Development Of Highly Durable Superhydrophobic And UV-Resistant Wood By E-Beam Radiation Curing

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Abstract

Developing a practical strategy to fabricate an anti-abrasion and durable superhydrophobic wood surface with ultraviolet (UV) resistance has great practical significance for expanding the application of natural wood. In this study, a robust superhydrophobic layer with a hierarchical micro/nano-roughness structure was modified on the wood surface through in-situ mineralization and polymerization using a simple sol-gel method along with efficient electron beam (EB) curing technology. Hydrophobic agent (polydimethylsiloxane, PDMS), and crosslinking monomer (γ-methacryloxypropyl trimethoxysilane, MAPS) form new covalent bonds between TiO$_2$ particle layer and wood substrate after EB radiation which endows robust superhydrophobicity and remarkable UV resistance on the wood surface. The as-prepared wood exhibited a water contact angle (WCA) of approximately 165.7° and obvious repellency to many aqua-phase liquids (cola, strongly acidic, alkaline droplets etc.). Furthermore, the hierarchical micro/nano-protrusion structures remained unchanged and micro/nano particles aggregated tightly on the as-prepared wood surface under harsh external environments (sandpaper abrasion and, ultrasonic treatment), confirming the desirable anti-abrasion and mechanically durable performance of the superhydrophobic surface. After the 18-day UV accelerated weathering test, the TiO$_2$ particle layer conspicuously retained the discoloration and maintained its exceptional repellency toward water. The biomimetic superhydrophobic wood with excellent mechanical durability and UV resistance reveals its potential application in the furniture and architecture fields.

Introduction

As an abundant renewable material, wood has been ubiquitously adopted in domestic housing decoration, building structures, and transportation field owing to its innate properties such as hierarchical structure, degradability, compatibility, and affordability (Chao et al. 2020; Guan et al. 2018; Mahltig et al. 2008; Zhu et al. 2016). The abundant presence of lignin, cellulose and hemicellulose in wood endows its exceedingly hydrophilic nature, resulting in the wood being readily deformed, cracked, discolored and decayed (Chen et al. 2019; Sargent 2019; Yue et al. 2021). These properties are not conducive to the dimensional stability and service lifetime of wood under various conditions, specifically in humid environments. Constructing a superhydrophobic layer on wood surfaces can effectively prevent the entry of moisture, thereby prolonging the lifetime of wood in practical applications.

Inspired by natural hydrophobic phenomena such as, butterfly wings (Han et al. 2017), water striders (Wang et al. 2015) and lotus leaves (Feng et al. 2002), researchers have developed superhydrophobic surfaces on solid substrates by fabricating micro/nano protrusion structures and modifying low-surface-energy materials. Superhydrophobic surfaces, possessing high water contact-angle (WCA) (> 150°) and low sliding-angle (WSA) (< 10°), not only exhibit excellent water repellency, but also endow the material with many new functions (e.g., self-cleaning (Wisdom et al. 2013), anti-corrosive (Zang et al. 2017), anti-fouling (Lin et al. 2018), and oil/water separation (Lin et al. 2020; Sun et al. 2018)). In view of the hierarchical microstructures and unique chemical components of natural wood, integrating this protocol into wooden-material surfaces becomes realizable. Thus, several methods have been developed to
achieve superhydrophobic functionalization on wood surfaces, such as sol–gel (Wang et al. 2011), hydrothermal reactions (Liu et al. 2015), spin coating (Guo et al. 2017), and layer-by-layer self-assembly (Renneckar and Zhou 2009). However, most of these methods require a multi-step, time-consuming, and expensive preparation procedure, which restricts the large-scale practical application of superhydrophobic wood (Guo et al. 2019; Wang et al. 2021; Wu et al. 2016). On the other hand, sunlight irradiation, moisture, and mechanical wear could destroy the hydrophobic outermost layer, such that the fabrication of biomimetic superhydrophobicity wood with outstanding mechanical stability and chemical durability remains a significant challenge. Through investigation, it has been realized that amelioration on wooden substrates can explicitly contain two aspects: (i) the existence of an interface binding force between the superhydrophobic layer and wood substrate and (ii) the strength of the micro/nano-roughness structure itself (Zhang et al. 2021). Based on these perceptions, considerable design strategies have been developed to construct robust superhydrophobic surfaces, such as using pretreated wood surfaces with stable hydrophobic material, creating a self-healing (light irradiation, high temperature) superhydrophobic coating and enhancing the adhesion between the superhydrophobic layer and wooden substrates (increasing the adhesive layer) (Jia et al. 2019; Tu et al. 2018; Yang et al. 2021). Although these strategies have been proven to improve the abrasion resistance and durability of superhydrophobic wood surfaces, the cumbersome procedure, high stimulus requirements, and the smooth adhesive layer surface exposed after multiple abrasions, make them undesirable for practical applications. To overcome the aforementioned deficiencies, there is an urgent need to develop simple, efficient and practical strategies for the fabrication of robust superhydrophobic layers on wood.

During recent decades, an alternative approach has shown many applications in improving the properties of coating materials; in particular, using EB curing technology can provide some advantages for chemical curing (Chen et al. 2018; Crivello 2002; Zhang et al. 2017). The EB curing process, which converts reactive monomers or oligomers into solids through polymerization, grafting, and even crosslinking reactions initiated by high-energy beams, has numerous attractive features such as low energy consumption, rapidly curing, and high efficiency (Wang et al. 2020; Zhang et al. 2021). For instance, Kumar et al. (Kumar et al. 2013) prepared abrasion-resistant and chemical-resistant organic/inorganic nanocomposite coatings using EB curing technology. Li et al. (Li et al. 2016) found that EB radiation enhanced the interfacial interaction between carbon nanotubes and the substrate, thus improving the elongation at break of carbon nanotube/epoxy composites. Additionally, low-energy EB radiation can cleave the chemical bonds in lignin (O-H bonds) and holocellulose (ether bonds), leading to the formation of free radicals, which are conducive to react with the added monomer to enhance the surface binding force of wood, as proven in previous literatures (Croitoru et al. 2014; Schnabel et al. 2015). More importantly, the aforementioned research indicates that the shortcomings of superhydrophobic wood surfaces can be anticipated to be addressed by combining the EB radiation technology.

In this study, low-energy EB radiation was applied to crosslinking and curing the as-obtained superhydrophobic wood to achieve robust superhydrophobicity wood-based materials. An essential micro/nano-roughness structure was obtained through the simple in-situ deposition of TiO₂ particles,
because TiO$_2$ is not only an environmentally friendly and easy-generated inorganic material, but also has intrinsic UV-absorption properties (Hu et al. 2016; Yang et al. 2019) that can provide a barrier to the underlying wood during UV irradiation. Subsequently, the hydrophobic agent PDMS was modified on the wood surface to endow wood with superhydrophobicity, which prevented the utilization of toxic and expensive fluorine-containing reagents. Simultaneously, the addition of MAPS can firmly grasp the micro/nanoparticle layer and wood substrate via the formation of Si-O-Ti and Si-O-C covalent bonds after EB radiation, which is related to the condensation of silyl, and the other is caused by free radicals on the wood surface polymerized with the methacryloxy groups of MAPS (Wang et al. 2019). Herein, we demonstrate a highly robust superhydrophobic surface with superior superhydrophobicity, anti-abrasion performance, and desirable UV resistance on wood via a convenient method, namely, simple sol–gel technology integration with efficient EB curing technology. Interestingly, the as-fabricated multifunctional superhydrophobicity wood essentially retains the original esthetic texture of natural wood, indicating its potential utility in the decoration market. More importantly, our protocol can be anticipated to overcome the limitations of the superhydrophobic wood preparation procedure, achieving large-scale and high-efficiency manufacture of multifunctional superhydrophobicity wood.

Experimental Section

2.1. Materials

Hydroxyl-terminated polydimethylsiloxane (CR, PDMS), absolute ethanol (AR), tetrabutyl titanate (AR, TBOT), and $\gamma$-methacryloxypropyl trimethoxysilane (CR, MAPS) were purchased from Sinopharm Chemical Reagent Co., Ltd. (China). All chemicals were used as received without further purification. Sapwood of poplar was cut with dimensions of 25 mm × 25 mm × 2 mm (longitudinal × tangential × radial) from Shijiazhuang (Hebei, China). The wood specimens were then ultrasonically rinsed in absolute ethanol for 20 min, and dried in an oven at 60 °C for 24 h, and directly used without further modifications.

2.2. Fabrication of superhydrophobic wood surfaces

Robust superhydrophobic surfaces were prepared on poplar wood by sol–gel technology along with radiation curing, described as follows: (1) in-situ deposition of inorganic TiO$_2$ particles on the substrate and (2) radiation crosslinking cured the introduction of PDMS and MAPS molecules through the creation of new covalent bonds on the wood surface. In detail, 0.4 mL of TBOT was first dissolved in 10 mL absolute ethanol in a 100 mL glass beaker under magnetic stirring, and then dribbled onto the surfaces of the wood specimens. Approximately 6 to 8 drops were added repeatedly and then placed an oven cured at 60°C for 20 min to obtain the Ti-wood.

Subsequently, the dipping solution was prepared by mixing PDMS and MAPS in absolute ethanol under constant magnetic stirring at room temperature for 30 min. The mass volume ratio of PDMS/MAPS/ethanol was set to 5:2:100. The Ti-wood was immersed in the above solution for 10 min, after which, the hydrophobic Ti-wood was removed, air-dried for 10 min, and dried in a vacuum overnight.
at 60°C. The obtained hydrophobic wood surface exhibited slight whiteness and a visible wood texture, namely, Ti&P-wood. Finally, the Ti&P-wood was placed a valve bag and redundant air was removed using vacuum packer. The sealed bag was radiated by EB at room temperature, and the total absorption was 5 kGy. The resulting superhydrophobic wood was denoted as R-Ti&P-wood, and the procedure is illustrated in Scheme 1.

2.3. Characterizations

Contact angle (CA) tests were conducted on an Attension Theta system (KSV Instruments Ltd., Finland) at ambient temperature, and the volume of the test water was 5 µL. Five different positions for each specimen were measured, and the average value was used to calculate the final WCA. Scanning electron microscopy (SEM) images of the wood surface morphology were obtained using an FEI Quanta–250 SEM at 5 kV under high vacuum conditions. The chemical composition of the wood surface was characterized by Fourier-transform infrared (FT-IR) spectroscopy (Bruker Tensor 207) from 4000 to 400 cm⁻¹ with a resolution of 4 cm⁻¹. X-ray photoelectron spectroscopy (XPS) analyses were conducted with a PHI-5702 electron spectrometer employing an Al Kα-line excitation source with the C 1s peak at 285.0 eV as a reference. The crystalline phases of the specimens were analyzed using X-ray diffraction (XRD) (model: RIGAKU D/MAX2200) equipped with a monochromatic high-intensity Cu – Kα radiation (λ = 1.54 Å). UV–vis spectra were collected using a Ruili 1100 spectrophotometer (Cary 50, America) within the wavelength range of 200–800 nm.

2.4. Ultrasonic vibration resistance tests

The hydrophobic wood specimens were immersed in absolute ethanol (20 mL) in a 500 mL glass with ultrasonic treatment (power 100 W, frequency 100 kHz), and after every 5 min, the wood samples were removed for further drying in an oven at 60°C. Subsequently, the WCAs of the new surfaces were measured to determine the endurance ability of the wood and to determine the hydrophobic effect of ultrasonic treatment.

2.5. Mechanical abrasion tests

A sandpaper abrasion test was conducted to qualitatively evaluate the wear resistance of the superhydrophobic wood. A piece of 800 mesh sandpaper was fastened on a desktop with a wood specimen of dimensions 25 × 25 mm was placed face-down on sandpaper. Then, a weight of 200 g was fixed in the middle of the specimen and was moved 10 cm along the ruler. The water CAs of the new surfaces were measured.

Results And Discussion

3.1 Characterization and chemical composition of as-obtained superhydrophobic wood
A durable superhydrophobic layer was efficiently constructed on the wood surface through in-situ deposition of hierarchical \( \text{TiO}_2 \) and a hydrophobic PDMS layer and crosslinking monomer MAPS. Owing to the abundant hydrophilic groups and dense tubular structure, the need to drop the precursor solution guaranteed the uniform coverage of particulate \( \text{TiO}_2 \) in the longitudinal section of the wood. Simultaneously, the presence of water in the air provided the conditions for the slow hydrolysis of the precursor solution. As a representative high-efficiency energy source, EB was used to induce the polymerization of free radicals on the wood surface with \( \text{C} = \text{C} \) bonds in MAPS, thus strengthening the interface binding force of the superhydrophobic layer and wood surface. A series of technical methods were applied to characterize the structure and properties of the prepared specimens.

The surface morphologies of pristine wood, Ti-wood, and R-Ti&P-wood at low and high magnifications are shown in Fig. 1. There are microscale protuberances with some small vessel wall structures in the pristine wood (Fig. 1a, b), indicating that the wood surface has self-roughness, which is conducive to the construction of a superhydrophobic surface. It can be clearly observed that microscale protuberances were neatly composed of abundant tubular structures with a relatively smooth surface (Fig. 1b). As expected, granular \( \text{TiO}_2 \) films were successfully covered on the exposed wood substrate by a hydrolytic process, resulting in a micro/nano-roughness structure (Fig. 1c, d). After being radiated by EB with PDMS/MAPS, the R-Ti&P-wood achieved superhydrophobicity and microscale \( \text{TiO}_2 \) particulates became more even and intensively scattered on the surface, which is largely beneficial for prompting superhydrophobic surface mechanical durability and abrasion performance (Fig. 1e). The higher magnification image revealed that many \( \text{TiO}_2 \) microparticles (~ 500 nm in diameter) clumped together into bigger aggregates and particles (> 1 µm) making up the granular roughness structures (Fig. 1f). This hierarchical micro-nano dual structure composed of countless tiny bumps can effectively trap air to generate superhydrophobicity.

The FT-IR spectra of pristine wood, Ti-wood, Ti&P-wood, and R-Ti&P-wood are shown in Fig. 2a. By comparison, the different stages of the wood samples have the same absorption peaks. The strong and prominent stretching vibration peak at 3392–3352 cm\(^{-1}\), which was attributed to the O-H group in all wood samples, shifted to the low-wavenumber direction (Gao et al. 2016), indicating that the covered \( \text{TiO}_2 \) particles and the added crosslinking agent (MAPS) interact with the hydroxyl groups on the wood surface. The bands at 2921 and 2855 cm\(^{-1}\) belonged to the asymmetrical and symmetrical stretching vibrations of C-H groups (-CH\(_3\) and -CH\(_2\)), and the peak at 1505 cm\(^{-1}\) is the characteristic C = C stretching vibrations from the lignin aromatic ring in wood (Dong et al. 2019; Ma et al. 2013). For Ti-wood, Ti&P-wood, and R-Ti&P-wood, the common characteristic peaks at 610 cm\(^{-1}\) can be ascribed to the Ti-O-Ti stretching vibration (Sun et al. 2011), which further illustrates that the \( \text{TiO}_2 \) particulates were successfully deposited on the surface of the wood samples and the coated \( \text{TiO}_2 \) film still on the wood surface after the addition of reactant and EB radiation. The absorption at 1039 and 801 cm\(^{-1}\) is assigned to the Si-O-C functional group and Si-C functional group (Mahadik et al. 2011; Wang et al. 2019; Wang et al. 2019), respectively, which confirm the presence of PDMS and MAPS chains on the Ti&P-wood and R-Ti&P-wood.
surfaces. Additionally, the peaks at 1736 and 1162 cm\(^{-1}\) correspond to the characteristic stretching vibration of the C(=O)-O-C groups in the MAPS molecules (Hu et al. 2016). After EB radiation, the decrease in the vibration peak at 1629 cm\(^{-1}\) is attributed to the C = C groups (Pantoja et al. 2009), which is related to MAPS participation in the radiation curing process. The above results suggest that TiO\(_2\) particulates have been combined with the functional groups on the wood surface and together with the low-surface-energy substance PDMS, promote the formation of superhydrophobic surfaces, particularly the double bonds in MAPS, providing the possibility for the excellent durability of superhydrophobic surfaces.

The chemical composition of the wood surface inevitably influences the wettability of the surface, which was investigated using XPS. As shown in Fig. 2b, the pristine wood only exhibited the presence of C and O. After in-situ sedimentation, new characteristic peaks of Ti 2s, Ti 2p, Ti 3s, and Ti 3p were observed for the Ti-wood, which is related to the generation of TiO\(_2\) particulates on the surface. Another major element, Si, was attached to the Ti&P-wood and the R-Ti&P-wood, indicating that the hydrophobic groups and cross-linked molecular chains were successfully covered on the surface. In the case of R-Ti&P-wood, the O 1s XPS spectrum shows two prominent peaks at 530.5 and 532.2 eV (Fig. 2c), corresponding to carbonyl oxygen in MAPS and weakly adsorbed oxygen on the surface, respectively (Li et al. 2017; Mostof SARKARI et al. 2019). The symmetrical doublets of Ti 2p centered at 458.9 and 464.7 eV were assigned to Ti 2p\(_{3/2}\) and Ti 2p\(_{1/2}\), and the splitting between the 2p doublet was 5.8 eV (Fig. 2d), confirming the Ti\(^{4+}\) chemical state on the surface of R-Ti&P-wood, which is attributed to the oxidation state in TiO\(_2\) (Esfandiar et al. 2012). Simultaneously, the typical Si 2p core-level spectrum (Fig. 2e) was resolved into three peaks: including Si-O-C (~ 101.7 eV) (Dong and Liu 2016), Si-O-Si (~ 102.2 eV) (Li et al. 2016), and Si-O-Ti (~ 102.7 eV) (Jiang et al. 2011), representing the -Si-O-CH\(_3\) groups in MAPS and the -Si-O-Si- groups from the PDMS hydrophobic agent. It is noteworthy that the existence of Si-O-Ti bonds further suggests the condensation reaction between Ti-OH groups (from tetrabutyl titanate hydrolysis) and the added reactant on the surface of R-Ti&P-wood. Figure 2f presents the XRD spectra of the pristine wood, Ti-wood, Ti&P-wood, and R-Ti&P-wood surfaces, where sharp peaks at 2\(\theta\) = 16°, 22°, and 35° observed in all samples can be ascribed to the crystalline phase of cellulose fiber (101, 002, and 040), which are the main constituents of lignocellulosic materials (Islam et al. 2012). After hydrolysis at room temperature, the product of the dealcoholization condensation of Ti(OH)\(_4\) was further condensed to form TiO\(_2\) particles. The detected peaks remained unaltered on treated wood surfaces (Fig. 2f), demonstrating that the crystallization condition of the surface underwent negligible EB radiation effect and the growth of TiO\(_2\) particles as an amorphous film structure. Overall, the above results unambiguously indicate that the rough synaptic structure and low-surface-energy material were successfully embellished on the wood surface. At the same time, owing to the high energy of EB radiation, the added crosslinking monomer (MAPS) is combined with the wood surface through chemical bonds, which are crucial for promoting the durability and stability of superhydrophobic surfaces for practical applications.

3.2 Anti-wettability of as-prepared superhydrophobicity R-Ti&P-wood
Natural wood is a hydroxyl-rich and high-porosity material, and the hydrophobicity and stability of the as-prepared wood surfaces are important for actual applications. When different liquids (water, cola, methylene blue, Congo red, acid droplets and alkali droplets) were dripped onto the pristine wood surface, the droplets gradually immersed into the wood along the circumference (Fig. 3a). Comparatively, the liquids can maintain the visible spherical shape on the R-Ti&P-wood surface and the WCA was approximately 165.7° (Fig. 3b, c), illustrating the excellent super-antiwetting capability of the obtained R-Ti&P-wood. At the same time, a water droplet (volume of 5 µL) easily rolls off the slightly inclined R-Ti&P-wood surface, indicating low WSA values (Video S1 and Fig. 3f). As shown in Fig. 3d, a sequence of optical photographs, a water droplet (volume of 5 µL) appeared on the as-prepared wood at room temperature, was recorded every 10 min for 30 min to investigate the stability of the fabricated superhydrophobic wood for resistance to water. It can be found that the droplet remains standing on the modified wood laminate and the WCA was greater than 165° (Table 1), demonstrating a consistent phenomenon of the excellent super-antiwetting stability of superhydrophobicity wood. Furthermore, as shown in Video S2, blue-colored water droplets falling vertically on the modified wood can quickly bounce off the superhydrophobic surfaces. As depicted in Fig. 3e, the jet of blue-colored water impacted the fabricated wood and experienced complete rebounding and departure owing to the interception of the air layer, further confirming the excellent water-repellency and stability of the modified wood (Video S3).

Table 1 Contact angle of a water droplet (5 µL) on the R-Ti&P-wood surface.

| Specimen   | R-Ti&P-wood |
|------------|-------------|
| Retention time (min) | 0 10 20 30 |
| Contact angle (θ, °) | 166 ± 1° 167 ± 1° 166 ± 1° 166 ± 1° |

### 3.3 Mechanical durability of as-fabricated R-Ti&P-wood surface

Fabrication of microroughness structure and modification of low-surface-energy materials are the key factors for the as-obtained superhydrophobic wood surfaces (Zhang et al. 2021). Specifically, the interaction between the wood surfaces and micro/nanostructure layers affects the mechanical durability of the as-prepared superhydrophobic surface. However, EB applies strong penetration to change the internal molecular chain of wood; in this course, the ether bonds (lignin) and O-H bands (holocellulose) are broken to produce free radicals, and subsequently combine with the MAPS monomer to form interface interactions to prolong the lifetime of the as-obtained superhydrophobic surface. In this study, a compact contact abrasion test and an ultrasonic treatment test were performed to destroy the as-obtained wood surface to qualitatively evaluate the mechanical durability of superhydrophobic wood. Figure 4a shows the results of the abrasion test. The superhydrophobic surface was rubbed on a refine-abrasion sandpaper (800 mesh) along a transparent ruler with a weight of 200 g. It can be observed that the WCA of Ti&P-wood rapidly decreased within the first abrasion length of 40 cm, and then the downward trend became less pronounced, but it still remained hydrophobic with a WCA of 119°. The
difference is that the R-Ti&P-wood surface retained its superhydrophobicity with a WCA higher than 150°, even after an abrasion length of 80 cm, exhibiting excellent superhydrophobicity and steady abrasive strength (Fig. 4a). The existence of the error bar was attributed to the hysteresis of the CA and the untouched surface area during the abrasion process. Furthermore, to explore the variation in the surface microroughness structure of the R-Ti&P-wood, SEM photographs after the compact contact abrasion test are displayed in Fig. 4c and e. The hierarchical micro/nanostructure still exists (Fig. 4c), which indicates that the as-prepared wood surface can provide a water barrier after harsh abrasion. In the magnified SEM image (Fig. 4e), the more important point is that aggregation of the TiO$_2$ particulates remains spherical and without missing traces, which provides evidence for the strong adhesion of the superhydrophobic layer.

To further evaluate the stability of the superhydrophobic wood surfaces before and after radiation, the WCAs were recorded after 5 min of ultrasonic treatment in anhydrous ethanol solution, and the results are displayed in Fig. 4b. After ultrasonic treatment, the superhydrophobicity of Ti&P-wood and R-Ti&P-wood gradually decreased. Remarkably, after 15 min of ultrasonic treatment, R-Ti&P-wood maintained its superhydrophobicity with WCAs greater than 150°, whereas, the WCA of Ti&P-wood displayed a significant decrease, which indicated that radiation treatment was beneficial to enhance the stability of the superhydrophobic surface structure. More importantly, a water droplet remained approximately spherical on the R-Ti&P-wood surface (inset), and the WCA value was still $> 150°$ after a 40 min test (Fig. 4b). These changes suggest excellent superhydrophobicity in harsh environments. In addition, the surface morphology of R-Ti&P-wood after ultrasonic treatment was investigated. As shown in Fig. 4d, the constructed micro/nanostructure on the wood surface spread out in all directions to form a corrugated microstructure, and TiO$_2$ particulates gather around the folds. Figure 4f shows the magnified SEM image of the R-Ti&P-wood surface after a 40 min test. Although the micro/nanostructure layers were destroyed, the wood surface densely packed with a variety of micron-scale superhydrophobicity particles (Fig. 4f) retains excellent water repellency. Overall, these results demonstrate that the superhydrophobic layer possesses strong adhesion to wood specimens and the interaction of chemical bonds between the reactants and wood surfaces is uniform. Furthermore, these properties contribute to the as-prepared superhydrophobicity wood, which prolongs the service lifetime in a demanding environment, thus, this superhydrophobic wood is a promising candidate for the fabrication of wooden construction materials.

### 3.4 UV resistance

Natural wood has extremely important practical applications in the furniture and architecture markets, but it is inevitably exposed to solar irradiation, which causes irreversible damage to the surface and mechanical properties of the wood (Yuan et al. 2019). Accordingly, the pristine wood and R-Ti&P-wood surfaces were subjected to an accelerated UV weathering test (duration: 18 days, UV lamp power: 16 W, wavelength: 254–365 nm, distance between sample surface and UV lamp: 25 cm), and the corresponding visual appearances were recorded (Fig. 5a, b). After 18 days of UV irradiation, the color of the pristine wood became noticeably darker from white to yellow. In contrast, there was no visible color change on the R-Ti&P-wood surface, which manifested its prominent resistance to discoloration. The changes in the
WCAs of R-Ti&P-wood upon UV irradiation are shown in Fig. 5c. As can be observed, when the R-Ti&P-wood was exposed to UV light for 18 days, the target surface maintained its superhydrophobicity with a WCA of ~150°. In addition, the UV-absorption ability of the pristine wood and modified wood were studied and the corresponding results are depicted in Fig. 5d. Broader absorption ranges of the pristine wood surface were observed in the range of 200–400 nm, which suggests that it has better absorption of ultraviolet light, thereby aggravating its photodegradation. As TiO\textsubscript{2} particulates were deposited on the surface, Ti-wood exhibited higher UV absorbance in the range of 200–330 nm than pristine wood. This result illustrates the existence of TiO\textsubscript{2} micro/nanoparticles that play an indispensable role in resisting UV radiation. At the same time, the absorbance of Ti&P-wood and Ti-wood remained nearly constant in the range of 200 to 410 nm, demonstrating that the added crosslinking agent and hydrophobic agent seldom affect its anti-UV performance when interacting with the wood surface. Although, R-Ti&P-wood exhibited a narrower absorption range than that of pristine wood, the maximum absorbance still reached 0.94. This phenomenon can be explained by previous research that the valence band electrons of TiO\textsubscript{2} absorb the photon energy and undergo a transition, resulting in strong absorption in the UV region (Lan et al. 2013). These results revealed that the as-fabricated superhydrophobic wood can effectively resist UV irradiation to prolong its lifespan, especially in the field of outdoor architecture.

**Conclusion**

In summary, a highly durable and stable superhydrophobic wood surface was successfully prepared to address the problem of superhydrophobic wood surfaces, the micro/nanostructure and low-surface-energy materials were easily destroyed, via the simple processes of sol–gel and efficient EB curing technology. In this way, the modified wood exhibits prominent superhydrophobic properties with WCAs of approximately 165.7°; meanwhile, a water droplet remains conspicuously spherical after standing on the wood surface for 30 min. It is a remarkable fact that R-Ti&P-wood also shows excellent antiwetting performance toward frequently used liquids in daily life, as well as highly acidic, and alkaline droplets. Simultaneously, the hierarchically micro/nano-protrusion structure still existed to confer superhydrophobicity on the obtained surface, even when subjected to mechanical abrasion (80 cm) and ultrasonic treatment (40 min). In addition, R-Ti&P-wood possess excellent UV resistance, with a maximum absorbance of 0.94, in the UV region, and the surface has no visible discoloration after long-term UV irradiation (18 days). More importantly, this protocol could be considered an efficacious pathway for the large-scale manufacturing of high-performance superhydrophobic materials on analogous hydroxyl-plentiful substrate surfaces.

**Declarations**

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Conflict of interest  The author declares that they have no conflict of interest.

Ethical approval  The study meets all relevant ethical standards and approvals.

Human and animal rights  No human or animal subjects were involved in this study.

Informed consent  All authors have consented to the publication of the manuscript.

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Figures
Figure 1

SEM photographs of a, b) the pristine wood, c, d) Ti-wood and e, f) R-Ti&P-wood at different magnifications.
Figure 2

(a) FT-IR spectra of pristine wood, Ti-wood, Ti&P-wood, and R-Ti&P-wood; (b) XPS survey-scan spectra of pristine wood, Ti-wood, Ti&P-wood, and prepared R-Ti&P-wood; (c) O 1s, (d) Ti 2p and (e) Si 2p spectra of R-Ti&P-wood; (f) XRD pattern of pristine wood, Ti-wood, Ti&P-wood, and R-Ti&P-wood.

Figure 3

Photograph of different aqua-phase liquid including water, cola, methylene blue, Congo red, water with pH = 2 and water with pH = 13 on (a) pristine wood and (b) modified R-Ti&P-wood; (c) static water contact angle photograph of R-Ti&P-wood; (d) contours of a water droplet on superhydrophobicity R-Ti&P-wood surface; (e) jet of blue-colored water rebounds on R-Ti&P-wood; (f) photographs of water droplet on a slightly inclined R-Ti&P-wood surface.
Figure 4

(a) Contact angle of Ti&P-wood and R-Ti&P-wood after each sandpaper abrading. (b) Effect of ultrasonic treatment time on the contact angle of Ti&P-wood and R-Ti&P-wood. SEM images: c, e) R-Ti&P-wood surface after sandpaper abrading (80 cm); d, f) R-Ti&P-wood surface after ultrasonic treatment (40 min).
Figure 5

(a, b). Photographs of the pristine wood and R-Ti&P-wood within 18 days (taken every three days) after UV irradiation. (c). Contact angles change of R-Ti&P-wood versus UV irradiation time. (d). UV–vis spectra of the pristine wood, Ti-wood, Ti&P-wood and R-Ti&P-wood.

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