



HAL
open science

Extraction and characterization of vascular bundle and fiber strand from date palm rachis as potential bio-reinforcement in composite

Haithem Boumediri, Abderrezak Bezazi, Gilberto Garcia del Pino, Abdelkrim Haddad, Fabrizio Scarpa, Alain Dufresne

► To cite this version:

Haithem Boumediri, Abderrezak Bezazi, Gilberto Garcia del Pino, Abdelkrim Haddad, Fabrizio Scarpa, et al.. Extraction and characterization of vascular bundle and fiber strand from date palm rachis as potential bio-reinforcement in composite. *Carbohydrate Polymers*, 2019, 222, pp.114997 -. 10.1016/j.carbpol.2019.114997 . hal-03487894

HAL Id: hal-03487894

<https://hal.science/hal-03487894>

Submitted on 20 Dec 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 **Extraction and characterization of vascular bundle and fiber strand from date palm**
2 **rachis as potential bio-reinforcement in composite**

3 Haithem Boumediri,^a Abderrezak Bezazi,^a Gilberto Garcia Del Pino,^b Abdelkrim Haddad,^a
4 Fabrizio Scarpa,^c Alain Dufresne^{d*}

5 ^a Laboratoire de Mécanique Appliquée des Nouveaux Matériaux (LMANM), Université 8
6 Mai 1945, Guelma, Algeria

7 ^b Department of Mechanical Engineering, State University of Amazonas, Manaus-AM/Brazil,
8 Brazil

9 ^c Department of Aerospace Engineering, University of Bristol, Queens Building, University
10 Walk BS8 1TR Bristol, UK.

11 ^d Univ. Grenoble Alpes, CNRS, Grenoble INP, LGP2, F-38000, France.

12 * Corresponding author: alain.dufresne@pagora.grenoble-inp.fr

13

14 **Keywords:** Date palm fibers; Vascular bundles; Fiber strands; Physicochemical analysis;
15 Surface roughness; Tensile properties.

16

17 **Abstract**

18 Date palm rachis fibers are rich in cellulose, relatively inexpensive, and readily available in
19 Algeria. The aim of this study is to investigate the morphology, structure, mechanical and
20 physicochemical characteristics of both vascular bundles and fiber strands extracted from
21 date palm rachis. The difficulties encountered are associated to the extraction of the fibers
22 without damaging them. The study focuses on the morphological and surface roughness
23 analysis using optical and scanning electron microscopies (SEM), and a non-contact 3D
24 profiler. The chemical, physical and thermal properties have been studied using Fourier-
25 transform infrared (FTIR) spectroscopy, energy dispersive X-ray spectroscopy (EDX), X-ray
26 diffraction (XRD), thermogravimetric analysis (TGA), and differential scanning calorimetry
27 (DSC). The mechanical properties were accessed by tensile tests and they were analyzed
28 using two-parameter Weibull distribution.

29

30 INTRODUCTION

31 The date palm (*Phoenix dactylifera* L.) is a monocotyledonous flowering plant of the family
32 Palmates (Arecaceae), one of the most important cultivated crops in North Africa and the
33 Middle East (NAME) (Chao & Krueger, 2007). According to Graziano da Silva, General
34 Director of the Food and Agriculture Organization (FAO), the date palm is a symbol of life in
35 NAME. Palm trees play an important role in the economy of the region, with the top ten
36 producing countries accounting for approximately 90% of the global date production
37 (Chandrasekaran & Bahkali, 2013; Ghnimi, Umer, Karim, & Kamal-Eldin, 2017).

38 Algeria, which is the largest country in Africa and in the Arab world, is among the leading
39 countries in the cultivation and production of palms dates. It is the world's fourth-largest date
40 producer with a total of more than 20 million palm trees and was responsible for more than
41 14% of the global date production in 2017, with an increase of more than 83% from 2012 to
42 2017, as confirmed by the Algiers Chamber of Commerce and Industry (Boumediri et al.,
43 2017).

44 However, as reported in 2011 by (Agoudjil, Benchabane, Boudenne, Ibos, & Fois, 2011) this
45 crop generates a large amount of by-products, such as: (a) the leaves: petiole, rachis, leaflets;
46 (b) the trunk; (c) the products obtained from the bunches (fruit bunch branch of palm, date
47 seeds). It can subsequently produce approximately 40 kg of residue per individual date palm
48 tree annually (Mallaki & Fatehi, 2014). This huge residue amount is not exploited because it
49 is often disposed of by burning or is considered as animal feed or waste and it has been rarely
50 used in handicrafts such as basketry, crates, ropes and traditional construction (Al-Oqla &
51 Sapuan, 2014; Bouguedoura, Bennaceur, Babahani, & Benziouche, 2015).

52 For researchers interested in lignocellulosic fibers, this agricultural residue is a natural
53 wealth, that can be exploited and valued in different ways such as the reinforcement for
54 biocomposite materials for many application and various industries sectors (Al-oqla,

55 [Allothman, Jawaid, Sapuan, & Es-Saheb, 2014](#); Anwar, Gulfraz, & Irshad, 2014; Jawaid &
56 Abdul Khalil, 2011; Rabetafika, Bchir, Blecker, & Richel, 2014). This is due to their unique
57 collective advantages, which include easy availability, recyclability, environmental
58 friendliness, biodegradability, low cost, low density, good thermal stability, and reasonable
59 strength and stiffness (Jayaramudu, Guduri, & Varada Rajulu, 2010; Manimaran,
60 Saravanakumar, Mithun, & Senthamaraiannan, 2016).

61 In fact, recent years have been marked by a sharp increase in studies and work on the use of
62 farming-based waste from the date palm. Studies have focused on the outer layer of the date
63 palm stem called mesh, due to their availability in the form of fiber with the objective of
64 using these fibers as reinforcement for composites materials ([Al-Kaabi, Al-Khanbashi, &
65 Hammami, 2005](#); [Al-Khanbashi, Al-Kaabi, & Hammami, 2005](#); [Alawar, Hamed, & Al-
66 Kaabi, 2009](#); [Alsaeed, Yousif, & Ku, 2013](#); [Oushabi et al., 2017](#)). Amroune et al. investigated
67 the mechanical properties of the fiber of date palm fruit branches for use as potential
68 reinforcement for polymer composites (Amroune et al., 2015). Other investigations are
69 dedicated to the use of date palm wood, petioles and leaves by cutting or hammering into
70 small pieces as material for the manufacture of particleboard ([Almi, Lakel, Benchabane, &
71 Kriker, 2015](#); [Saadaoui, Rouilly, Fares, & Rigal, 2013](#)). Also, Khiari et al. study the
72 application date palm rachis as a source of lignocellulosic biomass for the production of pulp
73 and paper ([Khiari, Mhenni, Belgacem, & Mauret, 2010](#)). Unfortunately, there is scarce
74 information available about the utilization and properties of the date palm rachis fibers as a
75 potential eco-friendly bio-reinforcement for bio-composites materials.

76 According to Agoudjil et al. an amount estimated to more than 800,000 tons of residues is
77 produced per year in Algeria. Botanic experts reported that each date palm tree can produce
78 an average of thirteen new rachis and petioles per year (Agoudjil et al., 2011; Nasser et al.,
79 2016) that corresponds to an average mass of 9.75 kg and 4.4 kg, respectively (Darwish,

80 Mansour, & Elmously, 2018). Based on this information, the cultivation of date palm can
81 then produce around 200,000 tons of fronds and 90,000 tons of petioles, which are available
82 per year in Algeria. There are more than 950 varieties of date palms in Algeria and the
83 analysis of their production by category shows that the variety of Ghars palm tree represents
84 up to 10% of the total production in Algeria (Bouguedoura et al., 2015).

85 This variety of date palm, with very good commercial value and availability, has not been
86 sufficiently explored. This is why it has been chosen to be the aim of this investigation. The
87 analysis of the rachis cross section morphology leads to identify for the first time the
88 existence of two main types of date palms rachis fibers namely: vascular bundles (VBs) and
89 fiber strands (FSs) and showing their location in the rachis. The first part of this work is
90 devoted to the development a new method of extracting VBs and FSs fibers from the Ghars
91 rachis without any damaging or breaking of them. To the author's knowledge, this is the first
92 investigation permitting to provide a comparison and detailed analysis of the two types of
93 Ghars rachis fibers (VBs and FSs), with emphasis on their physicochemical, thermal and
94 tensile mechanical properties. Furthermore, their morphology and roughness have been
95 identified and compared. To do this, various techniques has been used to characterize the
96 extracted fibers by scanning electron microscopy (SEM), non-contact 3-D profiler,
97 thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), Fourier-
98 transform infrared (FTIR) spectroscopy, energy dispersive X-ray (EDX) spectroscopy, X-ray
99 diffraction (XRD) and tensile test. To the author's knowledge, the ultimate tensile stress of
100 FSs obtained show the greatest values compared to VBs and also to all the fibers date palm
101 existing in the literature.

102 **MATERIALS AND METHODS**

103 **Materials**

104 There are more than 950 varieties of date palm in Algeria such as Deglet Nour, Ghars, Fergus

105 and Mech Degla (Bouguedoura et al., 2015) and they can be classified into 04 categories
106 from the commercial point of view and their availability:

107 - *Variety of very good commercial value*, such as: Deglet-Nour, Ghars, Degla-Beida,
108 Tafenoquine, Itima, Mech-Degla, etc ...

109 - *Ordinary variety*, such as: Arechti, Boudheroua, Taouri, Hamraia and Ksebba, etc...

110 - *A rare variety, less value, very little available*: Oum-rouah, Oum-Soualef, Oum-
111 aidjet, Oum-Chouika, Azenchi, etc ...

112 - *A rare variety, not available* (limited number to recently discovered), such as
113 introduced foreign varieties: Zohdi, Halami, Ftemi, Alig, etc ...

114 Apart from being classified by commercial and availability, another classification for date
115 palm is based on the external quality of the fruit of the crops in three classes (Biglari,
116 AlKarkhi, & Easa, 2008):

117 - Palm trees producing *soft dates*: which are aqueous, of fibrous texture such as:
118 Ghars, Hamraia, Itima, Zegraia, etc ...

119 - Palm trees producing *semi-dry dates* or *semi-soft dates*: which dry up such as:
120 Deglet-Nour, Arechti, Sebaa, Boudraa, Amdj-Zenina, Deglet-Messaoud, etc ...

121 - Palm trees producing *dry dates* or *hard dates*: which harden on the tree and have a
122 floury texture, such as: Degla-Beida, Laalami, Lahlou, Deglet-Zohra, Arelou, etc...

123 In this work, we used leaves of a female palm tree Ghars, this variant of date palm tree
124 represents up to 10% of the total production in Algeria. It is known by its earliness in
125 ripening, its productivity and the ability of this tree to withstand large amounts of alkali and
126 much neglect. This variety of date palm has a very good commercial value and great
127 availability but has not been sufficiently explored. The Ghars rachis used was collected in
128 November 2017 from a local farm in El-Oued located in the south of Algeria, this farm used
129 brackish water for irrigation. The rachis taken from the palm tree (Figure 1a) was obtained by

130 removing the leaflets and it was cut about 20 cm in length using a knife. The fibers were
131 extracted from the rachis by a manual peeling process. After 150 min of boiling in an
132 autoclave at 120 °C the fibers were extracted from the rachis outer and inner peripheries, and
133 it was observed that it consisted of two types of fibers: vascular bundles (VBs) and fiber
134 strands (FSs) VBs and FSs looks like for the anatomy of pineapple leaves (Mohamed,
135 Sapuan, Shahjahan, & Khalina, 2010). Then, the separated fibers were washed thoroughly
136 using water and then sun dried for one week to ensure maximum moisture removal. Finally,
137 the dried VBs and FSs fibers were collected as shown in Figure 1d for further investigations.



138
139 **Figure 1.** Photographs of (a) date palm tree, (b) date palm rachis and leaflets, (c) cut rachis,
140 and (d) vascular bundles (VBs) and fiber strands (FSs).

141 **Characterization**

142 ***Morphology and surface elemental composition (SEM–EDX analysis).*** The micrographs
143 were obtained with an environmental scanning electron microscope (SEM) (FEI Quanta 250)
144 equipped with a secondary electron large-field detector (LFD). Micrographs were obtained
145 under low vacuum mode (at a pressure of 40 Pa) under an accelerating voltage between 10 to
146 20 kV, with a spot size of 3-5 nm and a working distance ranging from 9 to 12 mm.
147 Elemental analysis of the fiber surface was performed by energy dispersive X-Ray
148 spectroscopy analysis (TEAM-EDX Model) to access the amount of existing elements and
149 results were expressed in weight and atomic percent.

150 ***Topographic characterization.*** The surface roughness of VBs and FSs fibers was optically
151 scanned in 3D using a confocal white light sensor with a high-resolution profilometer (CT-
152 100, Cyber Technologies). The samples were scanned with a step size of 5 μm for an
153 illumination time of 0.5 ms. After scanning, the measured roughness characteristics were
154 analyzed with the SCAN-SUITE software.

155 ***Fourier-transform infrared (FTIR) spectrometry.*** FTIR spectra were obtained with FTIR
156 spectrometer (Nicolet iS10 from Thermo Fisher Scientific equipped with a Golden Gate
157 single reflection ATR accessory) in the wavenumber range 4000-500 cm^{-1} at a temperature of
158 25°C and 55% relative humidity. All spectra were collected with a 1 cm^{-1} wavenumber
159 resolution after 32 continuous scans. Spectrum analysis was performed with Smart OMNI-
160 Transmission accessory (Software OMNIC 9.5).

161 **Thermogravimetric analysis (TGA).** Thermogravimetric analysis (TGA) and derivative
162 thermogravimetry (DTG) of the fiber samples were carried out using a TGA/DSC 3+
163 (METTLER TOLEDO). Approximately 10 mg of the sample were filled in ceramic alumina
164 crucible capsule and heated from 30°C to 600°C at a constant heating rate of 10 °C/min,
165 under nitrogen atmosphere at a flow rate of 20 mL/min to prevent any oxidative degradation.
166 The DTG data were also obtained from the analysis using STARe-Evaluation Software.

167 **Differential scanning calorimetry (DSC).** Differential scanning calorimetry (DSC)
168 analysis was performed using DSC 3+ (METTLER TOLEDO). The equipment was
169 calibrated with aluminum oxide before analysis. The sample (weighing approx. 6 mg) was
170 encapsulated in a hermetic aluminum pan before analysis, and an empty pan was used as
171 reference. The sample was then heated from 30°C to 600°C at a heating rate of 10 °C/min.
172 The nitrogen source was adjusted to a flow of 100 mL/min. All thermograms were analyzed
173 using STARe-Evaluation Software.

174 **X-ray diffraction (XRD) analysis.** Powder X-ray diffraction (XRD) patterns of the
175 samples were obtained using an X-ray PANalytical Empyrean diffractometer equipped with a
176 PIXcel-3D detector and Cu-K α radiation ($\lambda = 1.540598\text{\AA}$). The generator was operated at 45
177 kV voltage and 40 mA current. Powder samples were mounted on a sample holder and
178 scanned from 10° to 40° (2 θ angle range) at a scan rate of 5°/min. The length of the specimen
179 used was 10 mm and the measurement temperature was about 23°C.

180 The crystallinity index (C.I.) and percentage of crystallinity (%Cr) were calculated based on
181 the Segal method (Segal, Creely, Martin, & Conrad, 1959) using the following equations (1)
182 and (2), respectively:

183
$$\text{C.I.} = (I_{002} - I_{\text{am}}) / I_{002} \times 100 \quad (\text{Eq.1})$$

184
$$\text{Cr (\%)} = (I_{002} / (I_{002} + I_{\text{am}})) \times 100 \quad (\text{Eq.2})$$

185 where I_{002} is the maximum intensity diffraction of the 002-lattice reflection of the
186 crystallographic form of cellulose at $2\theta=22^\circ$, and I_{am} the minimum intensity of the amorphous
187 material at an angle of approximately 18.5° in the valley between the peaks.

188 The crystallite size (CS) for VBs and FSs was calculated using Scherrer's equation (Maache,
189 Bezazi, Amroune, Scarpa, & Dufresne, 2017):

$$190 \quad CS = k \lambda / \beta_{002} \cos \theta \quad (\text{Eq.3})$$

191 where CS is the crystallite size (nm), k is the Scherrer constant (0.9), λ is the wavelength of
192 X-ray beam (1.5405 \AA), β is the full width half maxima (FWHM) of peak diffraction (in rad)
193 and θ is the diffraction angle. XRD data were deconvoluted using MagicPlot-Pro 2.7.2
194 software by adjusting one amorphous and three crystalline peak sum for each original curve
195 via Gaussian deconvolution.

196 **Fiber density.** The density (ρ_f) for VBs and FSs fibers was calculated by liquid immersion
197 test using pycnometer with distilled water (ASTM D2320-98) and was determined by the
198 following equation (4):

$$199 \quad \rho_f = [(m_2 - m_1) / (m_3 - m_1) - (m_4 - m_2)] \rho_{wt} \quad (\text{Eq.4})$$

200 where m_1 , m_2 , m_3 , m_4 and ρ_{wt} are the mass of empty pycnometer (g), the mass of pycnometer
201 with fibers (g), the mass of pycnometer with distilled water (g), the mass of pycnometer with
202 fibers and distilled water (g), and the density of distilled water (0.997 g/cm^3), respectively.

203 **Technical fiber tensile tests.** The tensile tests were conducted using Zwick/Roell universal
204 testing machine Z2.5 equipped with a 200 N load cell attached to an automatic data
205 acquisition system. 20 samples were analyzed for each group according to ASTM D3822-07
206 for a fiber length of 30 mm at a constant speed of 1 mm/min. All tests were carried out at a
207 temperature of 23 °C and a relative humidity of approximately 45%. The cross-sectional area
208 was evaluated from the diameter measured using an optical microscope (Motic-BA310
209 Met, Motic Images Plus 2.0 software) at three different points along the effective fiber
210 length. The statistical analysis of tensile strength values has been analyzed by two parameters
211 Weibull distribution model. The obtained results were treated by Minitab software.

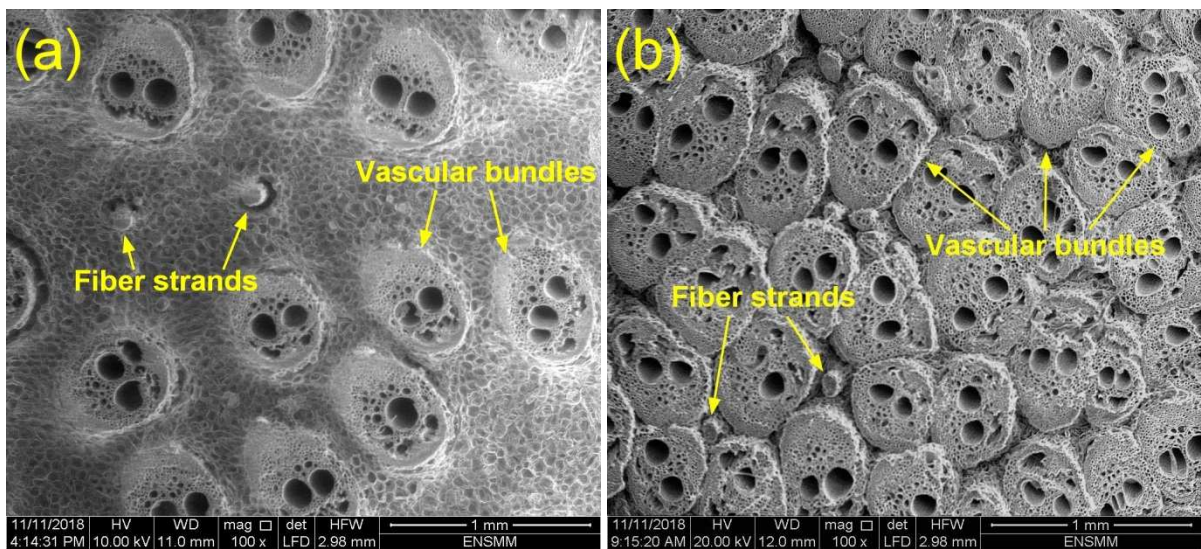
212 **RESULTS AND DISCUSSION**

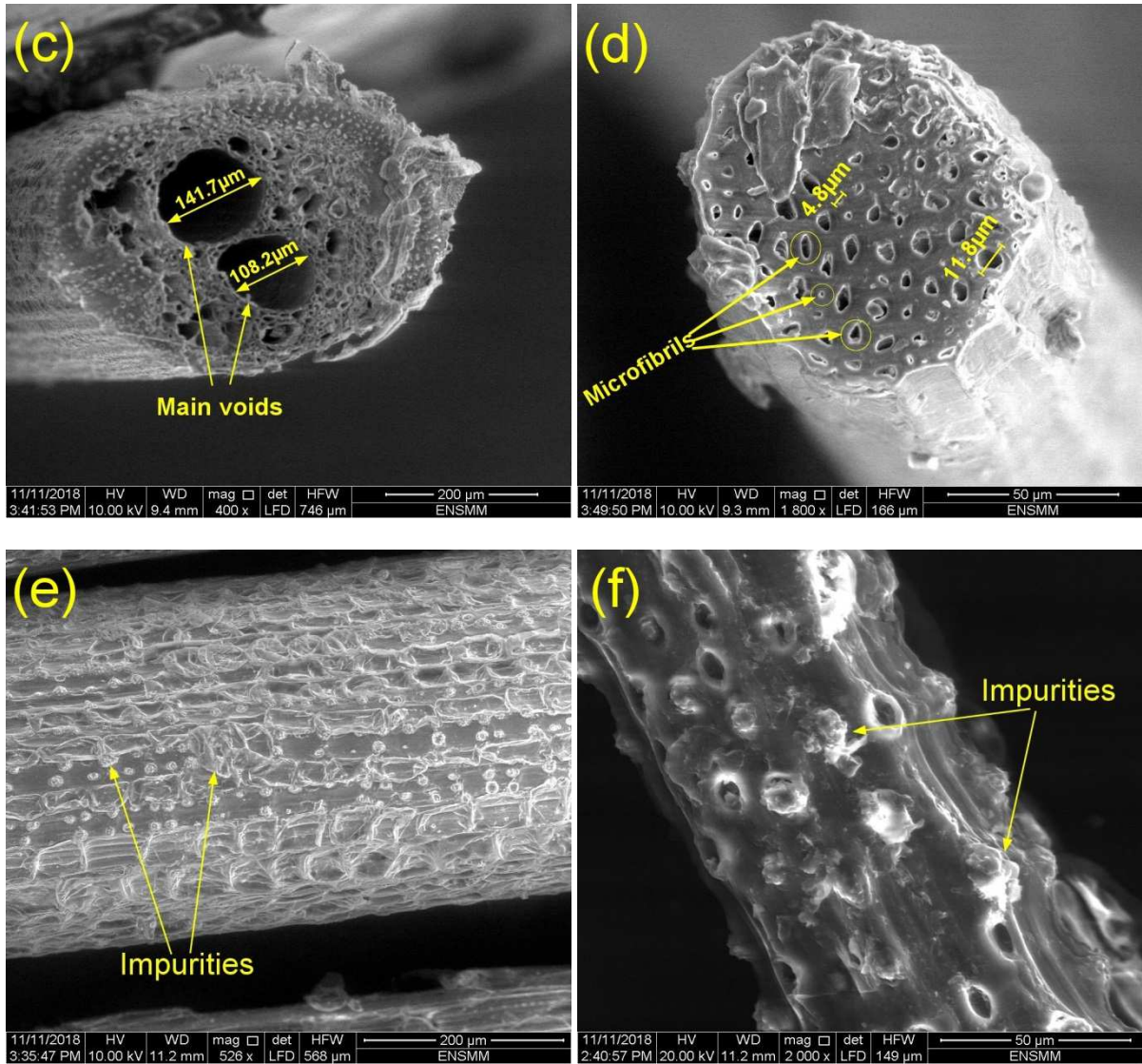
213 **Morphological analysis**

214 Figures 2a and 2b show SEM micrographs of the cross-section at the base and 20 cm before
215 the tip of the date palm rachis, respectively. The micrographs clearly show a gathering of
216 several fibers dispersed and separated by chlorenchyma cells. However, there is a clear
217 difference in the microstructure of these fibers, which can be classified into two types, the
218 first called vascular bundle (VBs) which is the thicker one and that appears in the middle of
219 the main voids, while the second called fiber strand (FSs) is the thinnest that do not contain
220 any main voids. It is worth noting that the parenchyma cells of the base rachis are much
221 denser compared to the tip from the rachis of date palm.

222 Figures 2c and 2d display the cross-section of VBs and FSs from the rachis of date palm,
223 respectively. The microstructural observation carried out for VBs showed that the surface
224 area is elliptical nearly circular in shape, the VBs being composed of two main voids with
225 diameter ranging from 100 to 150 μm with a large number of spherical microfibrils with a
226 smaller diameter in the range 6-22 μm , aligned and bonded together by lignin, pectin and
227 other non-cellulosic materials (Manimaran, Senthamaraikannan, Sanjay, Marichelvam, &

228 Jawaid, 2018). FSs are composed of several individual microfibrils with a diameter in the
229 range 4 to 12 μm , compactly arranged to form a technical fiber whose shape is approximately
230 cylindrical and whose diameter was found in the range 80 to 120 microns.
231 The SEM micrographs of the surface (longitudinal direction) for VBs and FSs are depicted in
232 Figures 2e and 2f, respectively. The presence of some impurities randomly distributed is
233 observed on the surface of VBs and FSs fibers, their existence resulting from the extraction
234 technique. The fiber structure exhibits an alignment in the direction of the fiber axis, in the
235 shape of a regularly distributed semi-rectangular and square tray, along with the length of the
236 lines on the surface of the fibers. Further, it shows small void holes or pits not uniformly
237 spaced and it has the shape of an almost circular elliptical at the surface. In general, this type
238 of structure is similar to other vascular fiber bundles such as arundo fibers (Fiore, Scalici, &
239 Valenza, 2014) and to fiber strands like banana fibers (Kambli, Basak, Samanta, &
240 Deshmukh, 2016).





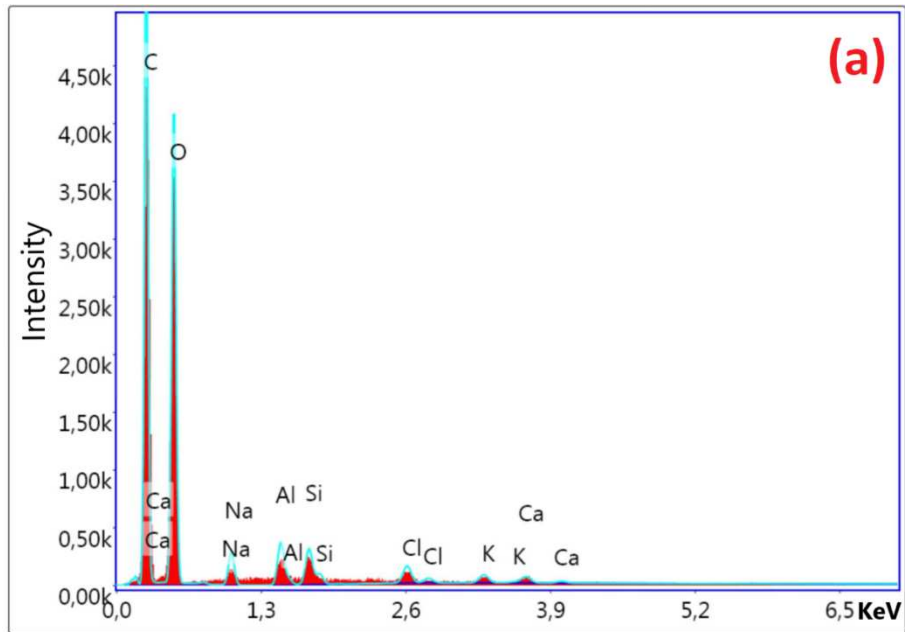
242

243

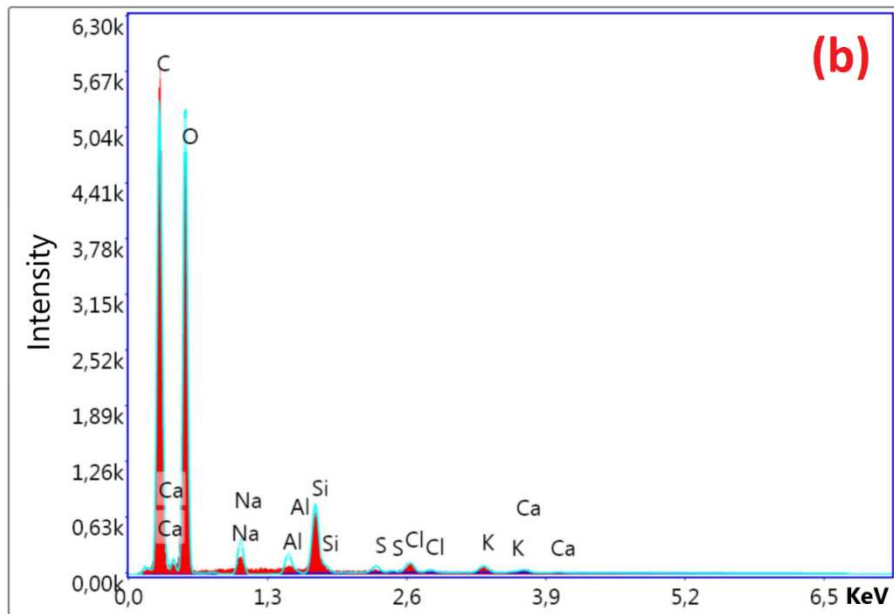
244 **Figure 2.** SEM micrographs of the cross-section at: (a) the base of the rachis, and (b) 20 cm
 245 before the tip of the rachis. SEM micrographs of the cross-section for (c) VBs (d) FSs and
 246 longitudinal view for (e) VBs, and (f) FSs.

247 **EDX analysis**

248 Figures 3a and 3b show the spectral imaging generated by energy dispersive X-ray
 249 spectroscopy (EDX) for VBs and FSs, respectively. The fibers consist of elements such as
 250 carbon (C), oxygen (O), small amounts of sodium (Na), aluminum (Al), silicon (Si) and
 251 traces of chlorine (Cl), potassium (K), calcium (Ca) and the existence of sulfur (S) only in
 252 FSs fibers.



253



254

255 **Figure 3.** EDX analysis for (a) VBs and (b) FSs.

256 Table 1 reports the results for the weight content and atomic content calculated from the peak
 257 areas for all elements. It indicates a similar composition for both fibers. Carbon and oxygen
 258 are the main constituents because they are the main components for natural fiber structures
 259 (Kambli et al., 2016), that corresponds to the known chemical composition of lignocellulosic
 260 fibers.

261 **Table 1.** Weight (W%) and atomic percentage (A%) for VBs and FSs fibers compared to

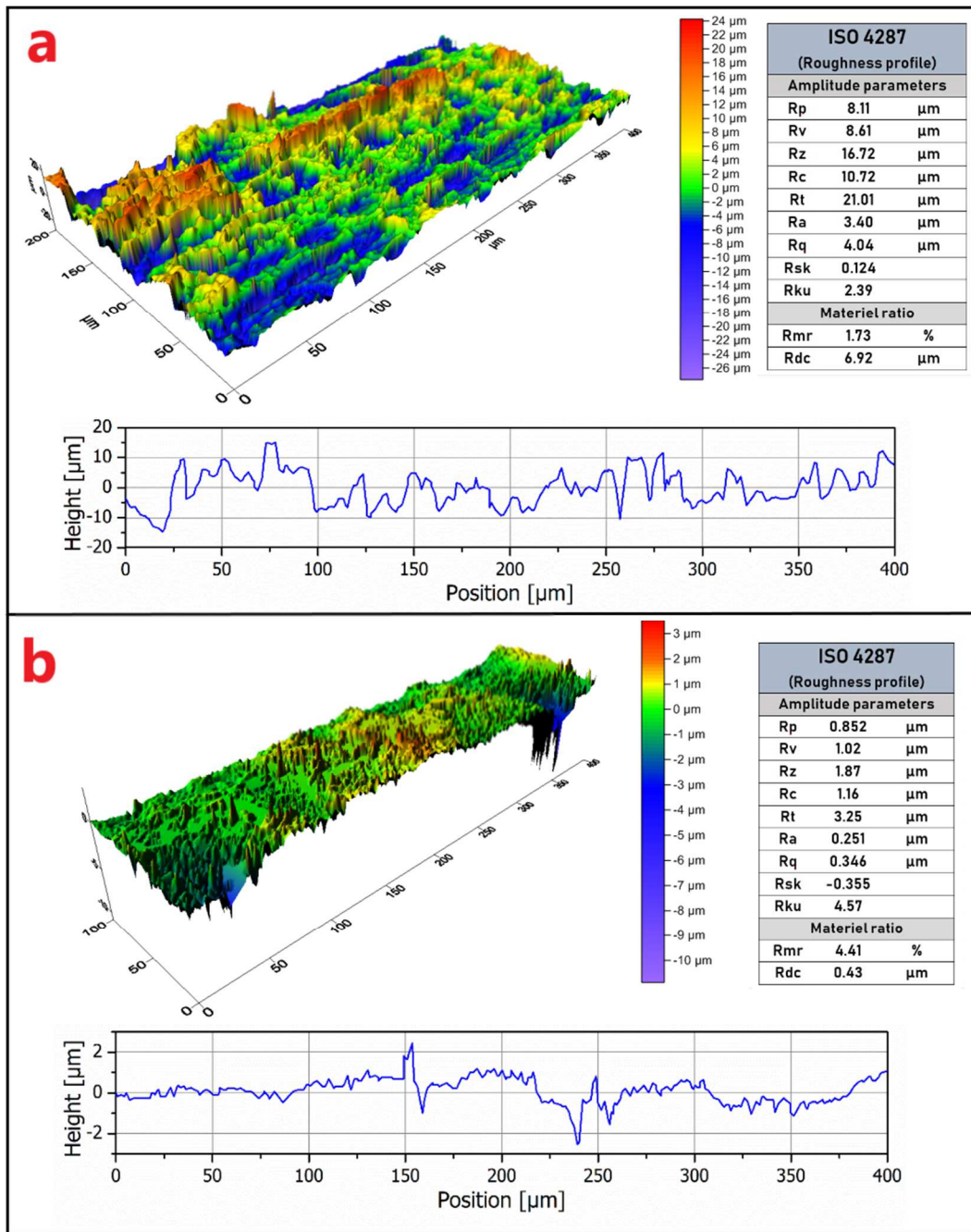
262 other lignocellulosic fibers.

Fiber		Element									Reference		
		C	O	Na	Al	Si	Cl	S	Mg	K		Ca	
Vascular bundles	W%	50.14	46.41	1.85	0.86	0.47	0.14			0.06	0.05	Present work	
	A%	57.88	40.22	1.12	0.44	0.23	0.06			0.02	0.02		
Fiber strands	W%	50.1	46.21	2.03	0.41	0.97	0.11	0.07		0.07	0.04		
	A%	57.89	40.09	1.22	0.21	0.48	0.04	0.03		0.03	0.01		
Furcraea foetida	W%	66.34	72.50										(Manimaran et al., 2018)
	A%	33.57	27.50										
Cornhusk fiber	W%	62.54	36.80			0.20			0.13		0.33	(Kambli et al., 2016)	
	A%	69.17	30.56			0.10			0.07		0.11		
Cotton fiber	W%	46.1	53.2										
	A%	53.9	46.8										
Jute fiber	W%	55.68	43.89			0.11		0.18					
	A%	62.72	37.11			0.06		0.08					

263

264 Surface roughness analysis

265 Figures 4a and 4b show the 3D roughness surface texture, 2D line diagram for roughness
 266 measurement and profilometry results conducted according to ISO 4287 for VBs and FSs
 267 fibers, respectively. The visual inspection of 3D topographic images makes it easy to observe
 268 the variation in peak value on the surface represented by red color because of the impurities,
 269 inorganic substances and the existence of lignin (Manimaran et al., 2018). The area of valleys
 270 found in the 3D roughness surface texture (blue color) is due to the presence of voids in VBs
 271 and holes or pits in FSs.



272

273 **Figure 4.** 3D surface roughness and 2D line diagram for roughness for (a) VBs and (b) FSs.

274 The 2D line diagram for VBs and FSs show a non-uniform surface roughness along the fiber

275 length. The profilometry results were evaluated and found to be as follow: for VBs (Ra =

276 3.40 μm , Rz = 16.72 μm , Rq = 4.04 μm , Rt = 21.01 μm) and it was lowest for FSs (Ra =

277 0.251 μm , Rz = 1.87 μm , Rq = 0.346 μm , Rt = 3.25 μm). The surface roughness for VBs was

278 higher than for other natural fibers like Ra = 0.613 μm for *Coccinia grandis* stem fiber

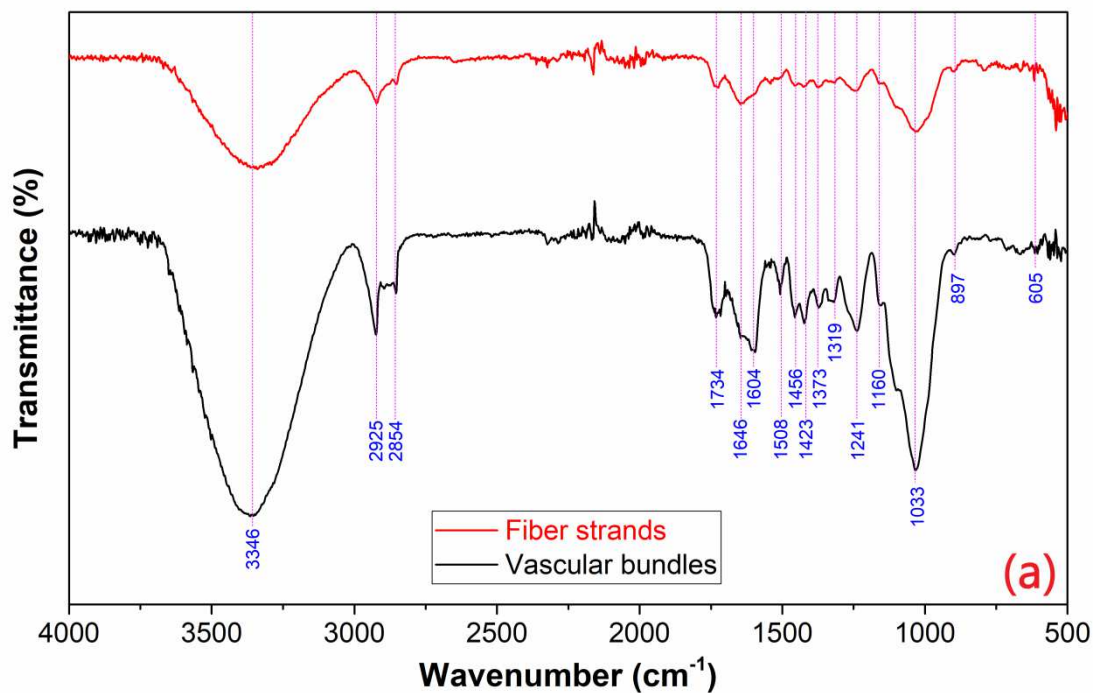
279 (Jebadurai, Raj, Sreenivasan, & Binoj, 2018), Ra = 0.611 μm for Veldt-grape stem fiber

280 (Mayandi et al., 2015) and $R_a = 0.625 \mu\text{m}$ for *Cyperus pangorei* fibers (Mayandi, Rajini,
281 Pitchipoo, Jappes, & Rajulu, 2016), but for FSs it was slightly lower. It was reported that the
282 surface roughness is one of the important properties for enhancing mechanical interlocking
283 between fiber and matrix when used as reinforcement in composite materials (Maache et al.,
284 2017).

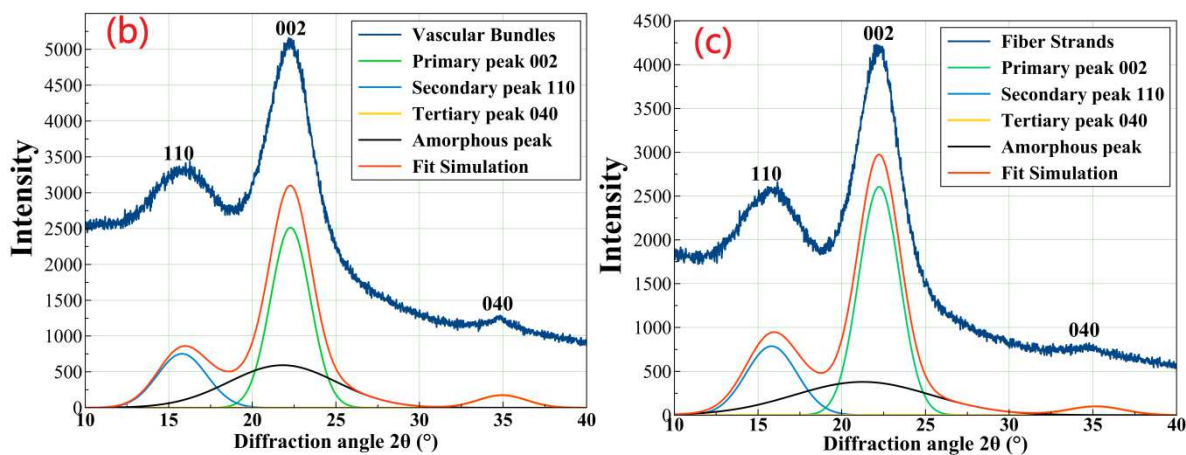
285 **FTIR analysis**

286 The FTIR spectra recorded for VBs and FSs of date palm rachis are represented in Figure 5a.
287 Both fibers presented the typical vibration bands of different chemical functional groups of
288 lignin, hemicellulose and cellulose. The strong and broad peak at 3346 cm^{-1} is associated with
289 the O-H stretching vibration and hydrogen bond of the hydroxyl groups (Amroune et al.,
290 2015). The double peak observed at 2925 and 2854 cm^{-1} are assigned to CH_2 asymmetrical
291 and symmetrical stretching, respectively. The absorption band centered at 1734 cm^{-1} can be
292 attributed to the $\text{C}=\text{O}$ group and stretching vibration of ester group in hemicellulose (Bezazi,
293 Belaadi, Bouchak, Scarpa, & Boba, 2014). The small band at 1646 cm^{-1} corresponds to the
294 O-H bending of absorbed water. Following three peaks are characteristic of lignin: 1604 cm^{-1}
295 (aromatic skeletal vibration of lignin plus $\text{C}=\text{O}$ stretching), 1508 cm^{-1} ($\text{C}=\text{C}$ stretching of
296 aromatic skeletal vibration of Lignin), 1456 cm^{-1} ($\text{C}-\text{H}$ deformation (asymmetric) and
297 aromatic vibration in lignin) (Amroune et al., 2015; Saravanakumar, Kumaravel, Nagarajan,
298 & Moorthy, 2014). The absorbance at 1423 cm^{-1} is attributed to the presence of $\text{C}-\text{H}$
299 deformation in lignin and CH_2 symmetric bending in cellulose (Maache et al., 2017). The
300 absorption band at 1373 cm^{-1} is assigned to the bending vibration of the $\text{C}-\text{H}$ group of the
301 aromatic ring in hemicellulose and cellulose (Bezazi et al., 2014). The absorbance at 1319
302 cm^{-1} is attributed to the CH_2 rocking vibration in cellulose (Saravanakumar et al., 2014).
303 The tiny peak at 1241 cm^{-1} is assigned to the $\text{C}-\text{O}$ stretching of acetyl group in lignin (Bezazi
304 et al., 2014). The two peaks observed at 1160 cm^{-1} and 1033 cm^{-1} are attributed to the $\text{C}-\text{O}-\text{C}$

305 asymmetric stretching vibration and C–O stretching ring in cellulose and hemicellulose,
 306 respectively (Saravanakumar et al., 2014). A small peak at 897 cm^{-1} is attributed to the β -
 307 glycosidic linkages between the monosaccharides. The small absorption peak at 605 cm^{-1} is
 308 associated with C-OH out of plane bending in cellulose (Fiore et al., 2014).



309



310

311 **Figure 5.** (a) FTIR spectra for VBs and FSs, and XRD patterns for (b) VBs and (c) FSs.

312 **XRD analysis**

313 The diffraction patterns obtained for VBs and FSs between 10 and 40° are shown in Figures
 314 5b and 5c, respectively. The deconvolution of the X-ray diffraction profiles showed the

315 presence of three peaks and an amorphous bump. For both VBs and FSs the highest intensity
 316 peak was observed at $2\theta = 22.2^\circ$, average intensity peak at $2\theta = 15.86^\circ$ and a peak of low
 317 intensity at $2\theta = 35^\circ$, which were assigned to the (002), (10 $\bar{1}$), and (040) crystallographic
 318 planes (Jebadurai et al., 2018).

319 The crystallinity index (C.I.) was found to be 47.82% and 56.68% for VBs and FSs samples,
 320 respectively, which means that FSs exhibit a better order of cellulose crystals at the fiber axis
 321 compared to VBs. On the other hand, the percentage of crystallinity (%Cr) for VBs and FSs
 322 was found equal to 65.71% and 69.77%, respectively. In addition, the crystallite size (CS)
 323 for VBs and FSs was calculated using Scherrer's equation and the value was found to be 5.78
 324 nm and 5.63 nm, respectively, which is smaller than the value reported for *Furcraea foetida*
 325 (28.36 nm), *Prosopis juliflora* bark (15 nm), but higher than for *Juncus effusus L.* (3.6 nm)
 326 and *Coccinia grandis* stem (1.91 nm) as reported by (Jebadurai et al., 2018; Maache et al.,
 327 2017; Manimaran et al., 2018; Saravanakumar, Kumaravel, Nagarajan, Sudhakar, &
 328 Baskaran, 2013). The obtained results are summarized in Table 2 and compared to (Roy et
 329 al., 2012; Wei & Meyer, 2015)

330 **Table 2.** Calculated and experimental crystalline parameters from XRD diffractograms of
 331 fibers.

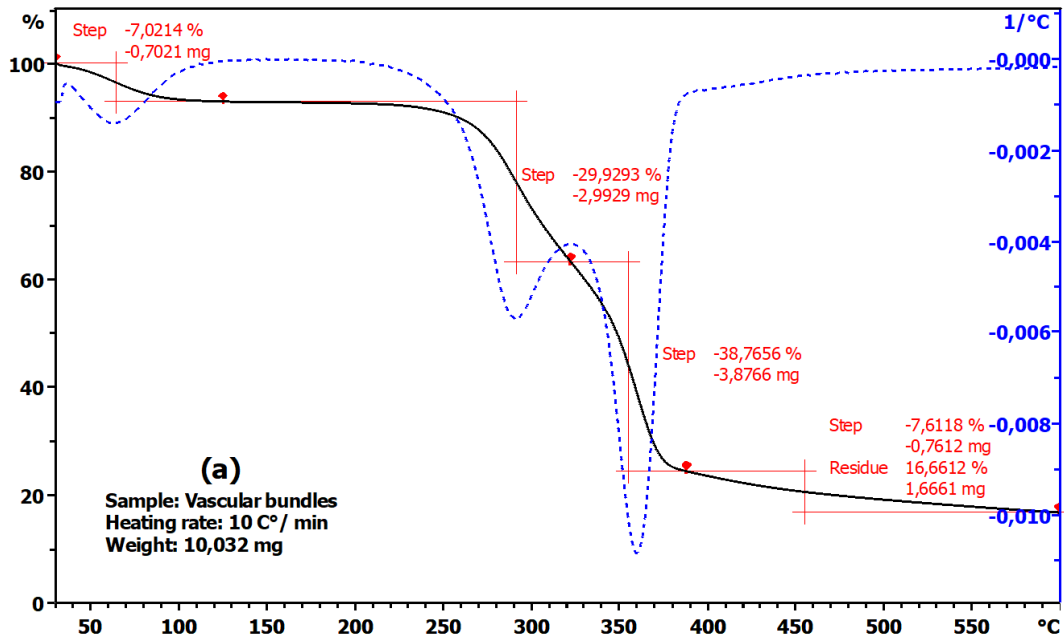
Type of fiber	Peak position ($^\circ$)	FWHM (rad)	Area (%)	Crystallinity (%)	Crystalline index (%)	Crystallite size (nm)	Reference	
Vascular bundles	15.79	1.74	2789.23	65.71	47.82	5.78	Present work	
	22.28	1.40	7487.62					
Fiber strands	15.81	1.79	3006.61	69.77	56.68	5.63		
	22.24	1.44	7980.62					
Sisal fiber	16,81	4.89		77.6	71.2	3.37		(Wei & Meyer, 2015)
	22,31	3.37						
Jute fiber	15.62	4,23	42.05	53.7		2.78	(Roy et al., 2012)	
	23.36	2.89	57.94					

332

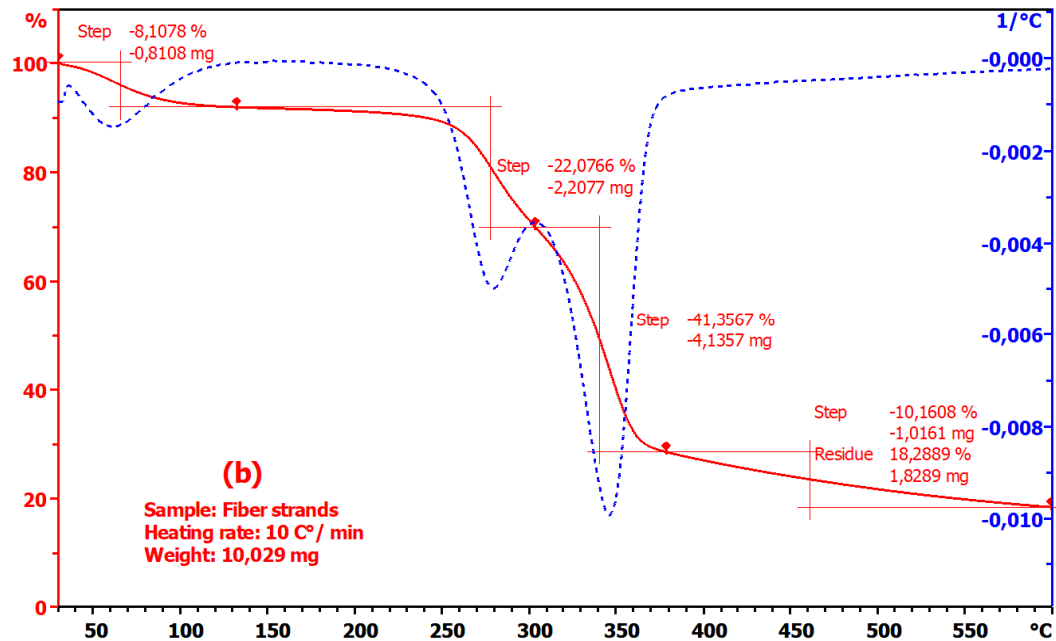
333 **TGA analysis**

334 Thermogravimetric analysis (TGA) and derivative thermogravimetry (DTG) are thermal
335 analysis techniques used to measure the weight loss of a material when heated, i.e. to access
336 its thermal stability, and characterize its decomposition temperature.

337 Figure 6 presents the TG and DTG curves for VBs and FSs, which show four weight loss
338 stages. The first stage associated with a small weight loss (8.10%) for VBs and (7.00%) for
339 FSs, corresponds to the dehydration phase that was observed in the temperature range 30-120
340 °C. This stage was attributed to the evaporation of adsorbed moisture, which is related to the
341 hydrophilic nature of lignocellulosic materials (Fiore et al., 2014). Then, it can be concluded
342 that both VBs and FSs can be considered thermally stable up to 230 °C and 220, respectively.
343 The thermal stability of lignocellulosic fibers is important for the processing and usage of
344 these materials as a reinforcement in biocomposites (Maache et al., 2015). In the second
345 stage, the degradation of hemicelluloses was recorded in the temperature range 220-325 °C
346 with a weight loss of 29% for VBs and in the temperature range 220-300 °C with a weight
347 loss of 22% for FSs (Martin, Martins, Da Silva, & Mattoso, 2010; Saravanakumar et al.,
348 2013). It is confirmed by the observation of a peak in the DTG curves at 296 °C for VBs and
349 280 °C for FSs. Afterward, the major weight loss occurred rapidly in the third degradation
350 stage, corresponding to the decomposition of cellulose in the temperature range 325-490 °C
351 associated with a weight loss of 39.00% for VBs and in the temperature range 300-480 °C
352 with a higher weight loss of 41.51% for FSs. The DTG plots showed distinct peaks at 360 °C
353 for VBs and 345 °C for FSs (Jebadurai et al., 2018). Lastly, the final stage corresponding to
354 the decomposition of lignin was observed in the temperature range 400-485 °C with a small
355 weight loss for VBs (10%) and in the temperature range 380-465 °C with a smaller weight
356 loss for FSs (7%) (Roy et al., 2012). In addition, amounts of charred residues were observed
357 for VBs (16.66%) and FSs (18.28%).



358



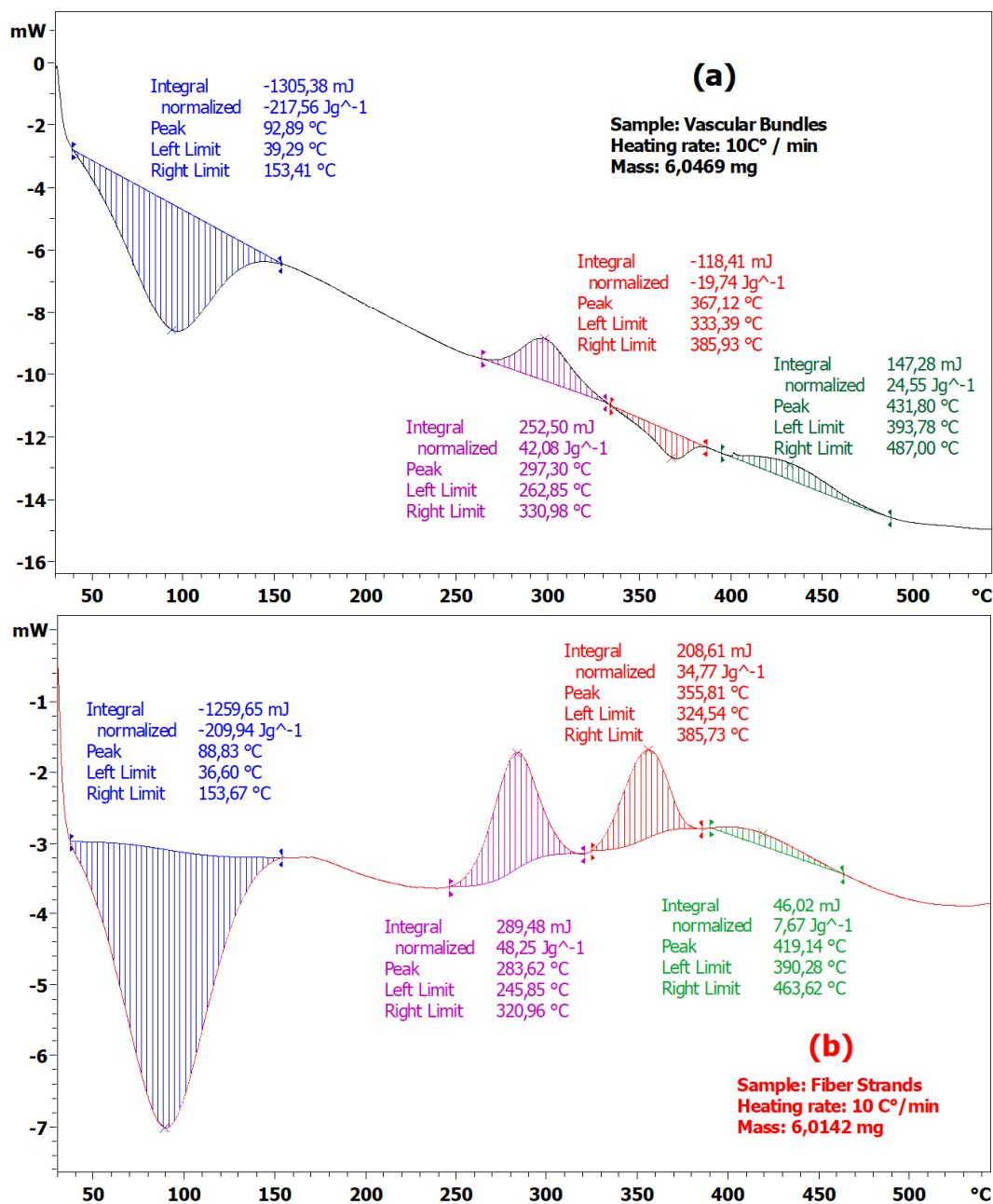
359

360 **Figure 6.** TGA/DTG curves for (a) VBs and (b) FSs.

361 **DSC analysis**

362 Differential scanning calorimetry (DSC) analysis was carried out for both VBs and FSs for
 363 determining its thermal behavior. DSC analysis allows observing physical changes through
 364 the absorption and release of thermal energy during heating, which allows the identification
 365 of thermal transitions. Figure 7 shows the DSC curves obtained for VBs and FSs presenting
 366 the endothermic and exothermic processes where some differences can be noted. The first

367 endothermic peak was centered at 92°C and 88°C for VBs and FSs, respectively. It
 368 corresponds to the loss/evaporation of absorbed water (Belaadi, Bezazi, Bouchak, Scarpa, &
 369 Zhu, 2014). The corresponding enthalpy calculated by integrating the peak was 217 J/g and
 370 209 J/g for VBs and FSs, respectively.



371

372

373 **Figure 7.** DSC curves for (a) VBs and (b) FSs.

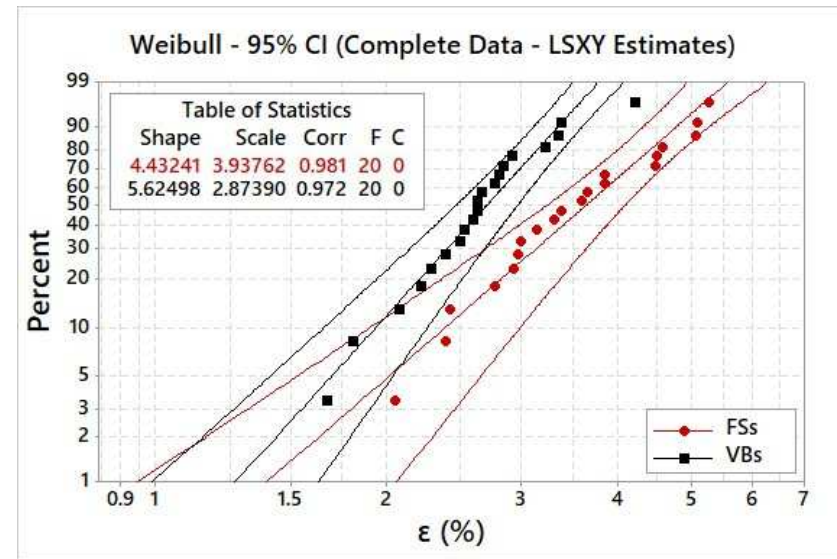
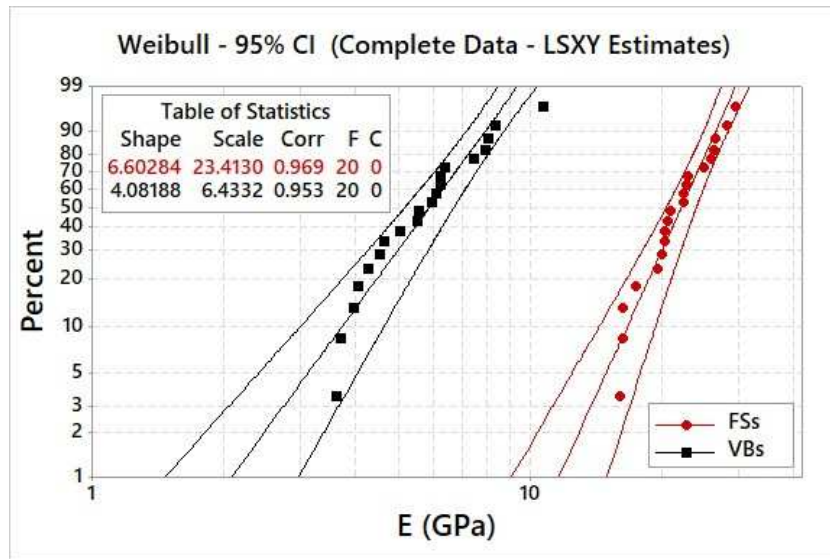
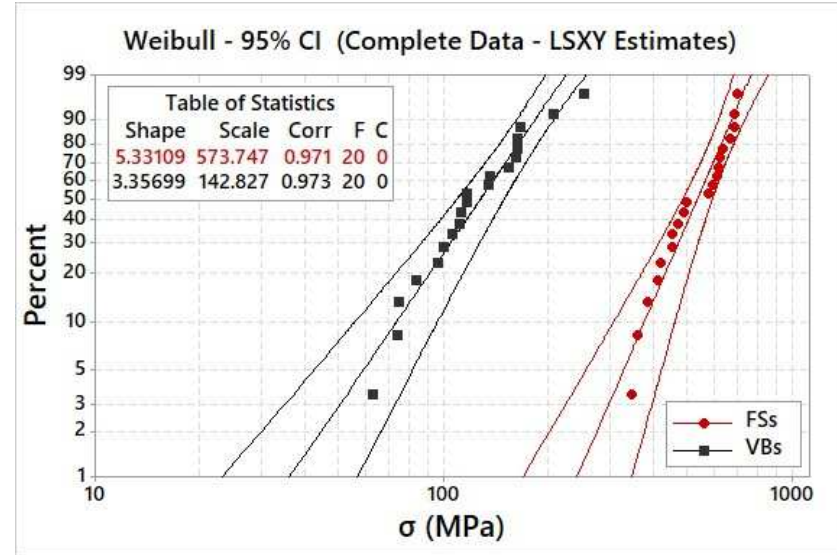
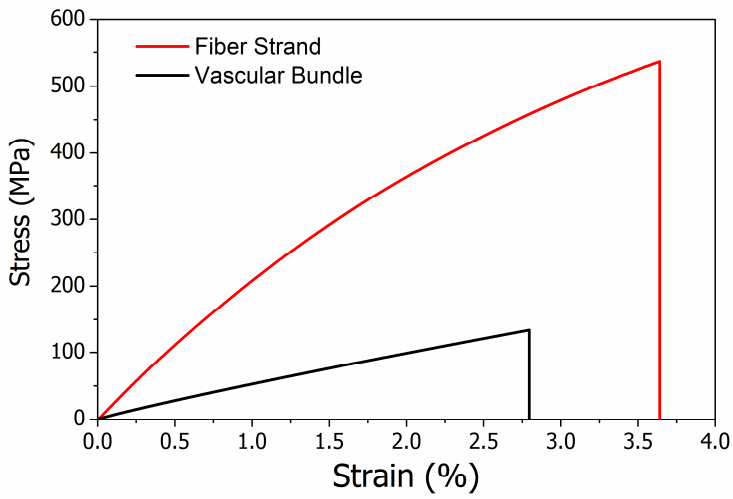
374 The exothermic peak observed at 297°C and 283°C for VBs and FSs, respectively, is mainly
 375 due to the degradation of hemicelluloses present in the samples which is associated with an

376 enthalpy of 42 J/g for VBs and 48 J/g for FSs (Martin et al., 2010). Then a different behavior
377 is observed between VBs and FSs with an endothermic peak around 367°C for the former and
378 exothermic peak around 355°C for the later. According to DTG results this signal should
379 correspond to the degradation of cellulose and the associated enthalpy is 19 J/g for VBs while
380 it is 34 J/g for FSs (Roy et al., 2012). Finally, a small exothermic peak observed at 431 °C for
381 VBs and 419 °C for FSs is mainly due to the thermal decomposition of lignin, were a much
382 higher enthalpy (24 J/g) is reported for VBs than for FSs (7 J/g).

383 **Technical fiber tensile tests and statistical analysis**

384 The typical stress-strain curves for VBs and FSs under tensile tests behave quasi-linearly and
385 non-linearly, respectively, until failure (Figure 8a). It is worth noting that the mechanical
386 properties of FSs are largely better compared to VBs. Due to the dispersion in the obtained
387 results, it was deemed necessary to analyze them statistically using two-parameters Weibull
388 distribution fit plots of the test data for all the 20 trials with 95% confidence level curves for
389 tensile strength, Young's modulus and strain at failure. The results are presented in Figure 8b,
390 8c, and 8d, respectively, for VBs and FSs having an average diameter of $520\pm 72\mu\text{m}$ and
391 $88\pm 12\mu\text{m}$, respectively, with low density of 0.914 g/cm^3 and 0.922 g/cm^3 , respectively.
392 The Weibull distribution provides a reasonable approximation of the experimental data for
393 evaluating the mechanical properties of different natural fibers. The experimental results
394 obtained for VBs and FSs were found to be $129.1\pm 47.3\text{ MPa}$ and $530.5\pm 115.2\text{ MPa}$ for the
395 ultimate tensile strength, $5.88\pm 1.84\text{ GPa}$ and $21.90\pm 3.96\text{ GPa}$ for the Young's modulus, and
396 $2.67\pm 0.57\%$ and 3.60 ± 0.95 for the strain at failure, respectively. These values are very close
397 to the ones obtained by Weibull distribution: ultimate tensile strength 142.8 MPa and 573.7
398 MPa , Young's modulus 6.43 GPa and 23.41 GPa , and strain at failure 2.87% and 3.93% ,
399 respectively, with precision adjustment R-Squared values ranging from 0.953 to 0.981.

400 In addition, the tensile strength value obtained for VBs was similar to the one reported for
401 agave fiber (135 ± 71 MPa) (Bezazi et al., 2014), fiber fruit bunch branch of palm date
402 (117 ± 35 MPa) (Amroune et al., 2015) and *Juncus effusus L.* (113 ± 36 MPa) (Maache et al.,
403 2017). It is much higher for FSs (530.5 ± 115.2 MPa), which value is close to the one reported
404 for pineapple leaf fiber strands (506 MPa) (Mohamed et al., 2010), *Prosopis juliflora* bark
405 fiber (558 ± 13.4 MPa) (Saravanakumar et al., 2013) and sisal fiber (605.86 MPa) (Wei &
406 Meyer, 2015). These results expressly demonstrated that the **tensile properties are influenced**
407 **mainly by the morphological structure and that the presence of the main voids decreases their**
408 **properties. It can also be seen from the results that the tensile properties are increased with**
409 **the increase in the crystallinity index of the fibers.**



410

411

412 **Figure 8.** (a) Typical stress–strain curve for VBs and FSs, and two-parameter Weibull distribution for VBs and FSs for (b) tensile strength, (c)
 413 Young’s modulus, and (d) strain at break.

414 CONCLUSION

415 The investigation of the Ghars date palm rachis fibers leads to the main following
416 conclusions:

417 - The existence of two main types of Ghars date palms rachis fibers have been identify, for
418 the first time, on the basis of cross-sectional geometry namely: vascular bundles (VBs) and
419 fiber strands (FSs) and showing their location in the rachis. Also, a new extraction method for
420 Ghars rachis has been developed without any damaging or breaking it.

421 - The noncontact 3D profiler observations show that VBs and FSs have a rough surface
422 ($R_a=3.40$ and $R_a= 0.251$, respectively), which is essential for adhesion to the polymer matrix.

423 - XRD analysis showed that FSs has a higher crystallinity index (56.68%) compared to VBs
424 (47.82%). In addition, the crystallite size (CS) for VBs and FSs was found to be 5.78 nm and
425 5.63 nm, respectively.

426 - The main chemical and molecular structure groups were identified by FTIR analysis
427 showing similar functional groups compared to other lignocellulosic fibers reported in the
428 literature and EDX indicates similar composition content for both fibers.

429 - TGA and DSC analysis for VBs and FSs show that it can be stable up to 230 °C and 220,
430 respectively, i.e. it has good thermal stability. The thermal events associated to hemicellulose,
431 cellulose, and lignin has been determined.

432 - The density was evaluated for at 0.914 g/cm^3 for VBs, which was slightly lower that for FSs
433 (0.922 g/cm^3).

434 - The statistical analysis with Weibull distribution function showed a good approximation fit
435 value with the experimental data obtained. These results clearly indicate the effect of the
436 crystallinity index and the structural morphology of the fibers on the tensile properties. In
437 other words, the high crystallinity index leads to have better tensile properties.

438 - The tensile strength for FSs was found to be $530.5 \pm 115.2 \text{ MPa}$, i.e. more than 4 times than

439 for VBs (129.1 ± 47.3 MPa),-and the Young's modulus of FSs and VBs was 21.90 ± 3.96 GPa,
440 5.88 ± 1.84 GPa, respectively.

441 - The mechanical properties obtained show high ultimate tensile stress for FSs compared to
442 VBs and also to all the fibers date palm existing in the literature. Therefore, the fibers
443 investigated show great potential for use as reinforcement for biocomposites in diverse
444 engineering applications.

445

446 REFERENCES

447 Agoudjil, B., Benchabane, A., Boudenne, A., Ibos, L., & Fois, M. (2011). Renewable
448 materials to reduce building heat loss: Characterization of date palm wood. *Energy and*
449 *Buildings*, 43(2–3), 491–497. <https://doi.org/10.1016/j.enbuild.2010.10.014>

450 Al-Kaabi, K., Al-Khanbashi, A., & Hammami, A. (2005). Date Palm Fibers as Polymeric
451 Matrix Reinforcement : DPF / Polyester Composite Properties. *POLYMER*
452 *COMPOSITES*, 26, 604–613. <https://doi.org/10.1002/pc.20130>

453 Al-Khanbashi, A., Al-Kaabi, K., & Hammami, A. (2005). Date palm fibers as polymeric
454 matrix reinforcement: Fiber characterization. *Polymer Composites*, 26(4), 486–497.
455 <https://doi.org/10.1002/pc.20118>

456 Al-oqla, F. M., Alothman, O. Y., Jawaid, M., Sapuan, S. M., & Es-Saheb, M. H. (2014).
457 Processing and Properties of Date Palm Fibers and Its Composites. In *Biomass and*
458 *Bioenergy* (pp. 1–25). Springer, Cham. <https://doi.org/10.1007/978-3-319-07641-6>

459 Al-Oqla, F. M., & Sapuan, S. M. (2014). Natural fiber reinforced polymer composites in
460 industrial applications: Feasibility of date palm fibers for sustainable automotive
461 industry. *Journal of Cleaner Production*, 66, 347–354.
462 <https://doi.org/10.1016/j.jclepro.2013.10.050>

463 Alawar, A., Hamed, A. M., & Al-Kaabi, K. (2009). Characterization of treated date palm tree
464 fiber as composite reinforcement. *Composites Part B: Engineering*, 40(7), 601–606.
465 <https://doi.org/10.1016/j.compositesb.2009.04.018>

466 Almi, K., Lakel, S., Benchabane, a., & Kriker, a. (2015). Characterization of Date Palm
467 Wood Used as Composites Reinforcement. *Acta Physica Polonica A*, 127(4), 1072–
468 1074. <https://doi.org/10.12693/APhysPolA.127.1072>

469 Alsaeed, T., Yousif, B. F., & Ku, H. (2013). The potential of using date palm fibres as

470 reinforcement for polymeric composites. *Materials and Design*, 43, 177–184.
471 <https://doi.org/10.1016/j.matdes.2012.06.061>

472 Amroune, S., Bezazi, A., Belaadi, A., Zhu, C., Scarpa, F., Rahatekar, S., & Imad, A. (2015).
473 Tensile mechanical properties and surface chemical sensitivity of technical fibres from
474 date palm fruit branches (*Phoenix dactylifera* L.). *Composites Part A: Applied Science
475 and Manufacturing*, 71(November), 98–106.
476 <https://doi.org/10.1016/j.compositesa.2014.12.011>

477 Anwar, Z., Gulfraz, M., & Irshad, M. (2014). Agro-industrial lignocellulosic biomass a key to
478 unlock the future bio-energy: A brief review. *Journal of Radiation Research and
479 Applied Sciences*, 7(2), 163–173. <https://doi.org/10.1016/j.jrras.2014.02.003>

480 Belaadi, A., Bezazi, A., Bourchak, M., Scarpa, F., & Zhu, C. (2014). Thermochemical and
481 statistical mechanical properties of natural sisal fibres. *Composites Part B: Engineering*,
482 67, 481–489. <https://doi.org/10.1016/j.compositesb.2014.07.029>

483 Bezazi, A., Belaadi, A., Bourchak, M., Scarpa, F., & Boba, K. (2014). Novel extraction
484 techniques, chemical and mechanical characterisation of *Agave americana* L. natural
485 fibres. *Composites Part B: Engineering*, 66, 194–203.
486 <https://doi.org/10.1016/j.compositesb.2014.05.014>

487 Biglari, F., AlKarkhi, A. F. M., & Easa, A. M. (2008). Antioxidant activity and phenolic
488 content of various date palm (*Phoenix dactylifera*) fruits from Iran. *Food Chemistry*,
489 107(4), 1636–1641. <https://doi.org/10.1016/J.FOODCHEM.2007.10.033>

490 Bouguedoura, N., Bennaceur, M., Babahani, S., & Benziouche, S. E. (2015). Date Palm
491 Status and Perspective in Algeria. In *Date Palm Genetic Resources and Utilization:
492 Volume 1: Africa and the Americas* (pp. 1–546). [https://doi.org/10.1007/978-94-017-
493 9694-1](https://doi.org/10.1007/978-94-017-9694-1)

494 Boumediri, H., Bezazi, A., Haddad, A., Saaidia, A., Scarpa, F., & Dufrene, A. (2017).
495 Physico-Chemical Characterization of Date Palm leaves (*Phoenix Dactylifera*-L) of
496 Algeria. In A. J. M. Ferreira, E. Viola, F. Tornabene, & N. Fantuzzi (Eds.), *Mechcomp3:
497 3rd International Conference of Mechanics of Composite* (p. 24). Esculapio.

498 Chandrasekaran, M., & Bahkali, A. H. (2013). Valorization of date palm (*Phoenix
499 dactylifera*) fruit processing by-products and wastes using bioprocess technology -
500 Review. *Saudi Journal of Biological Sciences*, 20(2), 105–120.
501 <https://doi.org/10.1016/j.sjbs.2012.12.004>

502 Chao, C. C. T., & Krueger, R. R. (2007). The date palm (*Phoenix dactylifera* L.): Overview
503 of biology, uses, and cultivation. *HortScience*, 42(5), 1077–1082.

504 Darwish, E. A., Mansour, Y. M., & Elmously, H. (2018). Date Palm Rachis as a Local and
505 Renewable Structural Material for Rural Communities in Egypt. *The International*
506 *Journal of Environmental Science & Sustainable Development*, 2(1), 1–11.
507 <https://doi.org/10.21625/essd.v2i1.173.g75>

508 Fiore, V., Scalici, T., & Valenza, A. (2014). Characterization of a new natural fiber from
509 *Arundo donax* L. as potential reinforcement of polymer composites. *Carbohydrate*
510 *Polymers*, 106(1), 77–83. <https://doi.org/10.1016/j.carbpol.2014.02.016>

511 Ghnimi, S., Umer, S., Karim, A., & Kamal-Eldin, A. (2017). Date fruit (*Phoenix dactylifera*
512 L.): An underutilized food seeking industrial valorization. *NFS Journal*, 6, 1–10.
513 <https://doi.org/10.1016/j.nfs.2016.12.001>

514 Jawaid, M., & Abdul Khalil, H. P. S. (2011). Cellulosic/synthetic fibre reinforced polymer
515 hybrid composites: A review. *Carbohydrate Polymers*, 86(1), 1–18.
516 <https://doi.org/10.1016/j.carbpol.2011.04.043>

517 Jayaramudu, J., Guduri, B. R., & Varada Rajulu, A. (2010). Characterization of new natural
518 cellulosic fabric *Grewia tilifolia*. *Carbohydrate Polymers*, 79(4), 847–851.
519 <https://doi.org/10.1016/j.carbpol.2009.10.046>

520 Jebadurai, S. G., Raj, R. E., Sreenivasan, V. S., & Binoj, J. S. (2018). Comprehensive
521 characterization of natural cellulosic fiber from *Coccinia grandis* stem. *Carbohydrate*
522 *Polymers*, 207, 675–683. <https://doi.org/10.1016/j.carbpol.2018.12.027>

523 Kambli, N., Basak, S., Samanta, K. K., & Deshmukh, R. R. (2016). Extraction of Natural
524 Cellulosic Fibers from Cornhusk and Its Physico-Chemical Properties. *Fibers and*
525 *Polymers*, 17(5), 687–694. <https://doi.org/10.1007/s12221-016-5416-0>

526 Khiri, R., Mhenni, M. F., Belgacem, M. N., & Mauret, E. (2010). Chemical composition and
527 pulping of date palm rachis and *Posidonia oceanica* - A comparison with other wood and
528 non-wood fibre sources. *Bioresource Technology*, 101(2), 775–780.
529 <https://doi.org/10.1016/j.biortech.2009.08.079>

530 Maache, M., Bezazi, A., Amroune, S., Scarpa, F., & Dufresne, A. (2017). Characterization of
531 a novel natural cellulosic fiber from *Juncus effusus* L. *Carbohydrate Polymers*, 171,
532 163–172. <https://doi.org/10.1016/j.carbpol.2017.04.096>

533 Mallaki, M., & Fatehi, R. (2014). Design of a biomass power plant for burning date palm
534 waste to cogenerate electricity and distilled water. *Renewable Energy*, 63, 286–291.
535 <https://doi.org/10.1016/j.renene.2013.09.036>

536 Manimaran, P., Saravanakumar, S. S., Mithun, N. K., & Sentharamaikannan, P. (2016).
537 Physicochemical properties of new cellulosic fibers from the bark of *Acacia arabica*.

538 *International Journal of Polymer Analysis and Characterization*, 21(6), 548–553.
539 <https://doi.org/10.1080/1023666X.2016.1177699>

540 Manimaran, P., SenthamaraiKannan, P., Sanjay, M. R., Marichelvam, M. K., & Jawaid, M.
541 (2018). Study on characterization of Furcraea foetida new natural fiber as composite
542 reinforcement for lightweight applications. *Carbohydrate Polymers*, 181, 650–658.
543 <https://doi.org/10.1016/j.carbpol.2017.11.099>

544 Martin, A. R., Martins, M. A., Da Silva, O. R. R. F., & Mattoso, L. H. C. (2010). Studies on
545 the thermal properties of sisal fiber and its constituents. *Thermochimica Acta*, 506(1–2),
546 14–19. <https://doi.org/10.1016/j.tca.2010.04.008>

547 Mayandi, K., Rajini, N., Pitchipoo, P., Jappes, J. T. W., & Rajulu, A. V. (2016). Analysis and
548 Extraction and characterization of new natural lignocellulosic fiber Cyperus pangorei.
549 *International Journal of Polymer Analysis and Characterization*, 21(2), 175–183.
550 <https://doi.org/10.1080/1023666X.2016.1132064>

551 Mayandi, K., Rajini, N., Pitchipoo, P., Sreenivasan, V. S., Jappes, J. W., & Alavudeen, A.
552 (2015). A comparative study on characterisations of Cissus quadrangularis and Phoenix
553 reclinata natural fibres. *Journal of Reinforced Plastics and Composites*, 34(4), 269–280.
554 <https://doi.org/10.1177/0731684415570045>

555 Mohamed, A. R., Sapuan, S. M., Shahjahan, M., & Khalina, A. (2010). Effects of simple
556 abrasive combing and pretreatments on the properties of pineapple leaf fibers (palf) and
557 palf-vinyl ester composite adhesion. *Polymer - Plastics Technology and Engineering*,
558 49(10), 972–978. <https://doi.org/10.1080/03602559.2010.482072>

559 Nasser, R., Salem, M., Hiziroglu, S., Al-Mefarrej, H., Mohareb, A., Alam, M., & Aref, I.
560 (2016). Chemical Analysis of Different Parts of Date Palm (Phoenix dactylifera L.)
561 Using Ultimate, Proximate and Thermo-Gravimetric Techniques for Energy Production.
562 *Energies*, 9(5), 374. <https://doi.org/10.3390/en9050374>

563 Oushabi, A., Sair, S., Oudrhiri Hassani, F., Abboud, Y., Tanane, O., & El Bouari, A. (2017).
564 The effect of alkali treatment on mechanical, morphological and thermal properties of
565 date palm fibers (DPFs): Study of the interface of DPF–Polyurethane composite. *South
566 African Journal of Chemical Engineering*, 23, 116–123.
567 <https://doi.org/10.1016/j.sajce.2017.04.005>

568 Rabetafika, H. N., Bchir, B., Blecker, C., & Richel, A. (2014). Fractionation of apple by-
569 products as source of new ingredients: Current situation and perspectives. *Trends in
570 Food Science and Technology*, 40(1), 99–114. <https://doi.org/10.1016/j.tifs.2014.08.004>

571 Roy, A., Chakraborty, S., Kundu, S. P., Basak, R. K., Basu Majumder, S., & Adhikari, B.

572 (2012). Improvement in mechanical properties of jute fibres through mild alkali
573 treatment as demonstrated by utilisation of the Weibull distribution model. *Bioresource*
574 *Technology*, 107, 222–228. <https://doi.org/10.1016/j.biortech.2011.11.073>

575 Saadaoui, N., Rouilly, A., Fares, K., & Rigal, L. (2013). Characterization of date palm
576 lignocellulosic by-products and self-bonded composite materials obtained thereof.
577 *Materials and Design*, 50, 302–308. <https://doi.org/10.1016/j.matdes.2013.03.011>

578 Saravanakumar, S. S., Kumaravel, A., Nagarajan, T., & Moorthy, I. G. (2014). Effect of
579 Chemical Treatments on Physicochemical Properties of Prosopis juliflora Fibers.
580 *International Journal of Polymer Analysis and Characterization*, 19(5), 383–390.
581 <https://doi.org/10.1080/1023666X.2014.903585>

582 Saravanakumar, S. S., Kumaravel, A., Nagarajan, T., Sudhakar, P., & Baskaran, R. (2013).
583 Characterization of a novel natural cellulosic fiber from Prosopis juliflora bark.
584 *Carbohydrate Polymers*, 92(2), 1928–1933.
585 <https://doi.org/10.1016/j.carbpol.2012.11.064>

586 Segal, L., Creely, J. J., Martin, A. E., & Conrad, C. M. (1959). An Empirical Method for
587 Estimating the Degree of Crystallinity of Native Cellulose Using the X-Ray
588 Diffractometer. *Textile Research Journal*, 29(10), 786–794.
589 <https://doi.org/10.1177/004051755902901003>

590 Wei, J., & Meyer, C. (2015). Degradation mechanisms of natural fiber in the matrix of
591 cement composites. *Cement and Concrete Research*, 73, 1–16.
592 <https://doi.org/10.1016/j.cemconres.2015.02.019>

593