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Effect of chemical treatments on physico-chemical properties of fibres from banana fruit and bunch stems

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Fibres have been extracted from fruit and bunch stems of banana plant by water retting and evaluated in terms of their performance characteristics. Banana bunch stem fibres have been found to be superior in terms of fineness, initial modulus and breaking strength, whereas elongation ratio shows an inverse trend. Thus, they have been further treated by bleaching and alkalization. Among the treated fibres, the bleached fibres show the highest initial modulus, breaking tenacity, and the lowest elongation. Alkalization results in increased breaking elongation and decreased initial modulus, whiteness and water absorption. The bunch stem fibres present higher water absorptive capacity and lower whiteness compared to that of fruit stem fibres. The characteristics of these unconventional fibres have been found to be comparable to natural fibres traditionally used in textiles. The ranges for properties of the studied banana fruit and bunch stem fibres in general can be given as: linear density 12.71-20.38 tex, initial moduli 168 -326 cN/tex, breaking tenacity 9.89-13.3 cN/tex, breaking elongation 4.42-16.4%, and moisture content 11.6-15.8%.

Keywords: Banana bunch fibre, Banana fruit fibre, Physico-chemical properties

Lignocellulosic fibres, which enjoyed common use until the beginning of industrial era, including but not limited to flax, hemp, jute and sisal, have once again become the subject of research studies since nineties[1-5]. However, sustainability of natural fibre production is under a potential risk, as more and more of agricultural land should be allocated for producing food crops to meet the requirement of growing world population. To solve this issue, residues of agricultural crops grown for food and other purposes can be considered as potential sources of fibres. Moreover, utilization of agricultural residues may have significant benefits for the environment and the agricultural community by preventing incineration on the field and by providing extra value to agricultural crops[6,12]. Accordingly, agricultural residues which have been studied as fibre sources include corn husks, okra stems, wheat straws and banana stems to name a few[6-11].

In the developing world, banana is considered as the fourth most important crop[13]. While 11.6 wt % of the total plant weight is occupied by the fruit[14], 54.3 wt% is fibrous by-product[15]. It is a common practice to leave banana plant stems on the field after cultivation[16]. Fibres may be obtained from different parts of the plant such as the bunch, stem, and leaf. Fibres are traditionally extracted by mechanical means[14]. The obtained fibres are used for pulping, composite production or consumed as fodder[13].

Researchers have tried to diversify the applications of banana fibres by various treatments. Asser *et al.*[16] reported decreased noncellulosic component and moisture content together with increased thermal durability upon sodium hypochlorite (NaClO) bleaching of banana fibres. Ganan *et al.*[14] reported reduction in hydrophillicity due to the alkalization and silanization treatment of banana plant stem and bunch stem fibres. Ganan *et al.*[15] found that the breaking tenacity and initial moduli of the fibres decreased with prolonged biological retting. In addition, the strength and moduli were affected by the location, i.e. the portion of the plant from where the fibre has been extracted[14].

As agricultural residues can be utilized for different purposes[6], it is necessary to know which parts of the banana plant are more suitable as a fibre source, whereas the other parts can be allocated for other practices[17]. Consequently, effects of fibre extraction location, namely the banana fruit and bunch stems, have been investigated in this study. To the best of our knowledge, this is the first study where the banana fruit stem fibres have been investigated. Within this concept, the biologically-extracted fibres have been compared in terms of their physical, mechanical and chemical performance. Based on the findings, the bunch stem fibres have been subjected to further treatments including bleaching and

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Table 1— Effect of fibre location and chemical treatments on the physical properties of banana fibres

Sample	Linear density, tex		Stensby whiteness index		Moisture content, %		Water absorption, g/g	
	μ	σ	μ	σ	μ	σ	μ	σ
Fruit	20.38	0.34	40.4	2.48	14.2	1.6	7.76	0.73
Bunch	13.48	0.89	33.7	2.94	11.6	1.2	12.6	0.71
Bleached	12.71	1.86	33.3	0.66	12.4	1.5	10.2	2.5
Alkalized	15.82	1.22	27.3	1.05	15.8	0.8	7.96	0.88

μ— mean value and σ— standard deviation.

alkalization. The effects of the treatments on fibres properties have also been investigated.

Experimental

Materials

Fruit and bunch stems of banana plant (*Musa sapientum*) were collected from local farmers in Aegean Region of Turkey. Analytical grade chemicals and reagents have been used.

Fibre Extraction and Sample Preparation

The banana fruit and bunch stems were separately immersed in plastic containers filled with tap water. The lid of container was kept close to avoid contact of stems with the air for prevention of darkening. The retting treatment which has been carried out in February – March months lasted for a period as short as 10 days. After the retting, the stems were taken out from the containers and the fibres were separated by hand. The separated fibres were dried under ambient conditions. The bunch stem fibres were further processed by bleaching and alkalization.

The banana bunch stem fibres were bleached with 7 g/L $NaClO_2$ solution buffered at *p*H 4 at 90-95°C for 90 min at a fibre-liquor ratio of 1:50. The fibres were treated with 2 % sodium metabisulphite ($Na_2S_2O_5$) solution to reduce chlorite action for 15 min and then rinsed thoroughly.

The bunch stem fibres were alkalized with 10 g/L NaOH solution at room temperature (22°C) for 3 h at fibre- to- liquor ratio of 1:50. No tension was applied to the fibres during alkalization. The alkalized fibres were then neutralized with diluted acetic acid, washed with distilled water and dried in ambient conditions.

Characterization

Conditioning at 21°C and 65% relative humidity was carried out for fibre samples for at least 24 h prior to characterization processes. Linear density of the fibres was determined according to ASTM D 1577-07. For each sample batch, at least 13 groups of fibres were measured.

Tensile characterization of the fibres was carried out according to ASTM D 3822. At least 20 specimens of each fibre set were measured at a crosshead speed of 15 mm/min and at a gauge length of 2.54 cm with a 10 N load cell using Tinius Olsen H10KT(R) Tester, US with QMat for Textiles(R) software. Whiteness level of the fibres was measured according to Stensby Whiteness Index using a Datacolor spectrophotometer with a D 65/10° observer[18]. Four replications were taken from each sample.

Table 2—Effect of fibre location and chemical treatments on the tensile properties of banana fibres

Sample	Initial modulus cN/tex		Breaking tenacity cN/tex		Elongation %	
	μ	σ	μ	σ	μ	σ
Fruit	182	90.6	10.08	6.43	16.36	8.76
Bunch	266	88.3	13.31	6.51	4.95	1.02
Bleached	326	106.4	13.09	7.12	4.42	1.87
Alkalized	168	63.2	9.89	2.59	11.09	4.01

The moisture content in the fibres was determined according to ASTM D2495 – 07. Three specimens of each sample batch were measured. The fibres were tested for their water absorptive capacity according to EDANA 10.3-99, ISO 9073-6.2000 as explained earlier[17]. The findings of aforementioned characterizations were subjected to analysis of variance with α at 0.05 significance level. The physical and mechanical properties of the fibres are presented in Tables 1 and 2 respectively. The results of the statistical analysis are summarized in Table 3.

Fourier transform infrared spectrometry (FTIR) measurements were recorded with a Perkin Elmer FT-IR Spectrophotometer Spectrum Two, US using attenuated total reflectance (ATR) mode. Scanning electron microscopy (SEM) images of fibres were obtained by using a Zeiss EVO LS 10 scanning electron microscope at 20 kV voltage and ×300 and ×1.5 k magnifications

Results and Discussion

Fibre Linear Density

As shown in Fig. 1, the linear density of banana fruit stem fibre is higher than banana bunch stem fibre. On the other hand, bleaching does not show

Table 3—Statistical analysis of effects of parameters on characteristics of banana fibres

Dependent variable	Independent variable	*p* value
Linear density	Location	2.33×10^{-4}
	Bleaching	0.55
	Alkalization	0.055
Stensby whiteness	Location	4.59×10^{-3}
	Bleaching	0.77
	Alkalization	1.68×10^{-3}
Moisture content	Location	0.08
	Bleaching	0.48
	Alkalization	7.12×10^{-3}
Water absorption	Location	1.25×10^{-3}
	Bleaching	0.19
	Alkalization	2.17×10^{-3}
Initial modulus	Extraction Location	5.11×10^{-3}
	Bleaching	0.047
	Alkalization	2.53×10^{-4}
Breaking tenacity	Extraction Location	0.12
	Bleaching	0.92
	Alkalization	0.035
Breaking elongation	Extraction Location	1.14×10^{-6}
	Bleaching	0.28
	Alkalization	7.56×10^{-8}

significant effect on the linear density (p = 0.55). Contrary to our expectations, there is some evidence that alkalization increases the coarseness of the bunch stem fibre (p=0.055), similar to the finding of De Rosa *et al*.[19] who reported that the diameter of okra bast fibres increases with basic treatments. It was expected that the linear density would be reduced with elimination of extracellulosic substances during alkalization. The increase in coarseness may be attributed to the fact that the treatment might have increased adhesion among fibrils. The attained linear density values that range between 12.71 and 20.38 tex agree well with that of conventional natural fibres (Table 4).

Fibre Mechanical Properties

The tensile properties of the fibres are presented in Fig. 2. The greatest initial modulus value (326.48 cN/tex) is found for the bleached stem bunch fibres and the greatest breaking tenacity (13.31 cN/tex) for the untreated bunch stem fibres, whereas the fruit stem fibres present the highest breaking elongation (16.31%).

The location of fibre extraction significantly affects the initial modulus (p=5.11×10^{-3}). The initial moduli of the bunch stem fibres are greater than fruit stems fibres. Consequently, the ductile behavior of the fruit stem fibres as well as brittleness of the

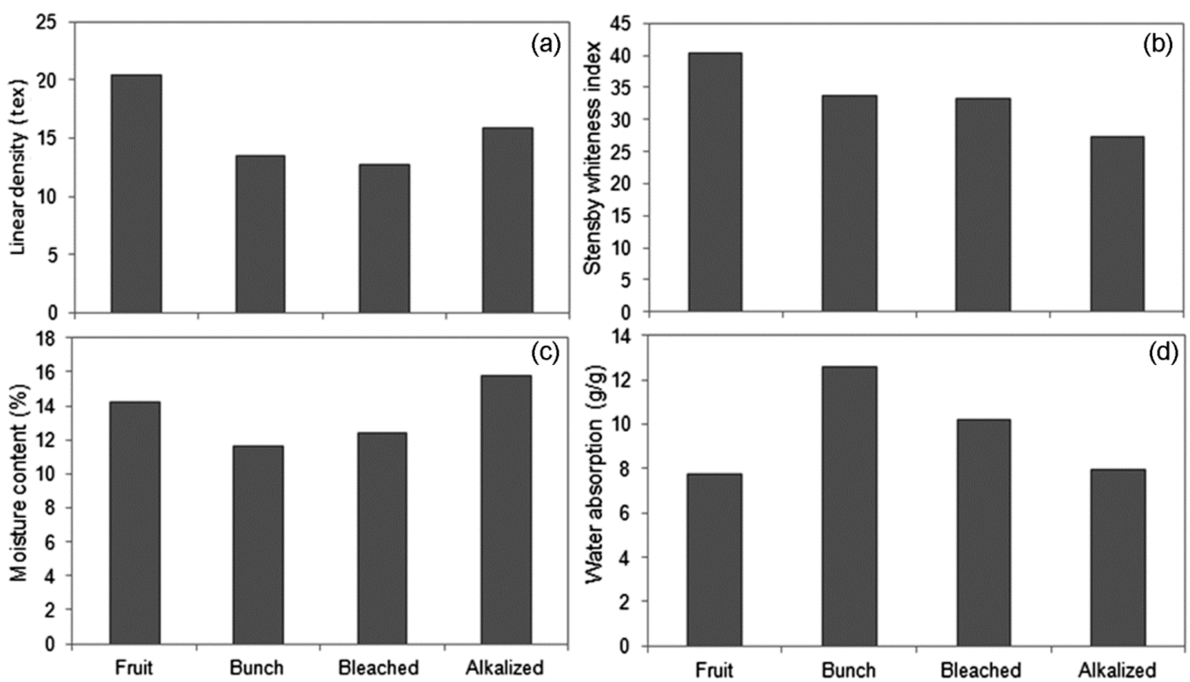

Fig. 1—Effect of fibre location and chemical treatments on (a) linear density, (b) moisture content, (c) whiteness, and (d) water absorption capacity of banana fibres

Table 4—Comparison of untreated banana fruit and bunch stem fibres with traditional textile fibres

Property	Banana		Cotton[25]	Flax[26,27,28]	Hemp[29]	Jute[30]	Agave[31]	Coir[32]
	Fruit	Bunch						
Fineness, tex	20.4	13.5	0.1-0.2	0.2-2	16-43	1.8	24	-
Length[a], cm	3.3	4.5	2-3.7	25-120	106-330	-	65-280	15-20
Tenacity, cN/tex	10.1	13.3	22-30	13-71	11-53	69	16-41	10
Elongation, %	16.4	5.0	8-10	1.5-5	0.9-2.9	1-2	2-4	30
Moisture content, %	14.2	11.6	6-8	7-15	-	-	8-9	10.5

[a]Length feature corresponds to the average maximum length of a technical fibre that can be extracted from a particular plant source.

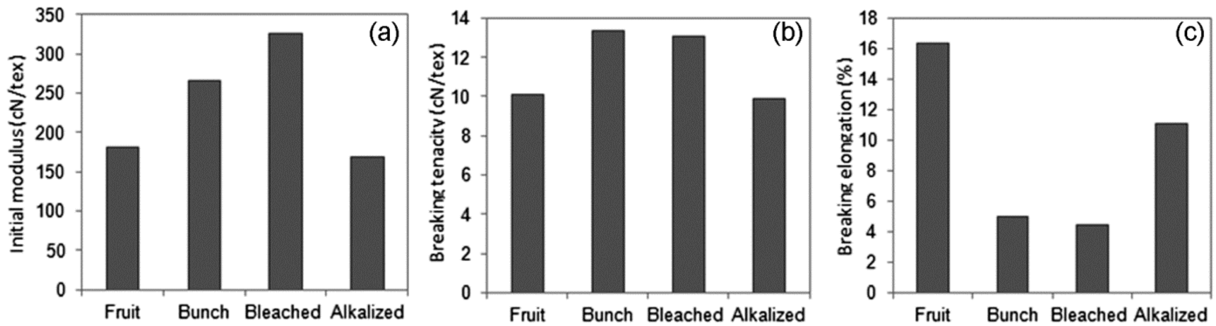

Fig. 2—Effect of fibre location and chemical treatments on (a) initial modulus, (b) breaking tenacity, and (c) breaking elongation rate of banana fibres

bunch stem fibres, can be seen in the stress-strain graphic given in Fig. 3. The increase in initial moduli due to bleaching may be attributed to the elimination of non-load-bearing materials from the lignocellulosic fibre[12]. De Rosa *et al*.[19] also reported increment of tensile properties okra bast fibres upon bleaching treatment. To the contrary, alkalization reduces the initial modulus. The alkalization may have changed the structure of fibre cellulose from cellulose I form into cellulose II form, which has lower chain modulus[20]. Similarly, Yilmaz[12] reported lower stiffness for corn husk fibres extracted by alkalization compared to the ones that were obtained by water retting.

The highest breaking tenacity is reported for raw bunch stem fibres with the average value of 13.31 cN/tex. There is not enough evidence that the location of fibre extraction affects breaking tenacity (p=0.12). The breaking tenacity of the bleached bunch stem fibres is almost the same as raw bunch stem fibres, while the alkali treatment causes reduction in breaking tenacity. De Rosa *et al*.[19] also reported decrease in breaking tenacity of okra fibres upon treatment with alkaline solution.

A huge dissimilarity has been found in breaking elongation for banana fibres extracted from different locations. The fruit stem fibres (16.36%) show much greater elongation at break ratio than the bunch stem fibres (4.95%). The lower initial modulus and higher elongation may suggest that the microfibril angle of the fruit stem fibres is higher than that of bunch stem

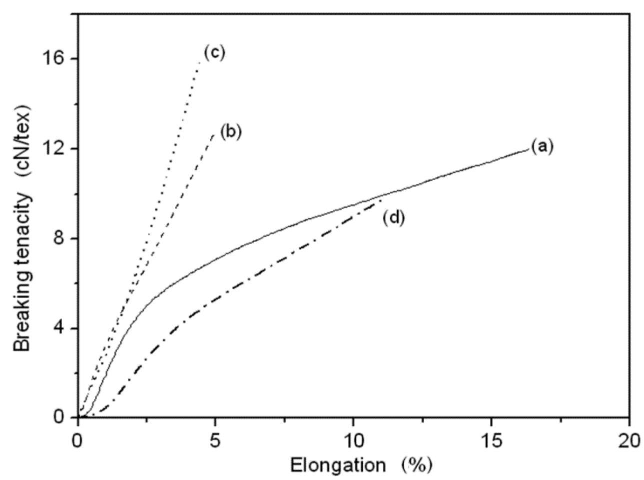

Fig. 3—Stress – strain curves of banana (a) fruit stem fibre, (b) bunch stem fibre, (c) bleached bunch stem fibre and (d) alkali-treated bunch stem fibre

fibres[20]. Alkalization leads to substantial increase in breaking elongation. The increase in elongation due to alkalization may be attributed to the change in the cellulose structure from cellulose I to cellulose II[19,21] and decrease in crystallinity as Mahato[22] found for alkalized coir fibres. On the other hand, no significant effect of bleaching on breaking elongation has been obtained (p=0.28).

On comparing the variability of the tensile properties (Table 2), we observe that the fruit stem fibres always give higher coefficient of variance results compared to untreated or treated bunch fibres. Whereas the fruit stem fibres give coefficient of variation values 50, 64 and 54% for initial modulus, breaking tenacity and elongation respectively, the corresponding average values for the bunch stem fibres are 34, 43 and 33%, in consecutive order.

Spectroscopic Characterization

The FTIR spectra of the banana fibres are investigated. The hydrophilic nature of these fibres is reflected by broadband absorbance peaks at around 3400 cm^{-1}, that are attributed to the axial deformation of the O-H groups[16,23]. This large band is commonly observed in the plant fibres[7,12,23]. The peaks at around 2918 cm^{-1} and 2869 cm^{-1} correspond to C-H stretchings in lignin and waxes respectively [14]. The peaks at around 1730 cm^{-1} and 1640 cm^{-1} are characteristic for the carbonyl band (C=O) of the hemicelluloses[15,23]. The bands at around 1503 cm^{-1} and 1597 cm^{-1} correspond to the aromatic skeletal vibration present in lignin[24]. The bands at around 1470 cm^{-1} are representative for the C-H asymmetric deformation of cellulose and lignin. The bands at around 1430 cm^{-1} stand for C=C aromatic ring of lignin[14]. The absorption bands at around 1420 cm^{-1} are attributed to the symmetric deformation of the CH_2 group of cellulose, while the bands at 1245 cm^{-1} refer to the C–O–C in the cellulose chain[23]. The peaks at 1160 cm^{-1} are due to the anti-symmetrical deformation of C-O-C band in cellulose and hemicellulose[22,23]. The strong absorption peaks around 1040 cm^{-1} are ascribed to the C-O and O-H stretching vibrations which belong to the polysaccharide structure of cellulose[19]. The peaks observed at around 890 cm^{-1} are attributed to the presence of β-glycosidic linkages between the monosaccharides[19].

Although no substantial change has been found between the fruit or bunch stem fibres, the chemical treated fibres show some dissimilarity compared to the raw fibres. The peak close to 1730 cm^{-1} disappears and peak intensity at around 1597 cm^{-1} is decreased upon alkali treatment. This may be due to the removal of hemicelluloses and reduction of lignin content. The peaks of lignin at around 1503 cm^{-1} and 1597 cm^{-1} disappear with the bleaching treatment of bunch stem fibres. The intensity of the broadband absorbance peak at around 3400 cm^{-1} reflects the hydrophilic nature and behaves in the same manner as the water absorptivity (Fig. 1).

Fibre Morphology

The morphology of the banana fibres is presented in Fig. 4 at magnification × 300 and ×1.5k. As seen from the images, the fibre structure is complicated in relation with the hierarchical organization where the fibrils are oriented parallel to the fibre axis. The diameter values of fibrils are in 80 -200 μm range. Fibres are covered with non-cellulosic materials such as lignin and pectin bonding fibrils together. In Fig. 4, the micrographs for the untreated (b), bleached (c), and alkali-treated (d) bunch stem fibres show remarkable change in morphology. The fibre surface has become cleaner by the removal of impurities with bleaching. As a result, surface roughness has increased. On the other hand, the fibril bundle becomes ready to collapse by the alkali treatment following bleaching. This may be due to the removal of incrusting materials as well as deterioration of the fibre cellulose.

Whiteness

Whiteness of fibres is generally a desired feature in textile production. As seen in Fig. 1, the fruit stem fibres show higher whiteness indices compared to bunch stem fibres. Alkalization results in loss of whiteness. Khan *et al*.[9] also reported the decrease in whiteness due to NaOH treatment for okra fibres. Bleaching does not result in a significant change in whiteness index (p=0.77). However, during visual inspection, a decreased grayish color is observed for the bleached fibres compared to untreated bunch stem fibres.

Moisture Content and Water Absorption Capacity

Moisture content of fibres is an undesired feature for technical applications such as composite manufacturing but it is desirable in textile applications[17]. The per cent of moisture content ranges from 11.6 to 15.8 based on the group of banana fibres (Fig. 1). This range is also close to that investigated by Aseer *et al*.[16], who reported a moisture content range of 10.4-12.1%. None but the alkalization increases the moisture content from 11.6 % to 15.8%. Besides, there is not enough evidence that the location of the banana plant or the bleaching treatment has a significant effect (p values 0.08 and 0.48 respectively).

The bunch stem fibres have higher water absorption capacity value than that of fruit stem fibres. The highest water absorption capacity is reported for the untreated bunch stem fibres (12.6 g/g) and the lowest is reported for the fruit stem fibres (7.76 g/g). Bleaching does not have a significant effect on water absorption (p=0.19), whereas

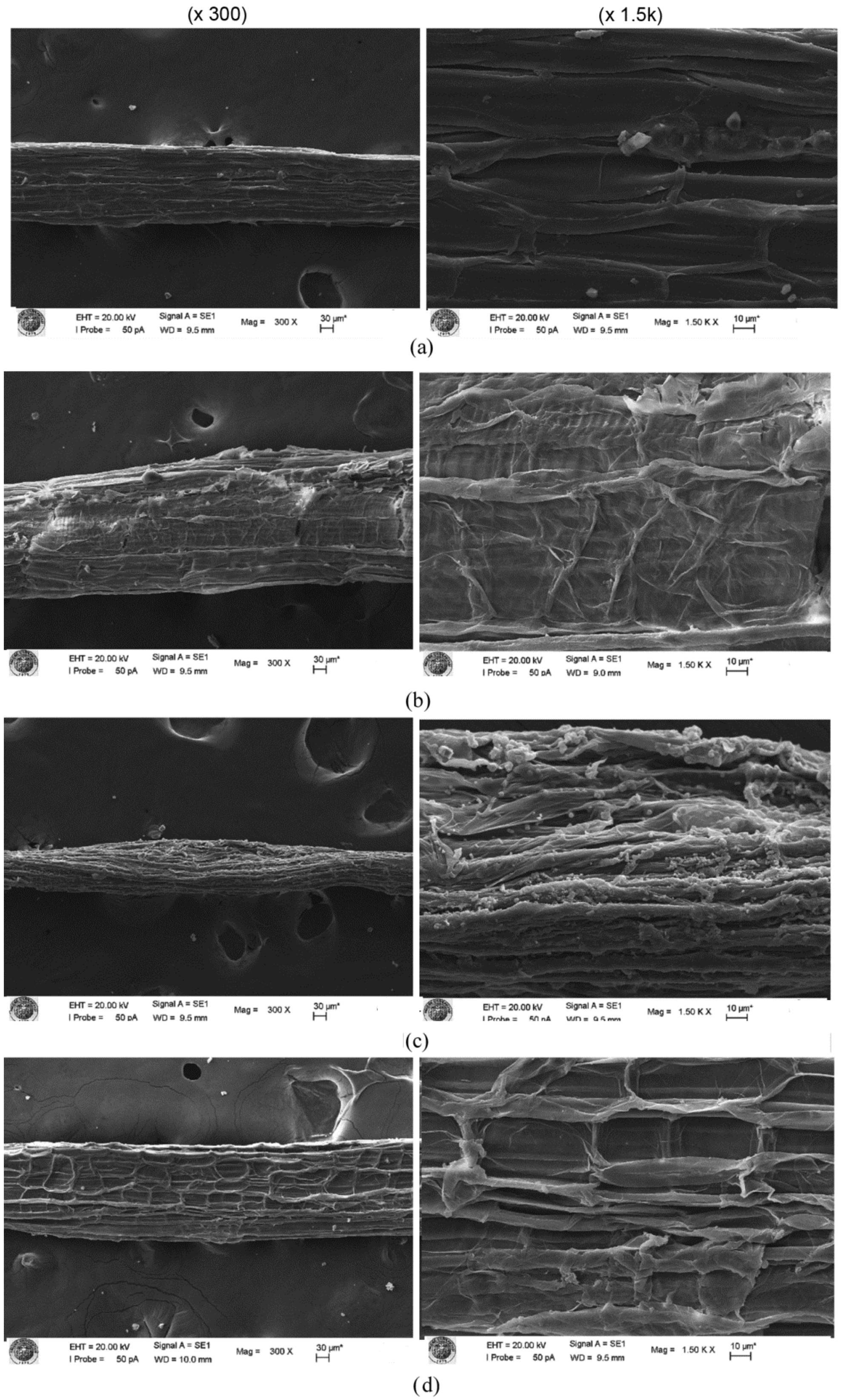

Fig. 4—SEM micrographs of the banana (a) fruit stem fibre, (b) bunch stem fibre, (c) bleached bunch stem fibre, and (d) alkali-treated bunch stem fibre

alkalization significantly decreases the water absorption capacity. Ganan *et al*.[14] reported decreased hydrophillicity of alkalized banana fibres, similarly. The difference between the water absorption of the fruit and bunch stem fibres may be due to the dissimilarity in coarseness. The finer bunch stem fibres might have higher water absorptive capacity due to the more effective capillary action that comes with highest fineness. Yilmaz *et al*.[17] also reported higher water absorption for finer fibres compared to coarser fibres extracted from corn husks.

Comparison with other Traditional Natural Fibres

A comparison of the untreated banana fruit and bunch stem fibres with other bast, leaf and fruit fibres is given in Table 4. Although the characteristics are generally comparable to the body of the other conventional fibres, the tensile tenacity is found to be within the range of that of coir fibres (a member of fruit fibres). It should be noted that, there is a good possibility of further enhancement of the properties of these unconventional fibres by means of different modification techniques.

The bunch stem fibres exhibit better tensile properties, i.e. higher initial modulus (266 cN/tex) and breaking tenacity (13.31 cN/tex) than the fruit stem fibres (182 cN/tex initial modulus and 10.08 cN/tex breaking tenacity); elongation rate shows a reverse trend. This situation suggests higher microfibril angle of fruit stem fibres in comparison with bunch stem fibres. The bunch stem fibres are further treated by bleaching and alkalization. Alkalization results in reduction of initial modulus and breaking tenacity and increase in breaking elongation. This finding proposes change of cellulose morphology into cellulose II from cellulose I. The fruit stem fibre presents higher linear density (20.38 tex) and whiteness than the bunch stem fibre (13.48 tex). Water absorption capacity follows the reverse order probably due to capillary action. Alkalization affects the water absorption adversely. The investigated fibres show performance characteristics comparable to the conventional natural fibres.

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