Separation of fiber bundles from willow bark using sodium bicarbonate and their novel use in yarns for superior UV protection and antibacterial performance

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Separation of fiber bundles from willow bark using sodium bicarbonate and their novel use in yarns for superior UV protection and antibacterial performance

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ABSTRACT

The development of a mild and green method for separating natural fiber bundles from willow bark is an essential step in exploring and preserving their natural functions. The isolation of well-oriented fiber bundles from the bark of a fast-growing willow hybrid solely using sodium bicarbonate under mild conditions was successfully demonstrated. Additionally, Lyocell fibers were mixed with an equal amount of the willow bark fiber bundles and proved their ability to convert into spun yarns, which provided excellent protection for ultraviolet radiation (UPF ≥ 140). Moreover, these yarns demonstrated strong antibacterial activity (A ≥ 8) against the Gram-positive pathogen Staphylococcus aureus, resulting in complete eradication of viable bacteria after 24-h incubation with the material. A laundering treatment had no effect on the UV protection or the antibacterial performance. Utilizing these inherent properties from natural fibers for technical textile applications is very promising.

1. Introduction

The value of tree bark can be significantly upgraded as a potential source of chemicals (Feng et al., 2013) and materials (Chen et al., 2020; Yu et al., 2020; Hobisch et al., 2020). Although studies on its bioactive compounds have been conducted, willow bark (WB), as part of highly productive willow biomass, is prevalently burned for energy use (Mola-Yudedge et al., 2015). Debarking was proposed as a key fractionation step in optimal valorization of willow biomass crops (Dou et al., 2016). The debarked wood can be used for biobutanol production (Han et al., 2013) or as activated carbon for high performance supercapacitor electrodes (Phiri et al., 2019). The WB was shown to be a rich source of biologically active extracts (Dou et al., 2018a, 2021; Ward et al., 2020) and fibrous products such as fiber bundles (FBs) and fibrils (Dou et al., 2019a, b). The bark extract was also found to act as crosslinking reagent for dyeing cellulosic materials (Lohtander et al., 2020).

As known, ultraviolet radiation (UVR) from sunlight can cause cancer and damage eyes seriously. The need for ultraviolet (UV) protective clothing has been growing significantly as skin cancer rates have soared and people are more aware of the dangers of excessive exposure to sun. However, skin cancer could be highly preventable by blocking most of the UVR exposure to the skin through the fabric (Lomas et al., 2012). The ultraviolet protection factor (UPF) of textiles depends mainly on the fiber type (Yu et al., 2015), fabric and yarn construction (Wong et al., 2016), coloration and organic UV absorber additives (Mavric et al., 2018). For example, unbleached naturally pigmented cotton has a higher UPF than bleached cotton (Alebeid and Zhao, 2017). Hollow fibers protect more than conventional circular cross-section man-made fibers. Darker color fabrics like black, blue and dark green protect sunlight better than light colors (Alebeid and Zhao, 2017; Dubrovski and Golob, 2009). UPF of man-made fibers could be increased artificially by introducing small amounts of titanium dioxide (TiO2) nanoparticles as UVR absorbing additives. However, TiO2 should be used with great consideration as TiO2 has been classified as “possible carcinogenic to humans” by the international Agency for Research on Cancer (Windler et al., 2012; Skocaj et al., 2011).

Antimicrobial finishing of the textiles has gained important attention especially for the use of technical protective textile products during the...
recent years. Antimicrobial protection of textiles is required to protect the textile itself and humans to avoid any effect due to growth of fungi and bacteria, which can result in unwanted features, e.g. unpleasant odor, stains, and strength reduction. Moreover, textiles can become the media for spreading pathogenic microorganisms. Therefore, introducing antimicrobial agents for avoiding exposure into any pathogenic environment has gained a great interest from the textile industry (Simoncic and Tomsic, 2010). Grafting antimicrobial agents, such as organic compounds (e.g. chitosan, quaternary ammonium compounds or halogenated phenols) (Simoncic and Tomsic, 2010; Tawiah et al., 2016) or inorganic compounds (e.g. nano-sized silver, gold, copper or zinc oxide) (Dastjerdi and Montazer, 2010) onto fibers can increase the introduced reactive groups for inhibiting the microbial growth on the textile’s surface. Meanwhile it should be stressed here that the release of both inorganic compounds (e.g. nano-sized silver, gold, copper or zinc oxide) (Dastjerdi and Montazer, 2010) or organic compounds (e.g. chitosan, quaternary ammonium compounds or halogenated phenols) (Simoncic and Tomsic, 2010; Tawiah et al., 2016) or inorganic compounds (e.g. nano-sized silver, gold, copper or zinc oxide) (Dastjerdi and Montazer, 2010) onto fibers can increase the introduced reactive groups for inhibiting the microbial growth on the textile’s surface. Meanwhile it should be stressed here that the release of both antibacterial additive compounds and the aforementioned TiO2 nanoparticles could have negative impact to the microbes in our microbiota (Lamas et al., 2020) and environment (Simoncic and Tomsic, 2010).

Surprisingly little has been explored about the inherent UV protection characteristics, like UVR protection and antibacterial functionality, of WB fibers and their antibacterial functions of natural woody based plant fibers depending on the content of their natural, organic UVR absorbing conjugated structures present in the fiber itself.

This study aimed at developing more sustainable and functional materials from bark fibers, in addition to the yarn fiber sources of natural cellulose (cotton, hemp) and regenerated cellulose (viscose, modal). Secondly, it was of great interest to explore whether the inherent characteristics, like UVR protection and antibacterial functionality, of WB fibers are comparable with the effects obtained by the usage of synthetic UV absorbers or antibacterial additives. Thirdly, the retention of the beneficial properties in laundering tests were important to uncover.

2. Material and methods
2.1. Materials and chemicals

All reagents were adopted as received unless described otherwise. Two years old willow (hybrid Klara) stems were harvested from a plantation of Carbons Finland Oy in Southern Finland (Kouvola) on May 2018. Lyocell fibers (Tencel™ 1.3 dtex, 38 mm staple length, without delustering agent, Lenzing AG, Austria) and 40 mm staple length WB FBs were used to prepare the yarns. The reference yarn for antibacterial test was bleached 20 tex cotton yarn (Gebrüder Otto, Germany). Sodium bicarbonate (NaHCO₃), pure cellulose (Whatman), pectin, arabinose, rhamnose, galactose and xylan were supplied from Sigma-Aldrich. UV absorber 2,2’-Dihydroxy-4,4’-dimethoxybenzophenone was ordered from Tokyo chemical industry (TCI).

2.2. Fiber bundle separation

Hot water extraction was applied first for removal of the hot water extracts (HWE) from WB and willow inner bark (WIB) under 80 °C for 20 min (Dou et al., 2018a). The alkaline treatment (liquid-to-bark ratio 8:1, 20 wt% dosage of NaHCO₃) was conducted in a preconditioned water bath at 100 °C for 60 min. Then the FBs were washed consecutively with distilled water, 95 % ethanol and acetone, and finally collected for further yarn spinning process. The diluted spent liquor was dialyzed (> 6 – 8 kDa) and centrifuged before freeze-drying the clear liquid into the lyophilized high molecular weight (HMW) fraction. The experimental flow is visualized at Fig. 1.

2.3. Yarn spinning

Visually coarse, stiff and staple WB FBs were opened by the fiber opening machine (Trash Analyzer code 281C, Mesdan Lab, Mesdan S.p.A, Italy) prior to the yarn spinning. And then the FBs and lyocell fibers were conditioned (20 °C, 65 % RH) overnight to minimize the effect of electrostatic charges during the yarn spinning (Fig. 1). The opened fibers were carded (Carding Machine 337A, Mesdan Lab, Mesdan S.p.A., Italy) through the rollers in order to obtain a thin web of fiber fleece, and then the web was further formed into narrow ropes called ‘sliver’. The carding batch contained 12.5 g WB FB and 12.5 g Lyocell fibers while the reference batch contained 25 g Lyocell fibers. The roving value for the WB/Lyocell blend (720 tex) was smaller than reference Lyocell (858 tex) because the shortest WB FB (ca. 16 % yield loss) dropped during the carding process. The sliver was further elongated using a draw frame (Stiro Roving Lab 3371, Mesdan Lab, Mesdan S.p.A, Italy). The elongated sliver was two-folded, elongated again into a thinner sliver and once more two-folded to ensure as homogenous sliver as possible. The two-folded sliver was elongated and formed into a false-twisted roving. The yarn was spun under a ring spinning machine (Ring Lab 828A, SER. MA.TES srl, Italy). The yarn was twisted in Z-direction at 600 twists/meter. The linear density of yarn was measured from the mass of 10 m skein (n = 3). The measured linear densities were 48 tex for the WB FB/Lyocell blend yarn and 47 tex for Lyocell yarns (tex = g/1000 m).

2.4. Fabric weaving

The yarns were woven into fabrics using the small-scale weaving frame. Twelve warp yarns (vertical yarns) were firstly twined to the frame holders. Then weft yarns (horizontal yarns) were intertwined with warp yarns using a plain weave structure. The weaving continued until reaching the required dimension for covering the sample holder of the ultraviolet–visible spectrophotometer. The average cover factor (0.1-yarns/cm. tex⁻¹) value for all the weaved samples was ca. 28 (Gandhi and
The wash liquor was prepared as 4.0 g/L of AATCC (American Association for Textile Chemists and Colorists) detergent (Dionex ICS-3000, Carbopec pa 20 column, Sunnyvale, CA, USA). The solid-state 13C cross polarization with magic angle spinning nuclear magnetic resonance (CP/MAS NMR) spectroscopy was acquired on a Bruker AVANCE III spectrometer operating at 100.61 MHz. Additionally, the surface lignin content of well-aligned FBs was evaluated with X-ray photoelectron spectroscopy (XPS). The experimental parameters for these methods were similar to those reported earlier (Dou et al., 2019a). The surface lignin content was estimated based on the high-resolution carbon-carbon fitting components at 285 eV, with the help of the in-situ XPS reference data (Johansson et al., 1999, 2004).

2.7. Yarn additives

A Lyocell yarn was treated with a synthetic UV absorber (i.e. 2,2′-dihydroxy-4,4′-dimethoxybenzophenone) and crude WB (hybrid Karin) HWE (Dou et al., 2018a) separately at the chemical concentration of 1.0 g/L in distilled water (liquid-to-yarn ratio 20:1) at 70 °C for 30 min. After the treatment, the samples were rinsed with water and then air-conditioned before further usage. Cotton yarn was treated similarly with the WB HWE.

2.8. UV protective properties

The solar UV protective properties were measured and calculated according to the European standard EN 13758–1:2001 using a Shimadzu UV 2600 spectrophotometer with the integrating sphere (Gambichler et al., 2006). The UV protective properties were determined from the yarn loops and the plain weaved fabrics. The ultraviolet protection factor (UPF) was used to express the protection efficiency, which was classified as low (UPF < 15), good (15 ≤ UPF < 24), very good (24 ≤ UPF < 39) or excellent (UPF ≥ 40) (Gambichler et al., 2006).

2.9. Laundering

The specimens were laundered following the standard ISO 105-C06. The wash liquor was prepared as 4.0 g/L of AATCC (American Association of Textile Chemists and Colorists) detergent WOB (without optical brightener). The specimens were transferred into 150 mL wash liquor that was preconditioned at 40 °C before being further placed into the washing device (Linitest, Original Hanau, Germany). Specimens were removed from the container after 30 min washing, and then rinsed twice for 1 min using 100 mL of 40 °C deionized water. The specimen were air-dried after rinsing until further usage.

2.10. Antibacterial test

The samples prepared for the antibacterial tests included cotton yarn (control reference; before and after laundering), cotton yarn dyed with crude WB HWE, Lyocell yarn (before and after laundering), WB FB/ Lyocell (50 wt% / 50 wt%) yarn (before and after laundering), and silver nanoparticles containing man-made cellulose fibers (Haslinger et al., 2020). The laundered samples were additionally rinsed with deionized water (3 times × 10 min) to assure that there was no residual detergent. Staphylococcus aureus ATCC 29,213, typical control strain in clinical microbiology, was selected as the test strain. The absorption protocol followed the standard ISO 20743:2013. Briefly, the autoclaved yarn samples were inoculated with 200 μL of bacterial suspension with concentration of 1 × 10^5–3 × 10^6 CFU/mL. A pre-wetting step with 500 μL of sterile ultrapure water before inoculating the yarn samples was added to the protocol to ease the absorption of the inoculum. Immediately after inoculation, as well as after 24 h incubation, 20 mL of physiological saline was added onto the samples and the vials were mixed thoroughly. The suspension was serially diluted (1:10) and samples from the saline suspension and dilutions were plated by using the agar pour plate method. The agar plates were incubated at 37 °C for 24 h, and the colonies were counted from plates with 30–300 colonies. The antibacterial activity (A) was calculated using the formula:

\[ A = \lg(C_t) - \lg(C_0) - (\lg(T_t) - \lg(T_0)) = F - G \]

where \( F = (\lg(C_t) - \lg(C_0)) \) is the growth rate on the cotton control, \( \lg(C) \) is the average of common logarithm of the number of bacteria obtained from the cotton specimen after 24 h incubation, \( \lg(C_0) \) is the average of common logarithm of the number of bacteria obtained from the cotton specimen immediately after inoculation, \( G = (\lg(T_t) - \lg(T_0)) \) is the growth rate of the test samples, \( \lg(T) \) is the average of common logarithm of the number of bacteria obtained from the test specimen after 24 h incubation, and \( \lg(T_0) \) is the average of common logarithm of the number of bacteria obtained from the test specimen immediately after inoculation. Three and two independent tests were performed, respectively, for non-washed and washed samples. The antibacterial effect was considered to be significant when \( 2 \leq A < 3 \) and strong when \( A \geq 3 \).

2.11. Tensile test

The breaking force and elongation at break were determined by MTS400 tensile tester (Eden Prairie, MN, USA) equipped with the 50 N load cell at the extension rate of 250 mm/min. The gauge length was 250 mm. The yarns were conditioned overnight at 20 ± 2 °C and 65 ± 2% relative humidity before testing.

3. Results and discussions

3.1. Separation and characteristics of fiber bundles

Hot water extracted (HWE) WB and WB were subjected to sodium bicarbonate (20 wt% dosage) treatment at 100 °C to enable separation of well-aligned FBs. Under these conditions, the FB yield was 46 % and 25 % respectively for HWE WB and WB (Table 1). The morphology of FBs is visualized in Fig. 2. The individual FBs were ca. 100 μm wide although they often formed larger aggregates typical of the original FB organization. Remains of the surrounding cells and starch granules were seen between FBs in the aggregates and on their surfaces (Fig. S1, supporting information). According to X-ray photoelectron spectroscopy.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>FB (fiber bundle)</th>
<th>Parenchyma cell</th>
<th>Outer bark</th>
<th>Rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>WB</td>
<td>0.46</td>
<td>0.19</td>
<td>0.32</td>
<td>0.35</td>
</tr>
<tr>
<td>WB</td>
<td>0.25</td>
<td>0.10</td>
<td>0.32</td>
<td>0.34</td>
</tr>
</tbody>
</table>

1 Determined gravimetrically.
2 Rest: including solubilized pectin, remaining parenchyma cells, ash, solubilized lignin, and others.
3 Willow bark and inner bark were extracted with water for 20 min at 80 °C.
spectroscopy (XPS), 20 % and 25 % of the surfaces (< 10 nm) of WB FB and WIB FB, respectively were covered by lignin (Fig. 3 and Table S1, supporting information). These values are 15–20 % lower than the previously reported lignin surface coverage of WB FB obtained after treatment with NaOH (Dou et al., 2019a). The harsher treatment with NaOH led to more complete separation of individual FBs and cleaner FB surfaces which explains the differences in the surface lignin contents.

The Klason lignin and extractive contents of WB/WIB FBs were significantly lower than those of the original HWE WB/WIB (Fig. S2). Because lignin locates mostly in FBs of WIB (Dou et al., 2016), a significant amount of lignin was solubilized by the mild treatment with NaHCO3. The extractives are mainly located in the parenchyma cells which were mostly separated from FBs during the treatment with NaHCO3. The decrease in the content of monosaccharides characteristic of pectins (i.e. arabinose, rhamnose and galactose) can also be partly connected with the removal of the parenchyma cells. 13C CP/MAS NMR spectroscopy of the lyophilized HMW fractions of the dissolved material verified that parts of the pectins (Sinitsya et al., 1998) were dissolved under the mild alkaline conditions (Fig. 4). The C6 carbon signal of pectic (poly)galacturonic acid (Fig. S3) was shifted downfield from 171.17 ppm (original WB) to 175.67 ppm (Figs. 4 and S4), which indicated that the galacturonic acid groups were demethylated and converted into the carboxylate anion (COO\(^{-}\)) form in the alkaline treatment. The disappearance of the methyl ester (−COOCH3) signal at ~ 53.35 ppm (Fig. 4) confirmed the complete saponification of pectins (Zhu et al., 2014). In all, we speculated that the applied NaHCO3 breaks down the crosslinking (Morris et al., 2012; Munarin et al., 2011) between pectin domains with calcium ions (approx. 130–150 mg/g ash) present at WB (Dou et al., 2019a).

The WB signals at 30–33 ppm, characteristic of suberin (Lopes et al., 2000) in the outer bark, were absent in WIB HMW but present in the corresponding WB HMW fraction suggesting that the suberin was partially saponified and solubilized (Dou et al., 2019a, b). The aromatic carbon signals at 116–154 ppm (Dou et al., 2018b) present both in WB and HMW fractions (Fig. 4) indicated that partial delignification took place under the mild alkaline conditions, thus confirming the results from the Klason lignin analyses (Fig. S2).

3.2. WB FB/ Lyocell (50 wt%/50 wt%) yarn properties

Inspired by their inherent brownish color, WB FBs were further carded with an equal amount of Lyocell fibers to produce functional yarns. The WB FB/Lyocell (50 wt%/50 wt%) yarn had a significantly higher UPF value (160 ± 20) than the reference Lyocell yarn (14 ± 1) despite of differences in the sample construction (Table 2). Additionally, the transmittance of UVA and UVB radiation of the WB FB/Lyocell fabric was as low as 1% (Table 2). The UVR protection ability of the WB FBs possibly originated from the presence of the brownish colorants that were formed during the alkaline treatment of the bark (Figs. S5 and S6).
(Dubrovski and Golob, 2009). Understanding the formation of the brownish color is beyond the scope of this study.

Laundering seemed to have no effect on UPF of the WB FB/ Lyocell fiber (50 wt%/ 50 wt%; plain weave) after one cycle of washing, which demonstrates excellent wash fastness properties. For comparison, the addition of 2,2′-dihydroxy-4,4′-dimethoxybenzophenone (a synthetic UV absorber) or the crude WB HWE improved the UV protection properties of the Lyocell (plain weave) only slightly and this small effect was lost in laundering (Table 2).

To evaluate the antibacterial properties of yarns against Gram-positive pathogen S. aureus we followed the international standard ISO 20,743 and calculated antibacterial activity value (A) after 24-h incubation of samples with bacteria. Untreated cotton yarn was used as a reference, as recommended by the protocol. The obtained results are summarized in Table 3. Ag nanoparticles containing cellulose fibers (with Ag content below ppm range) used as a positive control (Haslinger et al., 2020) demonstrated strong antibacterial activity (A = 3.44). The activity of cotton dyed with WB HWE and Lyocell yarns was insignificant regardless of whether laundering was applied or not, although the Lyocell yarn showed some inhibition of bacterial growth. Interestingly, no bacteria were recovered from the WB FB/Lyocell (50 wt%/ 50 wt%) yarn after 24-h incubation (A = 8.9), demonstrating stronger bactericidal activity than Ag nanoparticles containing cellulose fibers. The laundering procedure seemed to have no effect on the bacterial growth inhibition by WB FB/Lyocell (50 wt%/ 50 wt%) yarn. This activity could possibly be attributed to the residual suberin (Tamm et al., 2016), lignin (Espinoza-Acosta et al., 2016) or chromophores (Tawiah et al., 2016) that are present in WB FBs.

The tenacity with elongation at break results from the WB FB/ Lyocell (50 wt%/ 50 wt%) yarn (11.4 cN/tex with elongation at break 7.5 %) were nearly twice smaller as the reference Lyocell yarn (25 cN/tex with elongation at break 12.2 %), as seen from Fig. S7 and Table 4, which was clearly weakened by the gaps between the FBs and Lyocell

### Table 2

UV transmittance and UPF values of the test fabrics before and after laundering. The numbers in the parentheses are the standard deviation.

<table>
<thead>
<tr>
<th>Fabric type</th>
<th>Fabric construction</th>
<th>UVA Transmittance %</th>
<th>UVB Transmittance %</th>
<th>UPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before laundering</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lyocell</td>
<td>yarn loop</td>
<td>13.1 (2.1)</td>
<td>7.2 (2.2)</td>
<td>12.6 (3.1)</td>
</tr>
<tr>
<td>WB FB/ Lyocell (50 wt%/ 50 wt%)</td>
<td>yarn loop</td>
<td>0.9 (0.1)</td>
<td>0.7 (0.1)</td>
<td>142 (12)</td>
</tr>
<tr>
<td>Lyocell</td>
<td>plain weave</td>
<td>13.2 (1.8)</td>
<td>5.3 (1.7)</td>
<td>15.4 (4.3)</td>
</tr>
<tr>
<td>WB FB / Lyocell (50 wt%/ 50 wt%)</td>
<td>plain weave</td>
<td>1.0 (0.3)</td>
<td>0.6 (0.2)</td>
<td>179 (37)</td>
</tr>
<tr>
<td>Lyocell + uv absorber</td>
<td>plain weave</td>
<td>16.0 (0.9)</td>
<td>9.7 (0.8)</td>
<td>9.1 (0.7)</td>
</tr>
<tr>
<td>Lyocell + wb hwe</td>
<td>plain weave</td>
<td>15.1 (0.3)</td>
<td>7.0 (0.3)</td>
<td>11.5 (0.4)</td>
</tr>
<tr>
<td>Lyocell</td>
<td>plain weave</td>
<td>21.3 (0.8)</td>
<td>12.4 (0.9)</td>
<td>7.0 (0.4)</td>
</tr>
<tr>
<td>WB FB/ Lyocell (50 wt%/ 50 wt%)</td>
<td>plain weave</td>
<td>0.9 (0.2)</td>
<td>0.6 (0.2)</td>
<td>172 (60)</td>
</tr>
<tr>
<td>Lyocell + uv absorber</td>
<td>plain weave</td>
<td>21.0 (0.2)</td>
<td>12.0 (0.2)</td>
<td>7.1 (0.1)</td>
</tr>
<tr>
<td>Lyocell + wb hwe</td>
<td>plain weave</td>
<td>19.0 (0.1)</td>
<td>10.2 (0.2)</td>
<td>8.3 (0.0)</td>
</tr>
<tr>
<td>After laundering</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lyocell</td>
<td></td>
<td>21.3 (0.8)</td>
<td>12.4 (0.9)</td>
<td>7.0 (0.4)</td>
</tr>
<tr>
<td>WB FB/ Lyocell (50 wt%/ 50 wt%)</td>
<td></td>
<td>0.9 (0.2)</td>
<td>0.6 (0.2)</td>
<td>172 (60)</td>
</tr>
<tr>
<td>Lyocell + uv absorber</td>
<td></td>
<td>21.0 (0.2)</td>
<td>12.0 (0.2)</td>
<td>7.1 (0.1)</td>
</tr>
<tr>
<td>Lyocell + wb hwe</td>
<td></td>
<td>19.0 (0.1)</td>
<td>10.2 (0.2)</td>
<td>8.3 (0.0)</td>
</tr>
</tbody>
</table>

### Table 3

Antibacterial activity of different fabrics against Staphylococcus aureus ATCC 29213. The table shows average antibacterial activity value for 3 independent experiments. The numbers in the parentheses represent the standard deviation.

<table>
<thead>
<tr>
<th>Yarn Sample</th>
<th>Antibacterial activity (A)</th>
<th>Antibacterial effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton (reference sample)</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>Cotton (after laundering)</td>
<td>0.18 (0.29)</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Cotton dyed with WB HWE</td>
<td>-0.08 (0.66)</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Ag nanoparticles containing cellulose fibers</td>
<td>3.44 (1.02)</td>
<td>Strong</td>
</tr>
<tr>
<td>Lyocell</td>
<td>0.88 (0.58)</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Lyocell (after laundering)</td>
<td>-0.23 (0.28)</td>
<td>Insignificant</td>
</tr>
<tr>
<td>WB FB/Lyocell (50 wt%/ 50 wt%)</td>
<td>8.90 (0.38)</td>
<td>Strong</td>
</tr>
<tr>
<td>(after laundering)</td>
<td>8.13 (0.74)</td>
<td>Strong</td>
</tr>
</tbody>
</table>

### Table 4

Tensile properties of the Lyocell yarn and WB FB/ Lyocell (50 wt%/ 50 wt%) yarn. The numbers in the parentheses are the standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>Lyocell (100 wt %)</th>
<th>WB FB/ Lyocell (50 wt%/50 wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breaking force (cN)</td>
<td>1324 (63)</td>
<td>542 (55)</td>
</tr>
<tr>
<td>Elongation at break (%)</td>
<td>12.2 (9.0)</td>
<td>7.5 (9.0)</td>
</tr>
<tr>
<td>Breaking tenacity (cN/ tex)</td>
<td>24.9 (1.2)</td>
<td>11.4 (1.2)</td>
</tr>
</tbody>
</table>

1. The specimens were taken directly from the bobbin before the measurement.
2. The breaking tenacity was calculated by dividing the peak force with the linear density of the yarn in tex.
fiber also visualized at Figs. 2 and S1. Although the mechanical strength of the FB yarn decreased compared with the Lyocell yarn, it was still higher than the betel nut husk fiber/cotton blend yarn (7.1 cN/tex with elongation at break 6.8 %) (Begum et al., 2019). This yarn was made by blending coarse fibers with finer fibers as in our study.

4. Conclusions

In summary, our study demonstrates that well-aligned fiber bundles can be easily isolated from willow bark with a hot (≤ 100 °C) sodium bicarbonate treatment. The process may provide a feasible research approach to be extended to other fast-growing tree species, like poplar and eucalyptus. Moreover, the addition of 50 wt% willow bark fiber bundles to man-made cellulose fibers can bring extra functionality to fabric for significantly enhancing its UV protection and antibacterial performance, which also exhibit excellent wash fastness. To be industrially viable, the proportion of the introduced willow bark fiber bundles should be minimized, and the extent to which we can preserve the overall functionalities is important to investigate. Further efforts are still required to conduct several subsequent laundering tests to verify the long-term durability of the UV protection and antimicrobial activity caused by WB FB. Overall, our study demonstrates that utilizing the natural functional fibers have chalke the promise in reducing the dependence on synthetic UV absorbing agents and antibacterial substances in functional textiles (e.g. wound dressing or UV protection clothing). Additional measures will be needed to control the coarseness of the FB and the tenacity of the yarns.

CRediT authorship contribution statement

Zinje Dou: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing - original draft, Supervision.

Marja Rissanen: Validation, Formal analysis, Investigation, Resources, Writing - review & editing.

Polina Ilina: Validation, Formal analysis, Investigation, Writing - review & editing.

Heidi Makkyla: Validation, Formal analysis, Investigation, Writing - review & editing.

Paivi Tamela: Resources, Project administration, Writing - review & editing.

Simone Haslinger: Resources, Tapani Vuorinen: Conceptualization, Methodology, Resources, Project administration, Supervision, Writing - review & editing.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.indcrop.2021.113387.

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Appendix A. Supplementary data

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