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State-of-the-art luminescent materials based on wood veneer with superior strength, transparency, and water resistance



Ming Wang ^{a,b}, Hongchen Liu ^{a,c,*}, Xiao Feng ^a, Xijun Wang ^a, Kaiyuan Shen ^a, Haisong Qi ^{a,*}, Orlando J. Rojas ^{b,d,*}

^a State Key Laboratory of Pulp and Paper Engineering, South China University of Technology, Guangzhou 510641, China

^b Bioproducts Institute, Department of Chemical and Biological Engineering, Department of Chemistry and Department of Wood Science, University of British Columbia,

2360, East Mall, Vancouver, BC V6T 1Z3, Canada

^c College of Textiles, Zhongyuan University of Technology, Zhengzhou 450007, China

^d Department of Bioproducts and Biosystems, School of Chemical Engineering, Aalto University, P.O. Box 16300, FIN-00076 Aalto, Espoo, Finland

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ABSTRACT

Current energy and luminescent materials utilize polymers to encapsulate fluorescent carbon nanodots and dyes but they usually lack stability and biodegradability. Here, we introduce an alternative wood nanotechnology to produce luminescent films (veneer) with UV resistance and tailorable surface energy. First, fluorescent and transparent wood (FTW) is shown as a support of aggregation-induced fluorescent emission (AIE) by *in-situ* Hantzsch reaction of acetoacetate delignified wood (AA-DW). Highly aligned cellulose nanofibers present in AA-DW facilitate FTW densification, ensuing exceptional mechanical performance (tensile strength and Young's modulus of up to 422 MPa and 45 GPa, respectively). Simultaneously, the conjugated structures display high transparency (83 %), haze (80 %) and optical anisotropy. The new luminescent system is demonstrated to be biodegradable and effective in optical (fluorescent) windows as well as encrypted films.

1. Introduction

Fluorescent films and light-responsive smart materials find applications in cutting-edge security printing, fluorescent sensing, biological imaging, and optoelectronics, among others [1-4]. So far, a variety of composite fluorescent films have been developed by physical coblending organic fluorescent dyes, such as fluorescein, rhodamine, methyl coumarin, pyrene, Alexa Fluor and quinolone [5,6]. The performance of conventional organic luminescence depends on π - π stacking interactions and intermolecular charge transfer in the aggregated state, which also limit their use due to quenching [7]. Moreover, aggregationcaused quenching effect (ACQ) greatly prevents the application of fluorophores and their derivatives in luminophores and related devices [8]. In contrast, aggregation-induced emission (AIE) fluorophores, characterized by strongly twisted conformations, do not emit when the molecule is solvated but show strong fluorescence in the aggregated state [9,10]. Driven by the fascinating application prospects of AIE, efforts in the past decade have been directed to develop new fluorescent materials. In parallel, biobased products are being proposed considering their cost, biosafety and sustainability prospects.

As a renewable biomass resource, the development of wood technologies is in line with the general trend of carbon neutrality and sustainable development [11]. Recently, fibrillated cellulose extracted from wood has been widely used in fluorescent films [12-14]; unfortunately, the associated processes often damage the original cellulosic structures. Hence, top-down, direct engineering of delignified wood (DW) has been proposed to preserve the layered and aligned structure of the plant cell walls [15-18]. Based on this approach, fluorescent optical wood has been attempted by compounding fluorescent carbon dots (CDs) and nondegradable polymers [11,19–23]. Such method, however, entails noncovalent interactions that tend to cause interfacial detachment and compromises the safety of the composites [24]. Moreover, synthetic polymers and CDs offset the intrinsic sustainability of wood, and present technical and economic obstacles as far as recycling. Altogether, the original purpose of developing green, all-biobased products has only been effective to a limited extent [25,26].

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^{*} Corresponding authors at: State Key Laboratory of Pulp and Paper Engineering, South China University of Technology, Guangzhou 510641, China (H. Liu). Bioproducts Institute, Department of Chemical and Biological Engineering, Department of Chemistry and Department of Wood Science, University of British Columbia, 2360, East Mall, Vancouver, BC V6T 123, Canada (O.J. Rojas).

E-mail addresses: liuhongchen.beyond@163.com (H. Liu), qihs@scut.edu.cn (H. Qi), orlando.rojas@ubc.ca (O.J. Rojas).

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To overcome some of the challenges described above, a suitable alternative is chemical modification of delignified wood (DW) with its tightly packed cellulose molecular chains as support for AIE. For this purpose, the Hantzsch reaction has been reported to produce fluorescent 1,4-dihydropyridine (DHP) rings in the presence of amine, β -diketone, and aldehydes [24]. Conveniently, the effective conversion to endow solid-state AIE properties can be conducted at room temperature.

Herein, we report on the synthesis of wood-based films that are transparent, fluorescent, hydrophobic, and UV-resistant by combining the principles of wood nanotechnology and AIE. Rotary cut wood veneers were used for efficient delignification and chemical treatment, with the added benefits of scalability and high-throughput nanomanufacturing. The delignification process was adjusted to obtain a nanostructured material that preserved wood's natural architecture. AIE-active functionalized DHP chromophores were immobilized in the DW *via* Hantzsch reaction under mild conditions. Subsequent densification led to the collapse of the cell walls, forming highly aligned cellulose nanofibers. The latter imparted the fluorescent films with high mechanical strength, transparency, haze and anisotropic light scattering, shown here as a new wood nanotechnology to support AIE.

2. Results and discussion

2.1. Fabrication of fluorescent/transparent wood films (FTW)

We applied a top-down strategy to fabricate fluorescent/transparent wood (FTW) films with AIE-active groups. This entailed the use of wood veneer subjected to partial lignin/hemicellulose removal following a two-step *in-situ* chemical modification, room temperature compression and drying (Fig. 1). We note that the S2 layer of the fiber cell walls represent the largest component (>80 %) and contains microfibers with the lowest angle with respect to the fiber axis, which has a significant impact on the macroscopic properties of wood [27]. Hemicelluloses are present in the S2 layer, enveloping the microfibrils, leading to an increased microfibril spacing, which is detrimental to the stiffness and optical quality of DW [28].

Delignification produced an off-white cellulose-rich system that preserved the structural integrity of the original wood. The next step involved *in-situ* chemical modification where the wood surface was esterified, producing cellulose acetoacetate, which created sites for the subsequent Hantzsch reaction. The latter is effective in the presence of β -ketoesters, aldehyde, and ammonia and occurs rapidly at room temperature [29]. 1,4-dihydropyridine (DHP) derivatives, known for their excellent aggregation-induced emission (AIE), [30] were considered in this study The type of aldehyde is tailorable, for instance by choosing different carbon chain lengths (for example, formaldehyde (FA) and dodecyl aldehyde (DA)). Hence, FA and DA were introduced to prepare FA-FTW and DA-FTW films. The compression and drying processes enhanced the hydrogen bonding interlocking and bonding between adjacent fibrils and formed coherent materials with uniform refractive index. By contrast to previously reported systems that rely solely on simple hydrogen bonding [31], the grafted DHP fluorescent groups helped to further cross-link cellulose molecular layers. As shown in Fig. 1b, FTW films showed high transparency and strong AIE fluorescence under visible and UV light.

2.2. Hantzsch reaction

We used ATR-FTIR, ¹³C solid-state NMR and XPS to investigate the chemical changes that occurred in DW and FTW films. During delignification and subsequent NaOH treatment, the hydroxyl groups on the cellulose surface were activated and esterified with tert-butyl acetoacetate. The ATR-FTIR spectra of DW and AADW films (Fig. 2a) confirmed the esterification of cellulose hydroxyl groups (see new peaks at 1705 and 1744 cm^{-1} , assigned to the C=O stretching vibrations of acetoacetyl groups) [32]. Fig. S1 shows a decrease in the intensity of the acetoacetyl groups peak as a result of their conversion to the DHP ring after the Hantzsch reaction. ¹³C solid-state NMR showed the typical cellulose molecular peaks located between 60 and 105 ppm (Fig. 2b) [32]. The carbon signals of acetoacetate esterified cellulose were observed at 202.5 ppm, 166.8 ppm, 48.3 ppm, and 28.9 ppm, corresponding to the keto carbonyl, acetoacetate ester, methylene and methyl moieties in the acetoacetate (C-9, C-7, C-8, C-10, respectively) [33]. The aldehyde carbon signals in the DHP ring were also confirmed.

Compared to the XPS spectra of DW and AADW films, those of FA-FTW included a new peak at 396 eV, which is attributed to the N 1s corresponding to the DHP ring (Fig. 2c). The deconvolution of the N 1s peak of FA-FTW indicated two peaks, N—H (395.6 eV) and R-NH-R (396.1 eV) (Fig. 2d). Also, the fine spectra of C elements with C=O, C—N and C—O bonds appeared in the spectra of FA-FTW, indicating the



Fig. 1. a) Schematic illustration of the synthesis of fluorescent/transparent films from wood veneer. b) Digital photographs of fluorescent/transparent (top) and transparent (bottom) wood films (FTW and TW, respectively) observed under sunlight (left) and under UV light (right).



Fig. 2. a) FT-ATR spectra of DW and AADW. b) ¹³C solid NMR spectra of DW, AADW and DA-FTW. c) Survey XPS spectra of DW and FTW, high-resolution spectra of d) N 1s, e) O 1s and f) C 1s.

presence of the DHP ring structure (Fig. 2e, f). Finally, images from energy dispersive spectroscopy (EDS) of films after the two-step modification showed a uniform distribution of C, N, and O, further indicating that the DHP structure was uniformly anchored on the surface of cellulose (Fig. S2).

2.3. Structure of FTW films

After removal of lignin and hemicelluloses, wood becomes weak, with well-defined channels, preserved from the original sample (Fig. 3a). A considerable number of microscopic pores were created at the corners of the cell walls. Meanwhile, the porous structure of wood was extended (pine, basswood, Figs. 3b, S3). The removal of polymers from the cell wall enhances the coherence of the material, with a single



Fig. 3. a, b) SEM images of DW (pine wood) in the cross-section to show aligned cell walls. c) SEM cross-section image of FA-FTW after compression. d) SEM image of DW tubular lumen. e) Cellulose fibrils are highly aligned along the fiber growth direction (white arrows). f) Flat surface of FA-FTW. Tight stacking of fiber bundles and evidence of a well retained orientation. g) 2D WAXS scattering diffractogram of FA-FTW. h) Radial integration. i) Azimuthal angle distribution of the (200) scattering plane.

light refractive index, and contributes to hydrogen bonding between cellulose upon compression. The FTW films were obtained by densification and drying at room temperature and the cross-section SEM images of FTW showed that the pore skeleton of the cell walls collapsed and stacked densely, forming an almost continuous cellulose matrix (Figs. 3c, S3). The chemical modification process produced negligible damage to the crystalline regions of cellulose, demonstrating the preservation of the structure (Fig. S4).

"Brush-like" cellulose fibrils (CNF) were observed on the surface of the stripped lumina cell wall, which were highly aligned along the fiber growth direction (Fig. 3d, e). SEM images of the surface of FTW showed it as a flat, anisotropic structure (Fig. 3f). The delignification process contributed to wood fiber shrinkage during drying. The cell walls collapsed during compression while maintaining the original fibril alignment in the cell wall, as shown by 2D wide-angle X-ray diffraction (WAXS) of the FTW films (Fig. 3g). The reflections of the cellulose crystalline planes (200) and (110) corresponded to symmetrical crescent-like arc patterns, indicating the fibril alignment. The slight variation in the (110) cellulose crystalline plane is likely the result of the small amount of Teflon particles that became attached upon compression. Cellulose I crystal (200) reflection was shown by the azimuthal change of the scattering peak at 1.56 A⁻¹ (Fig. 3h). The (200) plane is parallel to the fibrils and its scattering patterns extracted from the azimuths showed a narrow distribution, confirming that the fibrils were highly oriented in the FTW film (Fig. 3i). There were two full circular patterns in the diffractograms, in the direction of the wood duct, suggesting isotropy in that direction and further indicating well-aligned cellulose fibrils (Fig. S5).

2.4. Optical, mechanical and wetting properties of FTW films

The color-emitting group in lignin (conjugated polyphenylene ring) was mainly responsible for the brown color and light absorption of natural wood, Fig. S6. To achieve transparency, in addition to delignification, the wood pores need to be removed or reduced to the nanoscale. Room temperature compression was used to avoid re-deposition of the lignin chromogenic groups during hot pressing. After compression, the porous structure of wood collapsed and the cellulose fibrils became aligned, which greatly reduced light refraction and scattering. Meanwhile, the initially rough surface of wood was flattened, reducing light losses due to diffuse reflection by the surface. Hence, wood acted like a thin fibrillated cellulose film, as a continuous matrix, allowing light to be transmitted, with little losses. What distinguishes the compressed TW, FA-FTW and DA-FTW from natural wood is their high transparency. As an example, a given text placed underneath TW and FTW films was clearly visible (DA-FTW films presented a transparent yellowish color), Figs. S6, 4a.

The UV–vis spectra indicated that light was transmitted through FTW films, over 83 % (~60 μ m thickness) in the visible range (Fig. 4b). Similar transmittance was obtained in the FA-FTW and DA-FTW films, indicating that the surface modification did not affect the transparency of the system. The air phase (pores) was removed during densification, leading to lower light scattering. Together with the smaller thickness and reduced refraction from air, a higher FTW transparency was determined (Fig. S7, Table S1). It is worth noting that transparent wood absorbed almost all of light in the UV region. This is related to the conjugated DHP structure introduced in wood, which absorbs UV energy



Fig. 4. a) Optical photograph of FA-FTW films. The FA-FTW film was placed 1 cm above a printed text (right). b) Light transmittance of TW, FA-FTW and DA-FTW films in the range of 200–800 nm. c) The conjugated structure of the DHP ring leads to UV-blocking properties. d) Haze and light scattering from direct light through a FA-FTW film. e) FA-FTW films used the windows of a model house to illustrate optical anisotropy, depending in the "window" tilting angle with respect to the illumination. f) Static water contact angle of natural wood (NW), TW, FA-FTW and DA-FTW films. g) Photographs of a FA-FTW film knotted, twisted, bent and rolled. h) A 3.5-kg load is supported by a FA-FTW film, showing tear resistance perpendicular to the fiber growth direction. i) Stress–strain curves of wood films in the fiber growth direction. j) Specific strength and specific Young's modulus of different materials compared to FA-FTW films.

and dissipates it in the form of visible light emission (Fig. 4c). Lignin is also UV resistant, but it is not transparent. Hence, in retrospect, the FTW film was designed to remove lignin and introduce a transparent "ligninlike filler". This material, which combines transparency and UV resistance, holds promise for a wide range of applications, *e.g.*, food packaging, sun protection, wearables, *etc*.

FA-FTW film placed 1-cm above a print pattern showed a blurred image indicating a high haze. The haze level (\approx 80 %) was tested by using the integrating sphere (Fig. 4d). A 532-nm single-mode laser light source was seen to form a spot that resembled a narrow ellipse as it passed through the FA-FTW film. The scattered light was normally distributed in the x- and y- directions (Fig. 4d inset). The long-axis direction of the scattered light spot was perpendicular to the fiber growth direction of the film. The observed optical anisotropy inspired us to design a conceptual window based on FA-FTW for interior lighting. Illumination of the entire room was possible when a light source was directed to the window, due to the scattering of light by FA-FTW (Fig. 4e).

The addition of AIE-active groups enhanced the hydrophobicity of the wood surface. Compared to the natural wood film (WCA = 17°), the water contact angle of FA-FTW and DA-FTW films were 96° and 118° , respectively (Fig. 4f). Both FTW films exhibited good hydrophobicity and water resistance. This is mainly due to the introduction of hydrophobic long carbon chains.

The FTW film showed a high degree of flexibility: it withstood various types of deformations, such as knotting, twisting, bending and rolling, without any visible cracks or damage. Moreover, the FTW film withstood large bending angles, even parallel to the fiber growth direction (Fig. 4g). The FTW films (4-mm wide) resisted a 3.5-Kg load and showed outstanding tear resistance in the direction perpendicular to fiber growth (Fig. 4h).

The compressed wood samples presented a significantly higher breaking strength compared to the original wood (Fig. 4i), with the FA-FTW films showing a tensile strength of 422 MPa and an elastic modulus of 45 GPa. The tensile strength of wood was significantly enhanced with the FTW compression ratio (Table S1). The compressed wood also exhibited remarkably higher fracture strength, even in the direction perpendicular to fiber growth (note the tensile strength of TW, AATW, FA-FTW and DA-FTW of 38.5, 34.7, 26.7 and 21.1 MPa, respectively, Fig. S8). When compared to TW films, FTW films exhibited a modest drop in both breaking strength and tensile strain in both directions. The elastic modulus and toughness of the produced films were similar (Fig. 4j). The observations indicate that hydrogen bonds between cellulose molecular chains were reduced by the addition of alkyl groups (hydrophobic chains). Nevertheless, when density is taken into account, the specific strength and modulus of FA-FTW films were much higher than those of most metallic alloys (steel, aluminum alloys, magnesium alloys, titanium alloys) [34-36], engineering plastics (polycarbonate (PC), polyamide (nylon), polyphenylene sulfide (PPS)) [37], pressed paper [38] or nanocellulose films [39-41]. The results highlight the potential to replace petroleum-based polymers or engineered materials in applications, such as those relevant to packaging and automotive materials.

2.5. Fluorescent wood

The DHP derivatives were used here to construct solid-state AIE active molecules since they induce distorted molecular conformations by introducing various substituents on the nitrogen atom. The appearance of TW and FA-FTW films under visible light was not noticeably different. The FTW films, on the other hand, fluoresced (bright blue) under UV light (365 nm), whereas the TW films showed no significant change (Fig. 5a). The fluorescence contrast became more apparent when the FTW and TW films were overlapped or soaked in water (Fig. S9). The fluorescence spectra revealed that the fluorescent films' maximum excitation wavelength was in the range of 350 to 400 nm, with a broader

emission spectrum in the range of 450 to 550 nm (Fig. S10). This means that the DHP rings on FTW films absorbed light energy in the UV region and dissipated energy in the form of fluorescence emission in the visible region. The AIE fluorescence of FTW can be tuned by adjusting the acetoacetate and Hantzsch reaction time (Fig. S10, S11). A vibrant blue hue was visible using the FTW films, even after prolonged immersion in common solvents such as water, ethanol, acetone, hexane, DMF, dimethyl sulfoxide (DMSO), and tetrahydrofuran (THF) (Fig. 5b). The results confirmed the solvent resistance of DHP. In addition, the fluorescence effect was very stable: FTW showed high fluorescence emission intensity for at least 3 months (Fig. S12).

We note that a general strategy toward fluorescent and transparent wood involves polymer encapsulation with fluorescent carbon dots [23,42–44]; however, the environmental friendliness of such composites is a topic of concern. Being fully derived from wood, FTW films can biodegrade naturally, at the end of their life cycle, with no negative environmental consequences (Fig. 5c). FTW as well as PET films (used as reference), were buried in moist humus soil to test their biodegrad-ability. FTW was completely biodegraded in soil after 60 days.

Compared to recently reported fluorescent and transparent films [1,23,42,43,45], our FTW achieved higher mechanical strength, transparency, optical anisotropy, UV-blocking, biodegradability, and hydrophobicity (Fig. 5d, Table S2).

FA-FTW films were implemented as a proof-of-concept window (using a model house), where a confined space was observable under UV light, with windows emitting intense fluorescence. The dark environment, where only the windows show strong fluorescence, demonstrate the possibility of decorative and multifunctional fluorescent wood (Fig. 5e). Taking advantage that the ester bond of the DHP ring tends to break under alkaline conditions, we performed a demonstration where fluorescence was triggered with a NaOH(aq) ink. The letters "UBC" were written on a FA-FTW film using the ink, Fig. 5f. Under visible light, the FA-FTW film showed no change but the written content became visible once exposed to UV light (Fig. 5g), indicating the possibility of fluorescent films for anti-counterfeiting and encryption applications. FTW and TW are being tested as contact layers in triboelectric nanogenerators and smart packaging materials, furthering the prospects of the proposed systems.

3. Conclusions

We presented a generic approach to synthesize multifunctional wood films following in situ chemical functionalization. Wood veneer was shown as substrate for the rapid formation (within 5 min) of different AIE-active groups, exhibiting great stability. The introduction of aldehydes of given carbon chain lengths, following the Hantzsch reaction, resulted in films with increased hydrophobicity while simultaneously maintaining fluorescence and transparency. With the additional advantage of a strong conjugation, AIE-active groups endowed FTW films with near full UV-blocking capability. Meanwhile, the delignification adjusted the nanostructure of the material and subsequent densification, leading to a complete collapse of the cell walls and the formation of highly aligned cellulose fibrils. The resultant films were demonstrated for their superior mechanical strength, transparency, haze, anisotropic light scattering and biodegradability. Such remarkable combination of properties augurs many prospects in the construction of materials for UV protection, encryption and luminescence.

4. Experimental

4.1. Materials

Wood films or veneer (basswood and pine, $200 \ \mu m$ in thickness) were obtained by using a rotary cutter and used as as precursor material. The veneer can be conveniently produced in continuous processes and easily delignified and modified by infiltration. Sodium chlorite, acetic acid,



Fig. 5. a) FA-FTW and TW films of given shapes were placed under visible (top) and 365-nm UV (bottom) light irradiation. b) FA-FTW and TW films exposed to different solvents for more than a week. c) Biodegradability of FTW films in moist decomposing soil with PET used as a reference. d) Performance comparison of FTW films and other fluorescent transparent films. e) Photographs of FA-FTW films used as conceptual windows under sunlight (I), strong UV light (II) and weak UV light (III), respectively. f) Mechanism of FTW-based encrypted letters. g) Photographs of encrypted letters under visible and UV light.

sodium hydroxide (NaOH), *tert*-butyl acetoacetate (*t*-BAA), ammonium acetate, *N*,*N*-dimethylformamide (DMF), formaldehyde (FA), and dodecyl aldehyde (DA), were all purchased from Sigma-Aldrich, Canada.

4.2. Preparation of delignified wood (DW) and acetoacetate DW (AADW)

The wood films were treated with aqueous sodium chlorite solution (2 wt%) at pH 4.6 (controlled by acetic acid). This delignifying system was applied at 80 °C for 3 h and the process repeated three times [46]. The produced wood films were soaked in 1 M (NaOH) solution to further remove lignin and hemicelluloses. The obtained delignified wood (DW) films were further modified by immersion (2 h in nitrogen atmosphere) in DMF containing *t*-BAA (mass ratio of 8:1 with respect to wood) at 120 °C, leading to acetoacetate DW (AADW). All the samples were washed with ethanol and water before the further modification.

4.3. Transparent wood (TW), formaldehyde-fluorescent/transparent wood (FA-FTW) and dodecyl aldehyde fluorescent/transparent wood (DA-FTW)

Acetoacetate DW (AADW) was subjected to the Hantzsch reaction system (ammonium acetate and aldehyde, molar ratio 1:1) for 1 h at 30 $^{\circ}$ C. Formaldehyde (FA) was introduced separately in the reaction to obtain FA-fluorescent DW (FA-FDW).

Transparent wood (TW) was obtained by compressing and drying DW and FA-FDW at room temperature. Briefly, DW, FA-FDW samples were sandwiched between hydrophilic PTFE membranes using two iron plates. A fast-action bar clamp was used to apply pressure (0.8–1 MPa, 24 h). The transparent wood (TW) and formaldehyde-fluorescent/ transparent wood (FA-FTW) were obtained by peeling from the PTFE membrane. Dodecyl aldehyde (DA) was used instead of formaldehyde to make DA-FTW. To protect the wood structure during the stirring procedure, AADW was compressed first to improve its mechanical strength, before Hantzsch reaction.

4.4. Characterization

Attenuated total internal reflectance Fourier transform infrared (ATR-FTIR) spectra, X-ray diffractometry (XRD) and X-ray photoelectron spectroscopy (XPS) were applied to the wood samples by using a Bruker Vertex 33 spectrometer, Thermo Scientific Nexsa and Rigaku Ultima IV, respectively. ¹³C solid nuclear magnetic resonance (NMR) spectra (600 MHz) were acquired with a Bruker Wide Bore Solid-State AV400 using ground wood samples. Scanning electron microscopy (SEM) images were recorded on a MERLIN SEM instrument of ZEISS. For the observation of wood cross-sections, a triple ion beam cutter was used to obtain a flat surface, with a particle beam energy of 5 keV and operating time of 2 h. 2D wide-angle X-ray diffractometry (2D WASX) measurements of FTW films were carried out by using an X-ray diffraction system (Rigaku, HomeLab) with X-axis angle f 5-45° ad beam direction perpendicular to the film surface and wood tube cavity. The optical characteristics of the films were examined by using a Shimadzu UV-2600 spectrophotometer with a integrating sphere. The static contact angle of the surface was tested by using Theta Flex 300-Pulsating Drop 200 Tensiometer. A FluoroLog-4 fluorescence spectrophotometer was used to record the fluorescence spectra. Instron Universal Mechanical Testing System with pneumatic chuck and non-slip pad was used to evaluate the tensile fracture properties. All tests were performed at room temperature.

Supplementary information

Attenuated Total internal Reflectance Fourier Transform Infrared (ATR-FTIR) spectra of AADW and FA-FTW; Energy dispersive spectroscopy (EDS) mapping of wood after two-step modification; cross-section SEM images of basswood; X-ray diffractometry spectra of TW, FA-FTW and DA-FTW films; 2D wide-angle X-ray diffractometry (2D WAXS) spectra of FA-FTW films along the direction of wood channels, diffraction patterns and radial integration of the diffractogram; appearance of NW, DW, TW, FA-FTW and DA-FTW films. Tailored FA-FTW and TW films showing AIE fluorescence; FA-FTW and TW films in water under UV light; fluorescence spectra of FA-FTW films; summary of recent work related to transparent and fluorescent films (tensile strength, transparency, anisotropy, UV-blocking properties, biodegradability, and water-resistance).

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.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cej.2022.140225.

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