that the fibers in these categories exhibit bending vibrations of C—OH bonds within the cellulose molecular.[53] Several researchers consider the peaks in the 1200–1000 zone to indicate the presence of C—O—C, O—H, and C—O stretching of celluloses and hemicellulose.[54,55] In this study, only one peak is found in this zone at 1041, confirming that the Algerian yucca fiber has the C—O Stretching in cellulose, hemicellulose, and lignin.[54]

Table 3. Diameter of all the yucca fiber categories.

Extraction Method	D1[um]	D2[um]	D3[um]	D4[um]	D5[um]	D6[um]	Dm [um]
Water retting	75.33	74.67	72.66	76.66	76	74	74.89
Traditional	90.22	86.18	90.39	88	91.19	90.06	89.34
Chemical – 3%NaOH	62.66	60	64.66	61.34	64	61.33	62.33
Chemical – 5%NaOH	90	88.57	92.89	90.42	87.15	92.99	90.34
Chemical – 10%NaOH	83.08	84.02	84.33	83.5	86.53	86.53	84.67

3.4. X-ray Diffraction

The XRD patterns of Algerian Yucca fiber extracted by several methods are shown in **Figure 11**. Three main peaks are identified ≈15, 22, and 34 degrees in all charts. The peaks ≈15°–16°

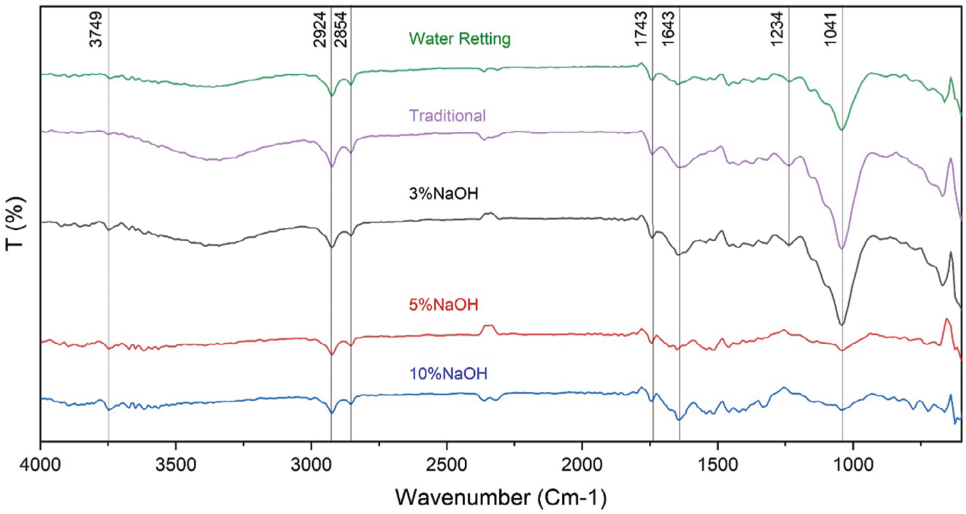

Figure 10. FTIR spectra of all extraction methods of yucca fiber.

and 34° are attributed to the amorphous nature of the fiber. The clearer and more accentuated peak at 22° in all the plots represents the crystalline nature of the structure of this bio-fiber. **Table 4** delineates the exact peaks identified (amorphous and crystalline peaks), the calculated crystallinity index, and the crystallite size in a comprehensive manner.

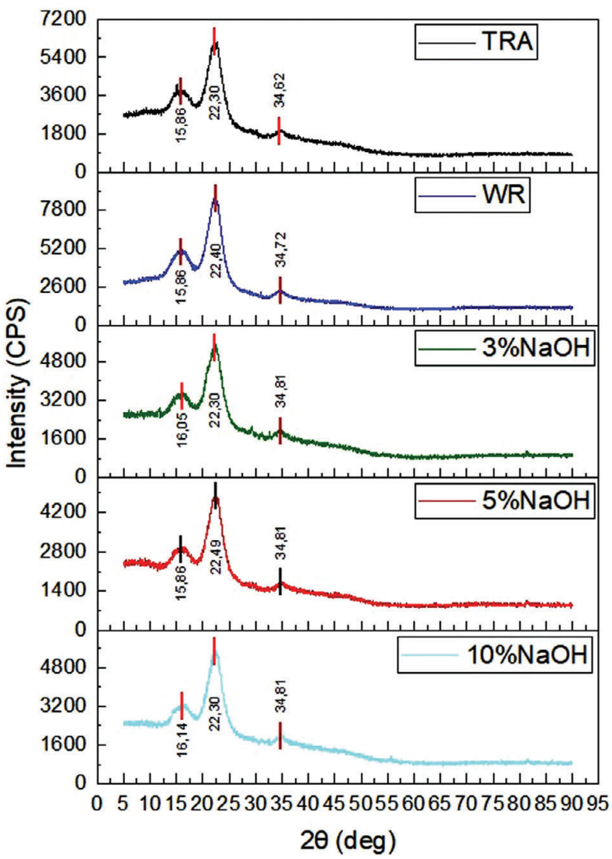

Figure 11. XRD of all categories of yucca fiber.

The crystallinity index (C.I.) of Algerian yucca fibers extracted by different extraction methods varies between 0.61 and 0.70, which is closer to the literature.[25,56] Also according to the calculated results, the size of the crystallite is inversely proportional to the crystallinity index, where the highest index is for the fiber extracted by water retting with C.I ≈70% but it is the lower crystallite size with 1.73 nm. Otherwise, the crystallinity index has a considerable impact on the mechanical properties of the fiber, when the index increases; there is a proportional increase in tensile strength. The mechanical test results on the fiber confirm this observation and the literature.[25] The principal peaks of diffraction were found ≈2θ = 15.8, 16.1, 22.3, and 34.8 which correspond to the Miller index (101), ($10\bar{1}$), (002), and (040) respectively, according to the literature.[50] Based on crystalline planes, Algerian Yucca fiber was classed as cellulose I.[57] In closing, these results demonstrate that Algerian yucca fiber is essentially semi-crystalline in structure.

3.5. Single Fiber Tensile Properties

3.5.1. Statistical Aggregation

The results of mechanical tests (all data can be found in the Supporting Information section) on Algerian yucca fiber were treated using two different data analysis methods. First, the classic method, which is presented in **Table 5**, the average calculation of the results obtained for each type of fiber showed that the fiber extracted by the water retting method is the highest, with a strength of up to 467 MPa, followed by the fiber extracted by the traditional method with a strength of 444.7 MPa. A variation in results was observed in the chemical extraction method using NaOH with resistance varying by 456.2, 443.4, and 235.8 MPa, for NaOH concentrations of 3%, 5%, and 10%, respectively. However, the results obtained in the strain show that the fiber extracted by water retting had the best result with a rate of 4.30%,

Table 4. Results were calculated using XRD analysis.

Extraction method	Amorphous peaks [°]	Crystalline Peaks [°]	Crystallinity Index [%]	Crystallite Size[nm]
Water retting	15.86 / 34.72	22.40	70.77	1.73
Traditional	15.86 / 34.62	22.30	68.12	1.75
Chemical 3%NaOH	16.05 / 34.81	22.30	65.90	1.76
Chemical 5%NaOH	15.86 / 34.81	22.49	65.57	1.84
Chemical 10%NaOH	16.14 / 34.81	22.30	61.75	2.04

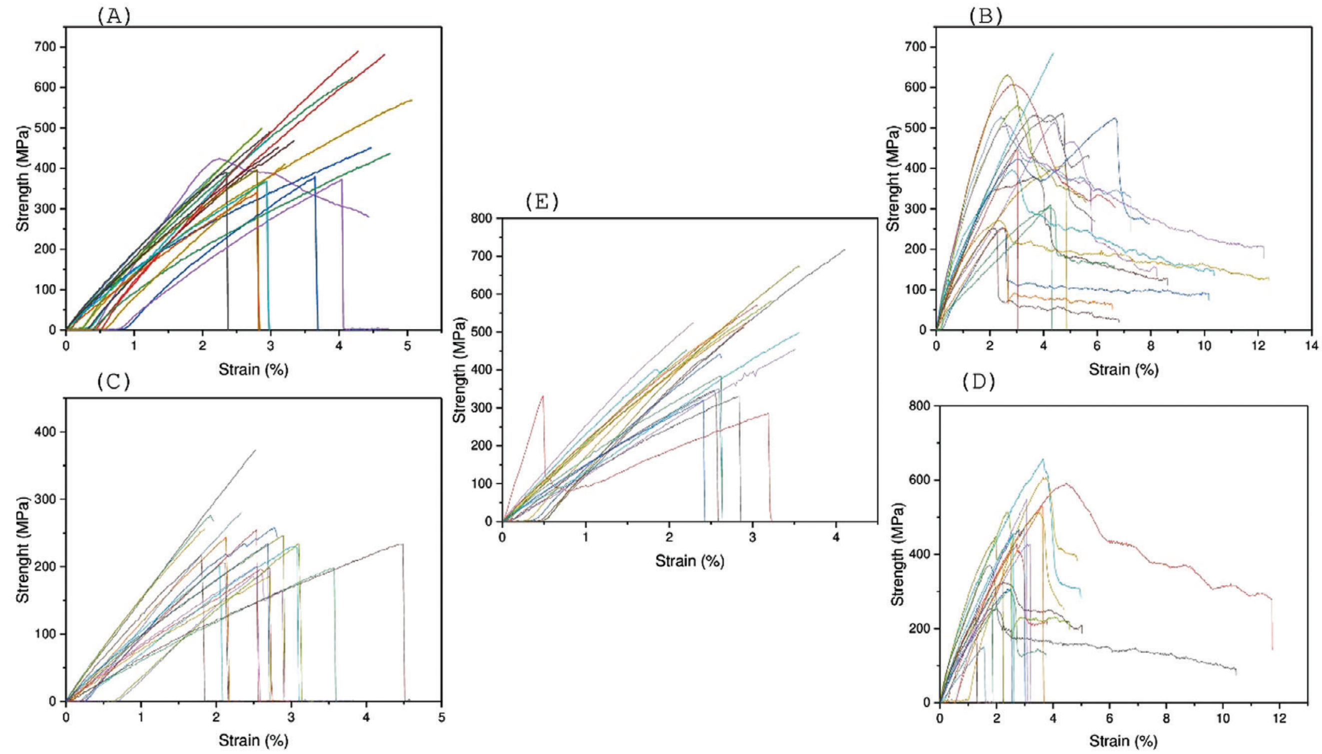

Figure 12. Tensile test results on yucca fiber extracted by: A) water retting, B) traditional method, C) Chemical 10% NaOH, D) Chemical 5% NaOH, E) Chemical 3% NaOH.

possibly due to the rate of hemicellulose present in the fiber,[14] followed by fiber extracted using the traditional method with a rate of 3.27%. Afterward, the fiber extracted by the chemical method was recorded with a rate of 2.64%, 2.79%, and 2.61% for the concentrations of 3%, 5%, and 10% NaOH, respectively.

Although this method of analysis is quicker and easier, in our case, the study of natural fiber with more numerous samples may lead to problems or defects in the final results. Therefore, this method is sensitive to outliers and does not consider extreme values obtained from fibers with surface cracking problems or fibers with low physicochemical properties. **Figure 12** shows the tensile test results on Algerian yucca fiber for all the extraction methods in a graph form. As can be seen in this figure, there are a variety of results for each type of fiber, and since the natural fibers

Table 5. Tensile test results of yucca fiber analyzed by the classical method.

Extraction methods	Tensile strength [MPa] [Mean]	SD [MPa]	Young's modul [Gpa] [Mean]	SD [GPa]	Strain [%] [Mean]	SD [%]
Water retting	467	98.5	14	2.86	4.3	0.81
Traditional	444.74	133.54	13.57	5	3.27	1.15
Chemical 3%	456.23	97.93	16.78	3.94	2.64	0.66
Chemical 5%	443.4	130.57	16.84	3.25	2.79	0.76
Chemical 10%	235.83	42.02	9.51	2.75	2.61	0.61

Table 6. Tensile test results of yucca fiber.

Extraction method	Tensile strength [MPa]	Young's modul [Gpa]	strain [%]
Water retting	690.48	16.13	4.28
Traditional	685.48	15.65	4.38
Chemical 3% NaOH	673.06	19.01	3.54
Chemical 5% NaOH	657.94	18.02	3.65
Chemical 10%NaOH	373.68	14.82	2.52

may not be homogeneous.[58] Consequently, this may generate a wrong value in the final result for this type of fiber. However, a decision analysis method (TOPSIS) will be used to define the mechanical properties of the fiber closest to the correct value.

In another context, in the application of yucca fiber in the composite field, this type of fiber may present a certain heterogeneity, and the forces and loads applied may not be distributed uniformly over all the fibers of the same value. Moreover, the fibers with the best performance may resist and withstand the forces applied compared with the fiber with the lowest performance. Hence, according to this opinion, the most correct value of yucca fiber is the value of the fiber with the best performance.

3.5.2. Achievement of TOPSIS

The results of tensile tests on yucca fibers, extracted by different methods, have been systematically compiled in **Table 6**. Subsequent to employing the TOPSIS method to identify the most favorable results from the 20 tests within each category with importance of (50% for Tensile strength, 30% for Young's modulus, and 20% for strain). These criteria have a major influence on the final choice of material for the required application, and each of these parameters has advantages in the final properties of the bio-composite subsequently. It becomes appears that the fiber extracted using the water retting method exhibited a higher mechanical strength with 690.48 MPa this indicates that the microorganisms degrade the non-cellulosic part of the fiber while preserving the cellulosic component, thereby imparting good mechanical properties. Afterward the fiber extracted with the traditional method yielded good results with a resistance of 680.48 MPa, as a consequence of the extraction methodology in which non-cellulosic components were manually separated, an impact on the fiber's mechanical properties was observed. However, the fiber extracted by the chemical method showed good mechanical properties, especially at 3% and 5% NaOH concentrations, where the tensile strength was measured at 673.06 and 657.94 MPa respectively, and this validates the efficiency of the chemical extraction method in eradicating organic matter.[59] On the other hand, the 10%NaOH concentration has a negative effect on yucca fiber's mechanical properties, where the tensile strength is ranked the lowest in this study as a value of 373.68 MPa, this might be attributed to degradation resulting from the high chemical concentration during a 5 h period. The large difference between the tensile strengths for fiber extracted by the chemical method using 10% of NaOH and the other fibers extracted by several methods is relative to the rate of the cellulose in their chemical composition, as is the chemical component that makes the fiber stronger.[13] These varieties of results support the view that the percentage of chemical contents has a considerable influence on the mechanical properties of the fiber,[15] and the diversity of mechanical properties reported in this study is intimately linked to the impact of the extraction method.

However, the use of the TOPSIS method in the analysis of mechanical results showed an increase in the performance of Algerian yucca fiber, ≈40–45%. This improvement was justified by the influence of the result analysis method on the final results, where the TOPSIS method is more favorable to correct values. The application of a variety of analytical methods may lead researchers and manufacturers to a better understanding of the properties of this natural yucca fiber.

Table 7 Shows further results on the mechanical properties of different types of natural fibers. As shown in this table, the Algerian yucca fiber in this study has superior mechanical properties to several other natural fibers, as well as to Iranian yucca fiber.

4. Conclusion

Natural fibers play an essential role in the reinforcement of a bio-composite, offering a sustainable, environmentally friendly alternative at a low cost. In this study, a new yucca fiber was extracted from the leaves of the yucca plant using various extraction methods. Several techniques and technologies were used in this research to evaluate the extraction methods and their influence on the physicochemical and mechanical properties of this type of natural fiber before determining their application as a reinforcement for a bio-composite material. The key findings may be summarized as follows:

- Natural fiber obtained from the yucca plant may be extracted by different extraction methods.
- The extraction method employed plays an important factor in the final properties of the natural fiber.
- The mechanical properties showed a direct relation with the crystallinity index (C.I.) and the chemical composition of the biofiber.
- Even without treatment, yucca fiber has proved to have good mechanical and physicochemical properties.
- The fiber obtained by the water retting method offers the best fiber quality due to its chemical properties with a cellulose content of 80%, a high crystallinity index of 70%, and a good tensile strength at 690 MPa, otherwise, the fiber offers excellent surface quality.
- From a practical point of view, focusing on the integration of the best-performing fibers may lead to substantial innovations and improvements in the natural fiber field, through the development of new technologies and methods.
- Yucca fiber may be a good reinforcement for the development of a new bio-composite material.

The development of a new bio-composite reinforced with yucca fiber would be recommended, as the fiber has given very good results in terms of its mechanical and physicochemical properties. This area of research is part of a global plan to develop more sustainable and environmentally friendly materials, particularly to replace conventional plastic-based materials. Future research would involve studying the properties of bio-composites

Table 7. Comparison of tensile test results of yucca fiber with other types of natural fiber.

Natural fiber	Extraction method	Tensile strength [MPa]	Young's modul [Gpa]	Strain [%]	Reference
Yucca	Water retting	690.48	16.13	4.28	Present study
Sisal	Raspador machine	422.0	3.431	2.42	[1, 60]
jute	Mechanical process	331-414	28.43	2.56	[61]
Bamboo	-	262	9.8	2.7	[62]
Pineapple	Water retting	630	9	7.9	[55]
Jute	Water retting	700	-	2.5	[63]
Kenaf	Water retting	775	56	1.75	[64]
Bamboo	Steam explosion	615-862	35.45	4.11	[61]
Iranian Yucca	Traditional method	605.11	11.34	6.12	[43]

obtained by combining yucca fibers with polymer matrices. This approach could explore new opportunities for using natural resources while reducing the environmental impact.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

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mechanical strength, morphology, natural fiber, sustainability, yucca fiber

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[1] A. Pappu, M. Saxena, V. K. Thakur, A. Sharma, R. Haque, *J. Macromol. Sci. A , Part A* **2016**, *53*, 424.
[2] R. Malkapuram, V. Kumar, Y. S. Negi, *J. Reinf. Plast. Compos.* **2009**, *28*, 1169.
[3] B. A. Oliver, Q. Dong, M. Ramezani, M. A. Selles, S. Sanchez-Caballero, *Macromol. Mater. Eng.* **2023**, *308*, 2300077.
[4] A. A. Ayalew, A. F. Wodag, *J. Eng* **2022**, *2022*, 8583213.
[5] H. Faria, N. Cordeiro, M. N. Belgacem, A. Dufresne, *Macromol. Mater. Eng.* **2006**, *291*, 16.
[6] V. Chauhan, T. Kärki, J. Varis, *J. Thermoplast.* **2022**, *35*, 1169.
[7] H. M. Akil, M. F. Omar, A. A. M. Mazuki, S. Safiee, Z. A. M. Ishak, A. Abu Bakar, *Mater. Des.* **2011**, *32*, 4107.
[8] L. Mohammed, M. N. M. Ansari, G. Pua, M. Jawaid, M. S. Islam, *Int. J. Polym. Sci.* **2015**, *2015*, 2.
[9] J. K. Pandey, S. H. Ahn, C. S. Lee, A. K. Mohanty, M. Misra, *Macromol. Mater. Eng.* **2010**, *295*, 975.
[10] G. Dorez, L. Ferry, R. Sonnier, A. Taguet, J. M. Lopez-Cuesta, *J. Anal. Appl. Pyrolysis* **2014**, *107*, 323.
[11] S. Mishra, A. K. Mohanty, L. T. Drzal, M. Misra, G. Hinrichsen, *Macromol. Mater. Eng.* **2004**, *289*, 955.
[12] A. Komuraiah, N. S. Kumar, B. D. Prasad, *Mech. Compos. Mater.* **2014**, *50*, 359.
[13] I. Elser, M. R. Buchmeiser, *Macromol. Mater. Eng.* **2024**, 2400013.
[14] Ş. Yildizhan, A. Çalik, M. ÖZcanli, H. SerİN, *European Mech. Sci.* **2018**, *2*, 83.
[15] S. R. D. Petroudy, in *Advanced High Strength Natural Fibre Composites in Construction*, Woodhead Publishing, Cambridge, UK, **2017**, p. 59.
[16] P. K. Parida, M. K. Pandit, A. K. Pradhan, *Cellulose* **2023**, *30*, 8819.
[17] L. Kerni, S. Singh, A. Patnaik, N. Kumar, *Materials Today: Proceedings* **2020**, *28*, 1616.
[18] K. Rohit, S. Dixit, *Polym. from Renew. Resour.* **2016**, *7*, 43.
[19] F. Ahmad, H. S. Choi, M. K. Park, *Macromol. Mater. Eng.* **2015**, *300*, 10.
[20] S. Karra, H. Sebii, H. Yaich, M. A. Bouaziz, C. Blecker, S. Danthine, H. Attia, S. Besbes, *J. Food Biochem.* **2020**, *44*, e13202.
[21] K. Wang, M. Li, Y. Wang, Z. Liu, Y. Ni, *Food Hydrocolloids* **2021**, *110*, 106162.
[22] B. A. Amel, M. T. Paridah, R. Sudin, U. M. K. Anwar, A. S. Hussein, *Ind Crop Prod.* **2013**, *46*, 117.
[23] M. Hasan, M. Rahman, Y. Chen, N. Cicek, *Polymers* **2022**, *14*, 1685.
[24] A. Melkamu, M. B. Kahsay, A. G. Tesfay, *J. Nat. Fibers* **2018**, *16*, 877.
[25] M. K. Moghaddam, E. Karimi, *J. Ind. Text.* **2022**, *51*, 8018S.
[26] M. Ramesh, K. Palanikumar, K. H. Reddy, *Renewable Sustainable Energy Rev.* **2017**, *79*, 558.
[27] K. M. M. Rao, K. M. Rao, *Compos. Struct.* **2007**, *77*, 288.
[28] H. M. do Nascimento, A. dos Santos, V. A. Duarte, P. R. S. Bittencourt, E. Radovanovic, S. L. Fávaro, *Cellulose* **2021**, *28*, 5477.
[29] A. Azanaw, A. Haile, R. K. Gideon, *Cellulose* **2018**, *26*, 795.
[30] A. Hulle, P. Kadole, P. Katkar, *Fibers* **2015**, *3*, 64.
[31] M. Di Candilo, P. M. Bonatti, C. Guidetti, B. Focher, C. Grippo, E. Tamburini, G. Mastromei, *J. Appl. Microbiol.* **2010**, *108*, 194.
[32] L. Segal, J. Creely, A. Martin, Jr., C. Conrad, *Text. Res. J.* **1959**, *29*, 786.
[33] A. A. M. Moshi, D. Ravindran, S. R. S. Bharathi, S. Indran, S. S. Saravanakumar, Y. Liu, *Int. J. Biol. Macromol.* **2019**, *142*, 212.
[34] A. Etaati, S. Pather, F. Cardona, H. Wang, *Polym. Compos.* **2016**, *37*, 213.

[35] Z. Pavić, V. Novoselac, *Int. J. Res. Eng. Sci.* **2013**, *1*, 5.
[36] A. Mahajan, V. Binaz, I. Singh, N. Arora, *Comp. Part C: Open Acc.* **2022**, *7*, 100224.
[37] F. M. Al-Oqla, S. M. Sapuan, M. R. Ishak, A. A. Nuraini, *Fibers Polym.* **2015**, *16*, 153.
[38] M. Noryani, S. M. Sapuan, M. T. Mastura, *J. Mech. Eng. Sci.* **2018**, *12*, 3330.
[39] P. A. Sreekumar, K. Joseph, G. Unnikrishnan, S. Thomas, *Compos. Sci. Technol.* **2006**, *67*, 453.
[40] L. Y. Mwaikambo, M. P. Ansell, *J. Appl. Polym. Sci.* **2002**, *84*, 2222.
[41] R. Moriana, F. Vilaplana, S. Karlsson, A. Ribes, *Carbohydr. Polym.* **2014**, *112*, 422.
[42] V. Johny, A. K. Mani, S. Palanisamy, V. K. Rajan, M. Palaniappan, C. Santulli, *Fibers* **2023**, *11*, 5.
[43] E. Taban, R. Mirzaei, M. Faridan, E. Samaei, F. Salimi, A. Tajpoor, M. Ghalenoei, *J. Environ. Health Sci. Eng.* **2020**, *18*, 883.
[44] S. R. Ferreira, M. Pepe, E. Martinelli, F. d. A. Silva, R. D. T. Filho, *Composites, Part B* **2017**, *140*, 183.
[45] A. Gholampour, T. Ozbakkaloglu, *J. Mater. Sci.* **2020**, *55*, 829.
[46] O. Y. Keskin, R. Dalmis, G. B. Kilic, Y. Seki, S. Koktas, *Cellulose* **2020**, *27*, 9963.
[47] V. A. A. J. I. Morán, V. P. Cyras, A. Vázquez, *Cellulose* **2008**, *15*, 149.
[48] A. B. D. Nandiyanto, R. Oktiani, R. Ragadhita, *Indones. J. Sci.Technol.* **2019**, *4*, 97.
[49] T. P. Sathishkumar, P. Navaneethakrishnan, S. Shankar, R. Rajasekar, *Compos. Interfaces* **2013**, *20*, 575.
[50] M. Benítez-Guerrero, L. A. Pérez-Maqueda, R. Artiaga, P. E. Sánchez-Jiménez, J. Pascual-Cosp, *J. Nat.Fibers* **2016**, *14*, 26.
[51] M. C. H. N. Sgriccia, M. Misra, *Composites, Part A* **2008**, *39*, 1632.
[52] J. K. A. Soundhar, *J. Nat. Fibers* **2021**, *18*, 1518.
[53] B. Sun, A. Huang, Y. Wang, J. Liu, *J. Nat. Fibers* **2015**, *12*, 1.
[54] I. L. A. da Silva, A. B. Bevitori, L. A. Rohen, F. M. Margem, F. d. O. Braga, S. N. Monteiro, *Mater. Sci. Forum* **2016**, *869*, 283.
[55] E. W. Gaba, B. O. Asimeng, E. E. Kaufmann, S. K. Katu, E. J. Foster, E. K. Tiburu, *Fibers* **2021**, *9*, 51.
[56] G. N. Guerra, E. C. D. M. C. Albuquerque, L. M. A. Campos, L. A. M. Pontes, *J. Nat. Fibers* **2021**, *18*, 203.
[57] Y. Peng, D. J. Gardner, Y. Han, A. Kiziltas, Z. Cai, M. A. Tshabalala, *Cellulose* **2013**, *20*, 2379.
[58] M. Tunák, J. Antoch, *Text. Res. J.* **2018**, *88*, 1226.
[59] T. Teklu, *J. Nat. Fibers* **2021**, *19*, 3825.
[60] A. Pappu, M. Saxena, V. K. Thakur, A. Sharma, R. Haque, *J.Macromol., Part A* **2016**, *53*, 4247.
[61] S. Biswas, Q. Ahsan, A. Cenna, M. Hasan, A. Hassan, *Fibers Polym.* **2013**, *14*, 1762.
[62] K. Zhang, F. Wang, W. Liang, Z. Wang, Z. Duan, B. Yang, *Polymers* **2018**, *10*, 608.
[63] S. S. Tripathy, L. Di Landro, D. Fontanelli, A. Marchetti, G. Levita, *J. Appl. Polym. Sci.* **2000**, *75*, 1585.
[64] W. Hu, M.-T. Ton-That, F. Perrin-Sarazin, J. Denault, *Polym. Eng. Sci.* **2010**, *50*, 819.