

Wood-based nanocomposite via *in-situ* formation of organic/inorganic hybrid porous polymer for robust superhydrophobicity and sustainable radiative cooling

Kaili Wang^{1,2}, Yijia Zhang¹, Chi Zhang¹, Miao Zheng¹, Yuanci Cai¹, Yaqing Wu¹, Youming Dong¹, Jin Wang², Dan Tian¹, Xiaorong Liu¹✉, and Jianzhang Li^{1,3}

¹Co-Innovation Center of Efficient Processing and Utilization of Forest Resources, College of Materials Science and Engineering, Nanjing Forestry University, Nanjing 210037, China

²Kingdecor (Zhejiang) Co., Ltd., No.20 Tianhu South Road, Quzhou 324022, China

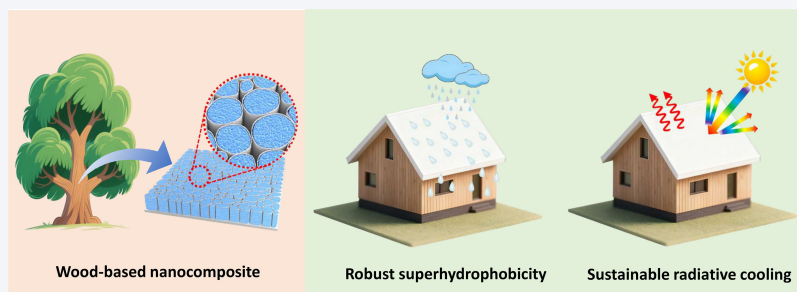
³MOE Key Laboratory of Wooden Material Science and Application, Beijing Forestry University, Beijing 100083, China



Cite this article: Nano Research, 2026, 19, 94908522. <https://doi.org/10.26599/NR.2026.94908522>

ABSTRACT: Bio-based radiative cooling materials hold significant application potential in carbon-free passive cooling but suffer from performance loss due to dust accumulation and rainwater washing. Superhydrophobic surfaces can enhance self-cleaning and durability, yet poor abrasion resistance often compromises superhydrophobicity. Herein, we develop a wood-based nanocomposite by infiltrating a highly porous and low-surface-energy copolymer and SiO₂ nanoparticles into a delignified wood scaffold. The resulting nanocomposite achieved satisfactory radiative cooling performance, with a solar reflectance of 91.29% and infrared emissivity of 98.77%, yielding a sub-ambient cooling of 8.36 °C and potential energy savings of 32.27 MJ/m² in cooling energy consumption in China's hottest regions. Furthermore, even after rigorous environmental testing, including 3000 abrasion cycles, water washing, and solvent immersion, the nanocomposite still maintained exceptional superhydrophobicity (contact angle > 160°, rolling angle < 4°). More importantly, the wood-based nanocomposite retained approximately 80% of its cooling capability after rigorous environmental testing. This work provides practical solutions to the two questions of inadequate abrasion resistance in bio-based superhydrophobic materials and poor long-term performance of bio-based radiative cooling materials, which is of great significance and value for the high-value application of bio-based functional materials.

KEYWORDS: wood-based nanocomposite, organic/inorganic hybrid porous polymer, radiative cooling, bulk superhydrophobicity, energy-saving



1 Introduction

Under the dual pressure of intensified global warming and energy crisis, the demand for cooling has surged. However, traditional cooling technologies consume extensive energy and generate substantial carbon emissions, exacerbating environmental burdens [1, 2]. Global carbon dioxide emissions have nearly tripled since

1850, reaching 3.39 billion tons in 2022. It is projected that global energy demand will increase by 25% by 2040 [3, 4]. Moreover, traditional cooling technologies, represented by air compression, are not suitable for outdoor scenarios. Therefore, the development of new cooling technologies that are highly efficient, energy-saving, simple, and environmentally friendly is particularly urgent.

Radiative cooling technology, as a passive cooling method, takes advantage of the high transparency of the Earth's atmosphere to specific wavelengths of infrared radiation (8–13 μm), known as the “atmospheric window”, to directly emit the heat from the Earth's surface into the cold outer space (about 3 K) in the form of thermal radiation. Simultaneously, it reflects sunlight in the 0.3–2.5 μm band to reduce heat absorption, thereby achieving a cooling effect

Received: November 18, 2025; **Revised:** January 31, 2026

Accepted: February 2, 2026

✉ Address correspondence to lxr2020@njfu.edu.cn

below the ambient temperature without any external energy input [5, 6]. This technology demonstrates broad application potential in building energy efficiency, electronic devices, agricultural production, transportation, personal protection and clothing, etc. [7–10].

Recent advances in radiative cooling materials include photonic crystals, hybrid metamaterials, inorganic coatings, microporous polymer films, nanotextiles, cooling wood, etc. [11–16]. Among these, cooling wood has garnered substantial attention due to its excellent passive cooling performance, green sustainability, low cost, and ease of processing [17–19]. The delignified wood cellulose framework retains natural wood's hierarchical porous structure, acting as a disordered scattering unit for visible light reflection [20]. Its molecular vibration of C–H, C–O, C–O–C, and –OH bonds align perfectly with the atmospheric window, enabling efficient radiative cooling [16, 21]. Simultaneously, the delignification process creates nanopores that disrupt heat transfer pathways, enhancing thermal insulation and reducing conduction/convection effects [22, 23]. More importantly, the hierarchical porous structure and modifiable chemical group of wood provide natural pathways and spatial sites for enabling permeation of modifiers, anchoring of inorganic particles, and functional group modification [24, 25]. This makes wood a natural template for constructing functional materials.

Wood-based radiative cooling materials (e.g., aerogels, films, and structural composites) have been investigated [16, 26, 27]. For the practical applications of wood-based radiative cooling material, it is essential to address some questions, including water resistance, flame retardancy, UV resistance, high-/low-temperature tolerance, organic solvent resistance, weather resistance, etc. Addressing all these questions simultaneously poses significant challenges. Current research on radiative cooling wood has focused on only one or two aspects of above issues. For example, constructing a hydrophobic surface to provide self-cleaning capability and prevent water and dust from degrading radiative cooling performance; or incorporating flame-retardant component to enhance fire resistance; or adding UV-blocking particles to improve resistance to UV aging.

Currently, a key and widespread challenge facing wood-based radiative cooling material is the degradation of its cooling performance due to rainwater washing and dust accumulation. Surface dust accumulation reduces the solar reflectivity, which is one of the key factors causing the attenuation of the cooling effect [28]. Therefore, converting the hydrophilic surface of wood to a superhydrophobic surface is a feasible strategy to enhance self-cleaning ability and long-term durability, potentially driving its large-scale application across diverse fields.

However, in practical applications of superhydrophobic materials, there is a significant challenge of insufficient mechanical wear resistance [29–31]. Traditional superhydrophobic materials usually rely on surface's elaborate micro-nano structures and hydrophobic molecular layers [32, 33]. These structures and/or layers are easily damaged by external forces such as friction, scratches, and impact, resulting in a substantial reduction or even complete loss of superhydrophobicity [34, 35]. Specifically for conventional superhydrophobic wood, common construction methods involve either *in-situ* synthesis of nanoparticles within the wood and their physical bonding to the cell walls, or the use of adhesives to attach nanoparticles to the cell walls, followed by modification with hydrophobic groups to achieve superhydro-

phobicity [36, 37]. The former is prone to wear and detachment due to the weak bonding force between the nanoparticles and the wood, while the latter is limited in wear resistance due to the thin thickness of the superhydrophobic layer. Therefore, there are still significant challenges in achieving long-term wood superhydrophobicity.

Wood cell walls typically comprise 20%–30% of the cellular structure, with lumen cavities occupying 70%–80% [38, 39]. Delignification further enhances porosity, creating a void-rich matrix [23]. We propose infusing these cavities with low-surface-energy porous polymers doped with nanoparticles to construct an organic–inorganic hybrid architecture. This approach would synergistically optimize spectral properties of cellulose framework of delignified wood, inorganic particles, and porous polymers while achieving bulk superhydrophobicity, where superhydrophobic functionality permeates the entire wood matrix. The resultant composite would exhibit full-life superhydrophobicity and long-term radiative cooling performance. This bulk design ensured that even after severe surface abrasion, the newly exposed interior remained functional and enabled performance recovery, a key advantage that conventional surface modifications cannot achieve. Thus, the core novelty lies in the integration of durable superhydrophobicity and sustained radiative cooling into a single, bulk-engineered wood composite, thereby addressing the classic trade-off between performance and durability in bio-based functional materials.

In this work, using delignified poplar wood as a template, a highly porous wood-based hybrid nanocomposite was developed by copolymerizing divinylbenzene and perfluorodecyl acrylate and incorporating silica nanoparticles within the wood porous structure via solvent thermal synthesis, as illustrated in Fig. 1. The pore structure of the hybrid wood was further regulated by adjusting the ethyl acetate dosage to modulate the material's spectral properties and cooling performance. Benefiting from the hierarchical micro/nano porous structure of the organic–inorganic hybrid system, the wood-based nanocomposite exhibited excellent bulk superhydrophobicity and long-term radiative cooling performance. Even after rigorous environmental tests, including 3000 times of sandpaper abrasion, sawing, water flushing, immersion in various organic solvents, etc., the wood-based nanocomposite still maintained a water contact angle greater than 160° and a rolling angle less than 4°. The optimized wood sample exhibited a reflectance exceeding 91.29% in the visible light wavelength range and an atmospheric window infrared emissivity as high as 98.77%, achieving a cooling of 8.36 °C, which could save 32.27 MJ/m² of cooling energy in the hottest regions of China. More importantly, even after harsh environmental tests, the wood-based hybrid nanocomposite could still retain approximately 80% of its cooling capacity. This work paves the way for the highly efficient and long-lasting superhydrophobic and radiative cooling of biomass materials.

2 Results and discussion

2.1 Microstructure morphology characterization

Figure 2 displays the microstructural morphology of cross-sections and longitudinal sections from different wood samples. The cross-section of the natural wood (NW) sample exhibited a honeycomb-like cellular structure with tightly bound cell walls. The longitudinal section revealed vertically aligned vessel cells with smooth, flat cell

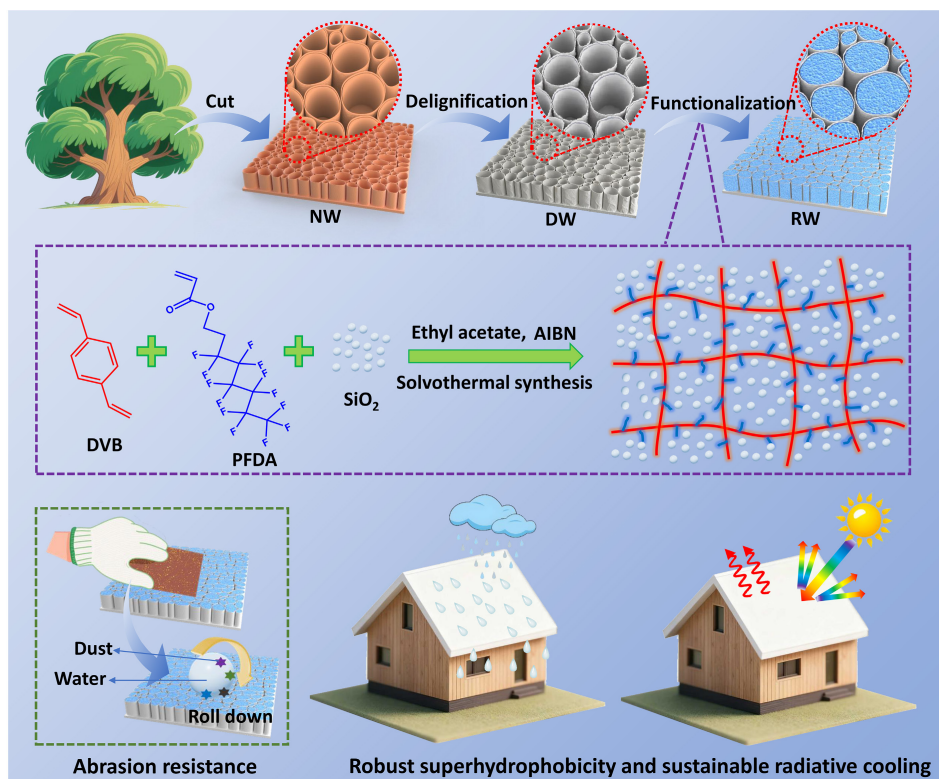


Figure 1 Schematic diagram of fabrication process for highly porous wood-based nanocomposites and their robust superhydrophobicity and long-lasting radiative cooling performance.

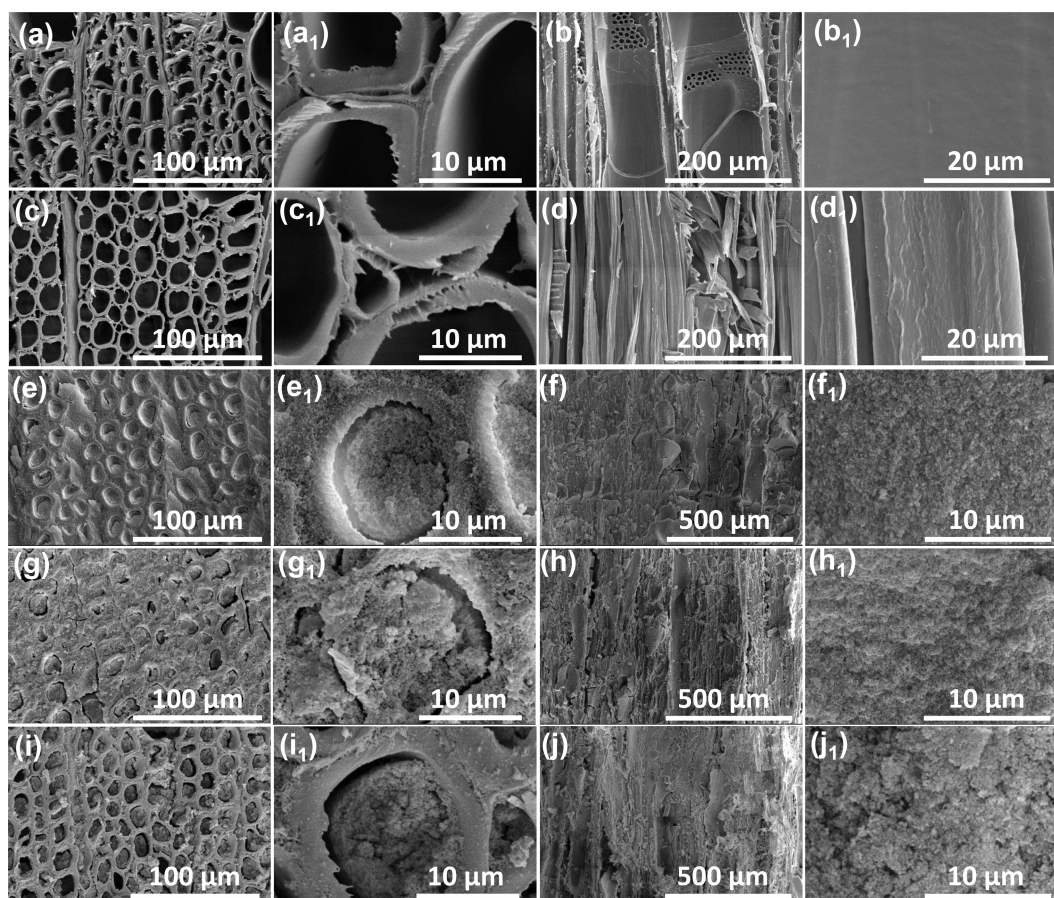


Figure 2 SEM images of cross-section of ((a) and (a₁)) NW, ((c) and (c₁)) DW, ((e) and (e₁)) RW1, ((g) and (g₁)) RW2, and ((i) and (i₁)) RW3 samples, respectively. Longitudinal section of ((b) and (b₁)) NW, ((d) and (d₁)) DW, ((f) and (f₁)) RW1, ((h) and (h₁)) RW2, and ((j) and (j₁)) RW3 samples, respectively.

wall surfaces. After delignification, the delignified wood (DW) sample retained its honeycomb-like cell structure, but the cell walls exhibited poor cohesion with numerous micro-pores appearing on their surfaces. This was because the lignin components in the middle lamella were extensively removed, resulting in loosely arranged cell walls. Meanwhile, the longitudinal section revealed mild wrinkling of the vessel walls.

The divinylbenzene, perfluorodecyl acrylate and SiO_2 nanoparticles were dissolved and dispersed in ethyl acetate as the polymer precursors, and then impregnated into the porous structure of the delignified wood. Under the action of thermal initiator AIBN, divinylbenzene and perfluorodecyl acrylate copolymerize (at a polymerization temperature of 100 °C), generating a copolymer system. Concurrently, through solvothermal action, that is, the volatilization of low-boiling-point ethyl acetate during copolymerization, a porous structure formed within the copolymer [40, 41]. Additionally, SiO_2 nanoparticles filled the copolymer, resulting in a hierarchical organic-inorganic hybrid porous structure within the delignified wood. As shown in Figs. 2(e) and 2(f), the cross-sections of the RW1 sample displayed the copolymer completely filling the cell cavities of the delignified wood (based on the amount of ethyl acetate used, the resulting radiative cooling wood samples were designated as RW1, RW2, and RW3, respectively. The specific naming rule was detailed in Materials and Methods in the Electronic Supplementary Material (ESM)). Longitudinal sections clearly showed the porous copolymer adhering to the surface of the wood cell walls. Comparing the microstructures of RW1, RW2, and RW3 in both cross-sections and longitudinal sections revealed that higher ethyl acetate content resulted in reduced copolymer filling within the cell cavities of the delignified wood, and distinct gaps appeared at the interface between the copolymer and the cell cavities. Furthermore, as the ethyl acetate content increased, the pore structure of the copolymer became rougher.

Additionally, the energy dispersive spectrometer (EDS) surface mapping was performed on the surface of the RW1 sample. The results showed that the four elements (C, O, Si, and F) were uniformly distributed on the sample surface, with atomic percentages of 57.3%, 31.6%, 7.1%, and 4.0%, respectively (Fig. S1 in the ESM). This indicated the uniform loading of silica particles and modification of fluorine-containing long-chain of the copolymer within the delignified wood.

The pore structure of the different wood samples was further analyzed by the nitrogen adsorption method (BET). Figures S2(a) and S2(c) in the ESM showed the nitrogen adsorption-desorption isotherms and pore size distribution curves of the NW and DW samples. The nanopores of the NW and DW samples are mainly mesopores ranging from 5 to 20 nm. However, compared with NW, DW showed a higher adsorption-desorption degree and a higher porosity. As shown in Fig. S3 in the ESM, the specific surface area of NW is 0.73 m^2/g . After delignification, the specific surface area of the DW sample increases to 1.921 m^2/g , which is 2.63 times that of NW. This indicated that delignification treatment resulted in the formation of more nanopores within the wood cell walls. After constructing the organic-inorganic hybrid pore structure in the delignified wood, the adsorption isotherm of the RW sample showed distinct hysteresis rings, indicating the presence of abundant mesopores [42, 43]. Their pore size distribution curves further confirmed the existence of numerous micropores and mesopores in RW samples. The specific surface areas of the RW1,

RW2, and RW3 samples were 215.489, 178.275, and 146.773 m^2/g , respectively, which were 112.18 times, 92.80 times, and 76.40 times that of the DW sample. It can also be seen from the pore size distribution curves that compared with the DW sample, the pore size distribution range and pore capacity of the RW sample have significantly increased. Meanwhile, with the increase in the amount of ethyl acetate, the specific surface area and pore capacity of the RW3 sample showed a decreasing trend. This result was consistent with the reports in related Ref. [40]. The microphase separation generated during the solvothermal process was the key factor for the change of the porous structure. The above microstructure analysis demonstrated the successful construction of the organic-inorganic hybrid structure in the delignified wood, and the addition amount of ethyl acetate changed the pore structure (including the interface gaps between the copolymer and the wood cell wall, the micropores and mesopores generated by microphase separation, etc.) and specific surface area.

2.2 Chemical component analysis

Figure 3(a) shows the relative contents of cellulose, hemicellulose, and lignin in NW and DW samples. Compared with the NW, the relative contents of lignin and hemicellulose in the DW decreased from 23.5% and 25.2% to 9.6% and 13.2%, respectively, while the relative content of cellulose increased from 51.3% to 77.2%. Thus, the DW can be considered a cellulose-based scaffold template [44, 45]. In addition, the density of the DW decreased from 0.56 to 0.23 g/cm^3 after delignification (Fig. 3(b)). After constructing an organic-inorganic hybrid system in the pore structure of the DW, the density of RW significantly increased. However, as the amount of ethyl acetate increased and the solution concentration decreased, the density correspondingly decreased.

The chemical composition of NW, DW, and RW samples was characterized by Fourier transform infrared spectroscopy (FTIR), as shown in Fig. 3(c). The characteristic peaks at 1732 and 1232 cm^{-1} in the NW sample corresponded to the hemicellulose, while the peaks at 1588, 1504, and 1456 cm^{-1} belonged to the characteristic peaks of lignin [46–48]. After delignification, the intensity of the hemicellulose characteristic peaks weakened, and the lignin characteristic peaks disappeared, indicating partial removal of hemicellulose and lignin components from the wood. After constructing an organic-inorganic hybrid structure in the DW, numerous new characteristic peaks appeared in the RW1 sample. The characteristic peaks at 708, 795, and 830 cm^{-1} assigned to meta- and para-substituted aromatic rings and vinyl groups, respectively [49, 50]. The strong peak at 1603 cm^{-1} ascribed to the stretching vibration peak of the C=C bond in poly(divinylbenzene) [51]. Additionally, the Si–O–Si stretching vibration peak at 795 cm^{-1} overlapped with the characteristic peak of the substituted aromatic ring [52]. The characteristic peaks at 1243 and 1215 cm^{-1} were attributed to the C–F group [53], indicating the successful modification with the fluorinated long-chain.

Further analysis of the chemical composition changes in the NW, DW, and RW samples was conducted using X-ray photoelectron spectroscopy (XPS), as shown in Fig. 3(d). Only C and O elements were present in the NW and DW samples. After constructing the organic-inorganic hybrid porous structure, signals for Si and F elements appeared in the RW sample. Figures 3(e)–3(g) present the C 1s peak fitting curves for NW, DW, and RW samples, respectively. The C 1s spectrum of both NW and DW exhibited four distinct peaks: 284.2 eV corresponded to C–C and/or

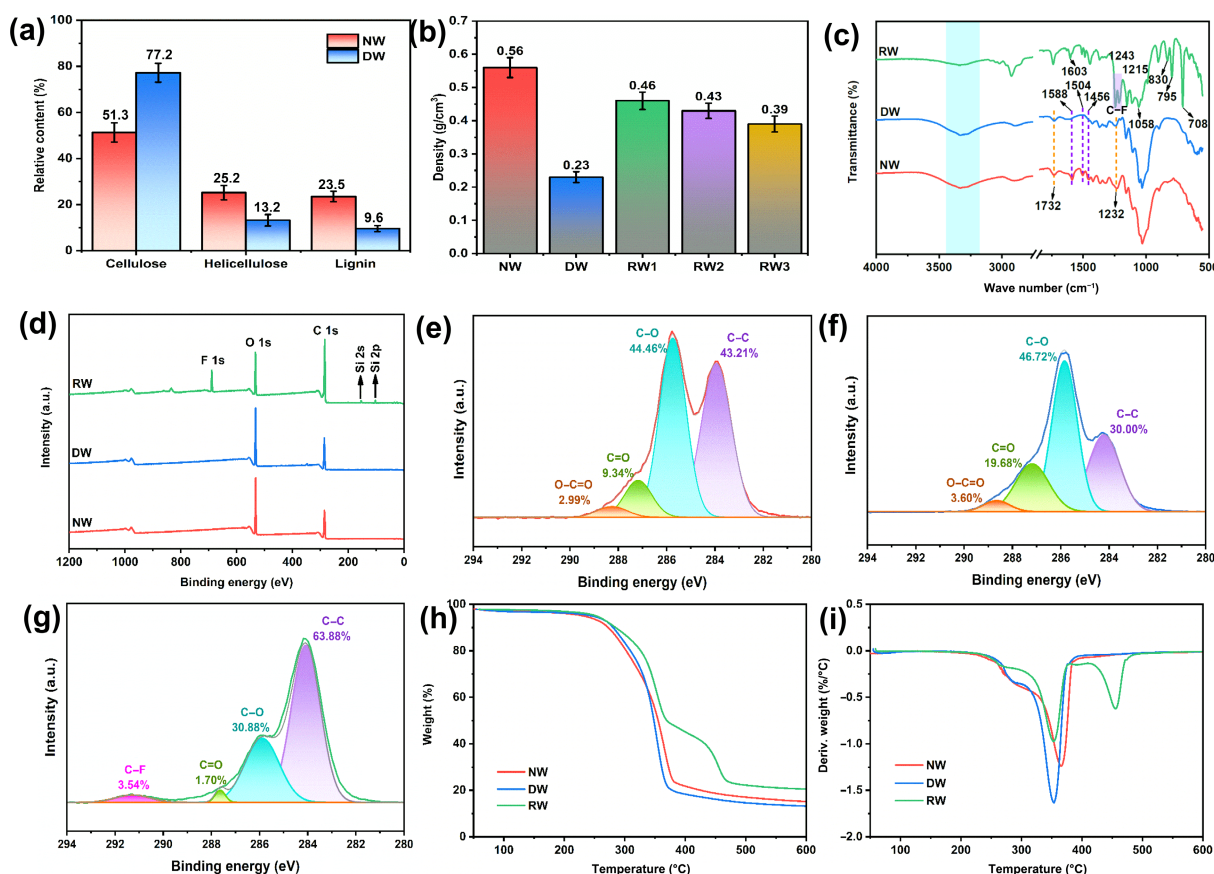


Figure 3 Chemical component of different wood samples: (a) relative contents of cellulose, hemicellulose, and lignin in NW and DW; (b) densities of NW, DW, RW1, RW2, and RW3; (c) FTIR spectra of NW, DW, and RW1; (d) XPS spectra of NW, DW, and RW1; (e)–(g) XPS C 1s spectra of NW, DW, and RW1, respectively; (h) TG curves and (i) DTG curves of NW, DW, and RW1, respectively

C–H bonds, primarily originating from lignin and wood extractives; while the peaks at 285.8 and 287.2 eV were attributed to C–O bonds and C=O and/or O–C–O bonds, respectively, primarily originating from cellulose [49, 54]. The peak at 288.5 eV represented carbon atoms connected to O=C–O units. This was consistent with the results of the three major components and FTIR analysis. Following the construction of an organic–inorganic hybrid porous structure in DW, a new signal peak appeared at 291.3 eV in the RW sample, attributable to the C–F groups in the polyperfluorodecyl acrylate [55]. Therefore, the above chemical composition analysis fully confirmed the successful construction of a SiO₂-doped divinylbenzene/perfluorodecyl acrylate copolymer within the delignified wood structure. The constructed organic/inorganic hybrid porous structure, combined with strong infrared-emitting particles and chemical groups, as well as the low-surface-energy components, collectively endowed the RW with exceptional radiative cooling and superhydrophobic properties.

The cellulose, hemicellulose, and lignin in wood have distinct thermal degradation behaviors due to their different structures. Figures 3(h) and 3(i) showed the thermogravimetric analysis (TG) and derivative thermogravimetric analysis (DTG) curves of NW, DW, and RW samples. Delignification treatment reduced the maximum pyrolysis temperature of cellulose from 365 to 355 °C, with a corresponding decrease in residual carbon content. RW exhibited a new degradation zone between 400–500 °C, attributed to the thermal degradation of the copolymer [56]. Concurrently, the residual carbon content of RW was the highest, which may be

attributed to the addition of SiO₂ inorganic particles in the system. The TG curve further indicated that prior to 200 °C, the RW sample underwent only moisture evaporation, with its chemical composition remaining largely unaffected by degradation.

2.3 Bulk superhydrophobic performance and environmental durability

The micro-nano rough structure and low-surface-energy components jointly determine the material's superhydrophobic properties [57]. The strong water repellency and anti-fouling self-cleaning capabilities of superhydrophobic materials effectively inhibit the attachment of dust and contaminants on surfaces, helping to address the degradation of outdoor radiative cooling performance [58, 59]. Figures 4(a) and 4(b) displayed the dynamic water contact angles and rolling angles of different wood samples. Due to the hydrophilicity and porosity of natural wood, water droplets rapidly spread and penetrated on both NW and DW surfaces, with DW exhibiting stronger water penetration. However, the contact angles of RW samples consistently remained above 150° within 180 s, with rolling angles below 5°, demonstrating their excellent superhydrophobic behavior. Figure 4(c) showed a water jet being repelled upon impact with the RW surface. The RW surface exhibited the silver mirror effect, as superhydrophobic surfaces trapped air to form solid–liquid–gas interfaces that maintained surface dryness. Concurrently, the outstanding superhydrophobicity endowed the RW with exceptional anti-fouling properties, allowing it to remain dry and

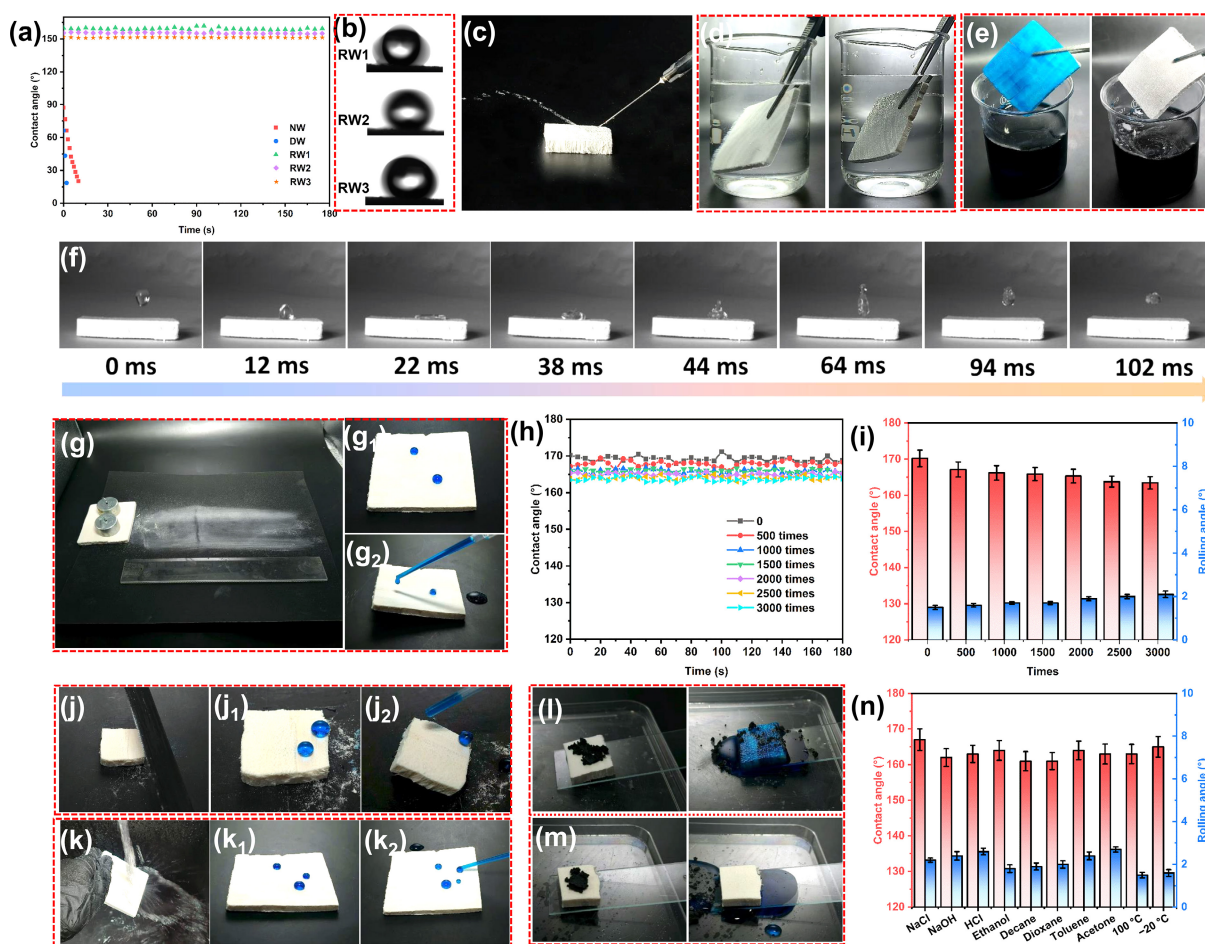


Figure 4 Superhydrophobic performance. (a) Contact angles as a function of time for NW, DW, RW1, RW2, and RW3. (b) Rolling angles of RW1, RW2, and RW3. (c) Jet water bounced on the RW1 surface. (d) Mirror-like phenomenon, the left is NW and the right is RW1. (e) Antifouling properties of the NW and RW1. (f) Photos of water droplet impacting RW1 surface from a height of 100 cm. (g) Sandpaper abrasion test; ((g₁) and (g₂)) static and roll-off diagrams of water droplets on abraded surfaces of sandpaper. (h) Contact angles as a function of time for RW1 surface with different abrasion times. (i) Contact angles and rolling angles for RW1 surface with different abrasion times. (j) Sawing test; ((j₁) and (j₂)) static and roll-off diagrams of water droplets on sawn surfaces. (k) Water washing test; ((k₁) and (k₂)) static and roll-off diagrams of water droplets on water jet washing surfaces. (l) and (m) Self-cleaning behavior of NW and RW1. (n) Contact angles and rolling angles for RW1 surface subjected to a series of harsh chemical and environmental tests.

clean even after immersion in stained wastewater. When a water droplet falls from a height onto the sample surface, a high-speed camera captured the droplet's bouncing phenomenon.

We hypothesized that the low-surface-energy porous copolymer doped with SiO₂ nanoparticles was completely filled into the cell cavities of the DW to construct a bulk superhydrophobic wood nanocomposite. Even after surface abrasion, the newly exposed surface still maintained the superhydrophobic property, which means it was expected to provide the superhydrophobicity throughout its entire lifespan. As our expectations were met, after the RW was worn by sandpaper, water droplets still formed spherical shapes on the surface and easily slid off the inclined surface. Even after 3000 wear cycles, the surface of the RW sample still maintained a contact angle of approximately 160° and a rolling angle below 3°. As shown in Figs. S4(a)–S4(d) in the ESM, the surface of the pristine DW3 sample exhibited a dense micro-nano rough structure. After 1000, 2000, and 3000 cycles of sandpaper abrasion, the fine nanostructures on the outermost surface were worn and damaged, revealing more pronounced micro-nano protrusions. Additionally, the thickness of the samples after 0, 1000, 2000, and 3000 abrasion cycles was shown in Fig. S4(e) in the ESM.

However, even after 3000 abrasion cycles, the newly exposed surface retained fundamental micro-nano roughness and porous characteristics. This demonstrated that the organic-inorganic hybrid copolymer formed a durable, bulk-permeating structure within the wood pores. The low-surface-energy chemical properties of the surface were preserved, enabling the abraded sample to maintain its superhydrophobicity.

Moreover, when the RW surface was sawn with a saw blade or impacted by a water jet for 10 min, the water droplets still remained spherical on the surface and easily rolled off. These results proved the exceptional overall superhydrophobicity. The accumulation of surface dust could reduce the solar reflectivity of the radiative cooling material, thereby causing a decline in the cooling effect. The superhydrophobic surface has excellent self-cleaning properties, as shown in Figs. 4(l) and 4(m), compared to NW, water droplets readily carried away dust from the RW sample surface, leaving a clean and dry surface. Moreover, environmental durability is crucial for the practical outdoor application of radiative cooling materials. As shown in Fig. 4(n), after immersing the RW sample in strong acids, strong alkalis, saturated salt solutions, and various organic solvents for 24 h, as well as exposing it to a 100 °C oven and a

−20 °C freezer for 24 h, the surface water contact angle remained greater than 160°, with rolling angles consistently below 4°, demonstrating the outstanding environmental durability.

2.4 Radiative cooling performance

Passive radiative cooling transfers surficial heat radiation through the atmospheric window into the cold outer space (~ 3 K). For daytime passive radiative cooling materials, high emissivity within the atmospheric window and high reflectivity within the solar spectrum are crucial to achieving effective cooling performance [60]. The reflectance and emissivity curves for NW, DW, RW1, RW2, and RW3 samples are shown in Figs. 5(a) and 5(b). Due to the presence of lignin absorptive groups, NW exhibited only 60.44% and 53.49% reflectance across the full wavelength range and visible light band, respectively. The DW sample, through partial removal of lignin components, increased its full-wavelength reflectance to 85.7% and its visible light reflectance to 94.13%. After constructing an organic–inorganic hybrid porous structure within the DW, the resulting RW sample exhibited little difference in reflectance within the full-wavelength and visible light ranges, both being higher than 86.02% and 91.29%, respectively (detailed data can be shown in Table S1 in the ESM). Regarding emissivity, the NW sample showed an emissivity of 92.66% in the atmospheric window, while the DW sample exhibited an atmospheric window emissivity as high as 99.05%. After filling the DW with a porous copolymer system composed of polyvinylidene/perfluorodecyl acrylate/SiO₂ nanoparticle, the atmospheric window emissivity of the RW sample exceeded 98.77%. The detailed data of RW1, RW2, and RW3 were provided in Table S1 in the ESM. The

organic–inorganic hybrid hierarchical porous structure of RW samples could effectively scatter and/or reflect sunlight. The solar light reflection/scattering of the RW sample can be explained by classical Mie scattering theory. The scattering efficiency is highest when the diameter of scattering particles is close to or slightly smaller than the incident wavelength. A high reflection/scattering rate helps improve the efficiency of solar light reflection, thereby enhancing radiative cooling performance. Additionally, a single particle or pore size can only effectively scatter specific bands of solar light. Constructing a hierarchical porous structure enables effective scattering across a broader solar spectrum, resulting in exceptional full-spectrum reflectance. The hierarchical pore structure of RW samples encompassed the cell lumen/wall structure of DW, the micrometer-scale interfacial gaps between the copolymer and the cell walls, the abundant mesoporous structure within the copolymer, and SiO₂ nanoparticles. Certainly, the particle diameter of SiO₂ would have a certain impact on the radiative cooling performance of the wood-based materials. Such multi-scale irregular interfaces enabled efficient and broadband diffuse reflection of sunlight. Meanwhile, C–H and C–O groups on cellulose molecular chains, the significant phonon-polariton resonance effect of SiO₂ nanoparticles, and C–F groups in perfluorodecyl acrylate all function as strong infrared emitters, all capable of radiating heat through the atmospheric window into outer space [61, 62]. Their synergistic effect endowed the RW with excellent radiative cooling and superhydrophobic properties.

Using a self-built outdoor radiative cooling test platform (Fig. 5(c) and Fig. S5 in the ESM), outdoor radiative cooling performance was conducted under sunny conditions at Nanjing

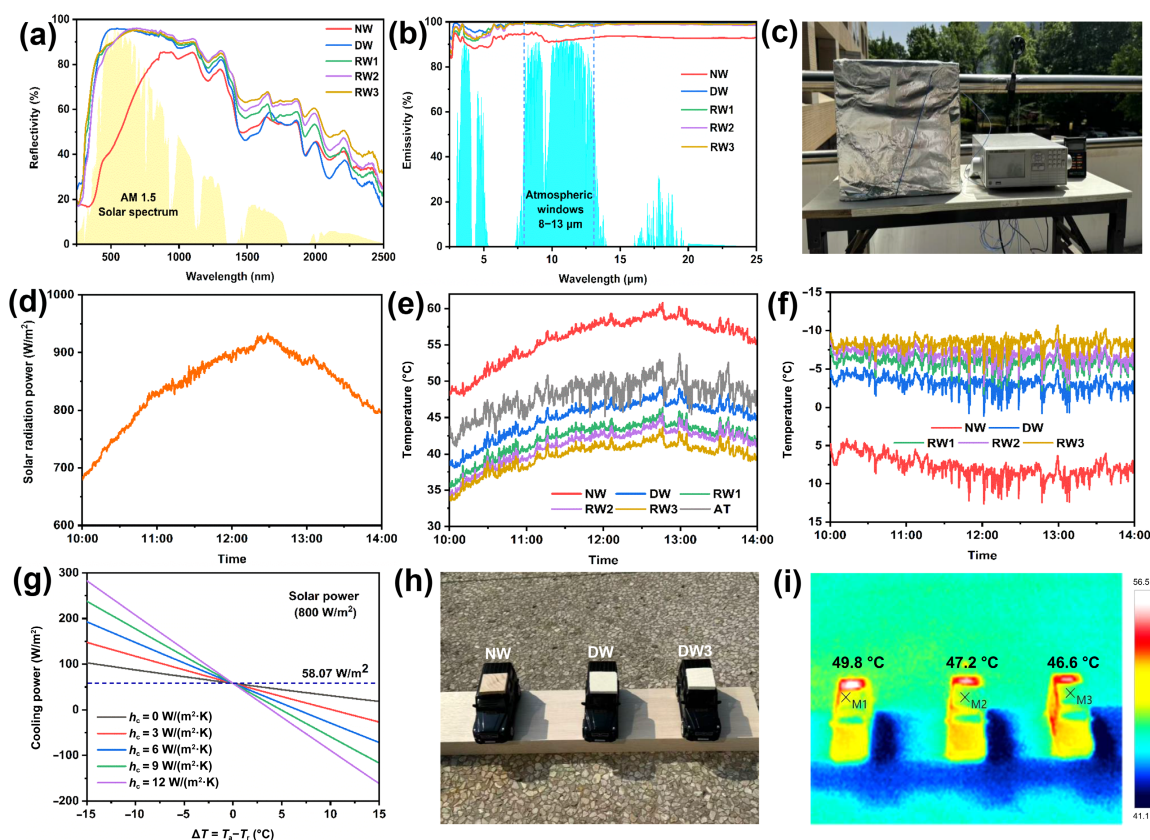


Figure 5 Radiative cooling performance: (a) and (b) solar light reflectance and infrared emissivity of NW, DW, RW1, RW2, and RW3, respectively; (c) photo of test device; (d) real-time solar radiation power; (e) and (f) real-time temperature and temperature difference of NW, DW, RW1, RW2, and RW3, respectively; (g) cooling power calculations; (h) and (i) photo, infrared thermal image, and surface temperature of NW, DW, and RW3 samples covering car model.

Forestry University (from 10:00 to 14:00, March 25, 2025). Solar irradiance power during the test period is shown in Fig. 5(d), while variations in wind speed and relative humidity are shown in Fig. S6 in the ESM. Results showed that the NW sample exhibited a heating effect, with its surface temperature rising 7.76 °C above ambient temperature due to lignin's photothermal conversion ability. The DW sample achieved a cooling effect of 4.95 °C. The further structurally modified RW1, RW2, and RW3 samples achieved cooling temperature of 5.87, 6.86, and 8.36 °C, respectively (Figs. 5(e) and 5(f), and Fig. S7 in the ESM). During the copolymerization process of the RW1, RW2, and RW3 samples, the degree of micro-phase separation varied due to different amounts of ethyl acetate added, leading to differences in the formation of pore structures. The RW1 sample exhibited a more compact and rough structure, while the RW3 sample presented a looser and rougher structure, with microscopic gaps between the copolymer and the cell wall. The radiative cooling performance of the material was not only related to the reflectivity and emissivity of the material, but also closely related to the roughness, thickness, thermal conductivity, and other intrinsic properties of the material, as well as the external environmental temperature, humidity, wind speed, and solar radiation power [63, 64]. Overall, the RW3 sample demonstrated superior cooling performance during the actual outdoor testing process. The RW3 sample with the optimal outdoor cooling performance was selected for the simulation calculation of the radiation cooling power. The solar radiation power was set at 800 W/m². The net cooling power of the RW3 sample under different non-radiative heat transfer coefficients is shown in Fig. 5(g). When the material surface temperature was the same as the ambient temperature, the corresponding cooling power was the maximum value. Through calculation, the maximum cooling power of the RW3 sample was found to be 58.07 W/m². The lowest achievable cooling temperature of the material corresponds to the point where its net cooling power is zero. As the non-radiative heat transfer coefficient (h_c) increases from 0 to 12 W/(m²·K), the minimum cooling temperature decreases, highlighting the significant influence of conductive and convective heat transfer on the material's overall cooling performance. Notably, even under h_c value of 12 W/(m²·K), the RW3 sample can still achieve a daytime sub-ambient cooling of approximately 3.87 °C.

Additionally, the thermal conductivity of the material is a key factor in evaluating its heat transfer capability, and also plays a significant role in radiative cooling behavior [65]. Generally, materials with lower thermal conductivity can effectively reduce heat exchange with the external environment, thereby enhancing radiative cooling efficiency [66]. As shown in Fig. S8 in the ESM, the thermal conductivities of the NW, DW, RW1, RW2, and RW3 samples were 0.2592, 0.1567, 0.2036, 0.1971, and 0.189 W/(m·K), respectively. The DW sample exhibited abundant porous structure, disrupting the original heat transfer pathway and consequently reducing the thermal conductivity. Meanwhile, by removing lignin-containing chromophores, DW demonstrated extremely high optical whiteness and negligible visible light absorption. Following the incorporation of organic-inorganic hybrid pore structure into the DW, the thermal conductivity of RW increased but remained lower than that of NW. Furthermore, due to the differences in pore structure caused by the different amounts of ethyl acetate added, there were also certain differences in the thermal conductivity among RW samples.

To fully explore the influence of the three heat transfer methods,

namely thermal radiation, thermal convection, and thermal conduction, on the actual cooling performance of the materials, we placed the black car model covering NW, DW, and RW samples under sunlight for 10 min, and then measured the surface temperatures of these three wood samples. As shown in Figs. 5(h) and 5(i), the surface temperatures of NW, DW and RW were 49.8, 47.2, and 46.6 °C, respectively. This result also confirmed the cooling capacity of the RW sample.

Additionally, a comparison of the cooling performance and robust superhydrophobicity for the wood-based nanocomposites of this work with those reported in other literature is shown in Table S2 in the ESM. Although the cooling performance of the RW sample is moderate, its outstanding superhydrophobicity throughout its entire lifespan is unmatched by other reported wood-based nanocomposites. Its robust superhydrophobicity effectively prevents cooling performance degradation caused by dust accumulation and rainwater runoff, offering the potential for long-term radiative cooling effects.

The correlation among solvent volume, porous structure, superhydrophobicity, and radiative cooling performance was clarified. With the increase in ethyl acetate volume, BET analysis showed a declining trend in specific surface area. SEM indicated that as the ethyl acetate volume increases, the organic-inorganic hybrid copolymer formed within the DW became looser, and the interfacial gaps between the copolymer and the cell walls enlarged. This directly proved that solvent volume was a key parameter for tuning the micro-nano porous structure of the nanocomposite.

Although there were microstructural differences among the RW samples, the sunlight reflectance and atmospheric window emissivity of all three RW samples remained at high levels with minimal variation. In fact, the DW itself provided strong solar light scattering/reflection and high emissivity due to its abundant C–O/C–H bonds. After introducing the organic-inorganic hybrid porous structure, its primary role was to construct a bulk superhydrophobic structure to enhance the durability of radiative cooling. Due to the porous structure and low-surface-energy components of the copolymer, all RW samples exhibited excellent superhydrophobic properties. Moreover, samples with lower ethyl acetate dosage showed a slightly enhanced superhydrophobic performance. This may be because the RW1 sample had a denser micro-nano structure on its surface, allowing water droplets to trap and retain more air, whereas the RW3 sample exhibited obvious gaps between the copolymer and the cell cavities, which may allow air to escape when water droplets were placed on the surface. The thermal conductivity showed a slight decrease from RW1 to RW3. The increased ethyl acetate volume led to a looser copolymer morphology with likely a higher air volume fraction. Since air has very low thermal conductivity, an increase in its proportion within the nanocomposite slightly reduces the overall thermal conductivity. This lower thermal conductivity contributed beneficially to the cooling performance by reducing parasitic heat gain from the environment. The radiative cooling performance of the material was closely related to its own properties as well as the external environment. The atmospheric window infrared emissivity varied little among the three RW samples, while RW3 exhibited higher solar reflectance and lower thermal conductivity, which were key factors contributing to its superior cooling performance.

2.5 Building energy consumption simulation and long-term application capability

In the context of global warming and energy crisis, the application

value of energy-saving building materials is becoming increasingly prominent. Using the building energy consumption simulation software EnergyPlus to simulate the typical annual average cooling energy consumption of mid-rise buildings (Fig. S9 in the ESM) in 34 provincial administrative regions of China (including 23 provinces, 5 autonomous regions, 4 municipalities directly under the Central Government, and 2 special administrative regions, taking the provincial capital cities as examples). The simulations compare scenarios with and without RW3 sample coverage on roofs and exterior walls. By calculating the difference between standard building energy consumption and that of buildings covered with RW3 samples, the average annual energy savings per square meter for entire mid-rise buildings across regions were determined. The visual analysis results were shown in Figs. 6(b) and 6(c). The simulation results showed that the radiative cooling performance of the RW3 sample delivered energy savings for building cooling systems across all regions of China, with particularly pronounced advantages in eastern and southern areas. This demonstrated the enhanced applicability of radiative cooling materials in hot, dry regions with high air conditioning energy consumption.

The thermal conductivity used for RW3 in this simulation (0.19 W/(m·K)) was measured from laboratory-scale samples. This value was lower than that of typical brick or concrete walls (usually > 0.5 W/(m·K)) but higher than that of dedicated insulation materials (e.g., extruded polystyrene, ~ 0.03 W/(m·K)). It is important to note the inherent limitations in directly extrapolating properties from small-scale laboratory samples to full-building simulations. In real-world applications, factors such as interfacial thermal resistance between the material and the substrate, performance degradation over time (e.g., due to dust accumulation, aging), local shading on the building facade, and complex thermal bridging effects at building details may all influence the actual energy-saving performance. Therefore, the results presented here aim to reveal the potential energy-saving trends and macroscopic geographical distribution when this material is applied to building envelopes and to guide priority application areas.

To verify the long-term performance of the RW sample's radiative cooling properties, the surface microstructure, spectral characteristics, and cooling performance of the RW3 sample were characterized after sandpaper abrasion. As shown in Figs. 6(d) and 6(e), the surface of the abraded RW3 exhibited a different microstructure compared to the original RW3, yet it retained a micro-nano scale rough structure. SEM images of NW, DW, and RW samples before and after the abrasion test were shown in Fig. S10 in the ESM. The full-wavelength and visible-light reflectance of the abraded RW3 sample were 84.76% and 90.30%, respectively, with an atmospheric window emissivity of 97.80%. These values were slightly reduced compared to the original RW3 sample, but the outdoor cooling tests still achieved a temperature reduction of approximately 6 °C. Therefore, although the surface structure changes after abrasion led to a slight decrease in spectral performance and cooling efficiency, the sample still maintained good cooling property and superhydrophobic performance, which was crucial for long-term outdoor applications.

We conducted a preliminary flame test using an alcohol lamp to ignite the sample, and as shown in Fig. S11 in the ESM, the wood-based nanocomposite did not exhibit flame retardancy. Regarding the issue of poor flame retardancy, we proposed several potential

mitigation strategies, including: (1) incorporation of flame-retardant additives (e.g., phosphorus- or nitrogen-based compounds) into the copolymer matrix during synthesis. (2) Surface treatment or coating with inorganic flame-retardant layers (e.g., silica, alumina, or magnesium hydroxide-based coatings) to create a protective barrier. (3) Utilization of intrinsically flame-retardant bio-based polymers as alternative matrices in future material designs.

The preliminary aging tests were also conducted by exposing the RW3 sample to UV irradiation for 120 h using a 30 W lamp with a wavelength of 365 nm. The results indicated that prolonged UV exposure led to obvious yellowing on the sample surface (Fig. S12 in the ESM), which inevitably reduced the solar reflectance and consequently weakened the cooling performance. This can be attributed to the photodegradation of organic components, especially in delignified wood. However, after removing the degraded surface layer via abrasion, the newly exposed subsurface would retain effective cooling performance. This observation directly corroborated our core design concept of "bulk functionality", where the radiative cooling and superhydrophobic properties were embedded throughout the material's volume rather than being merely a surface coating.

In addition, it is necessary to state the potential biodegradability and environmental safety that fluorinated monomer may have. Developing fully fluorine-free, bio-based hydrophobic agents to enhance the environmental profile of radiative cooling composites, without compromising performance, remains a critical objective and a pivotal direction for future work.

2.6 Mechanical properties

The compressive strength and flexural strength of NW, DW, RW1, RW2, and RW3 were shown in Fig. S13 in the ESM. Since the cross-sectional poplar was selected as the template to construct the nanocomposite utilizing its vertical pore structure, and after delignification treatment, the mechanical strength suffered a significant loss. The compressive strength and flexural strength of NW were 47.5 and 2.93 MPa, respectively. After delignification, these values for DW decreased to 1.2 and 0.21 MPa. Following the in-situ construction of the organic-inorganic hybrid porous polymer within the porous structure of the DW, the compressive strengths of RW1, RW2, and RW3 were 8.3, 4.9, and 3.3 MPa, respectively, while their flexural strengths were 0.5, 0.43, and 0.40 MPa. Compared with the DW, the strength of RW has been enhanced, and with the increase of ethyl acetate dosage, the mechanical strength showed a downward trend. Consequently, our material is suitable for overlaying or surfacing applications rather than for load-bearing purposes.

In fact, traditional wood is a porous and anisotropic material whose longitudinal strength is far superior to its transverse strength. Commercial construction and furniture panels are generally made from longitudinal boards, which possess satisfactory mechanical strength for structural and load-bearing applications. Utilizing the longitudinal structure of wood, combined with processes such as delignification, structural/chemical modification, and compression densification, holds promise for constructing high-strength wood-based functional materials.

3 Conclusions

In summary, the wood-based organic-inorganic hybrid

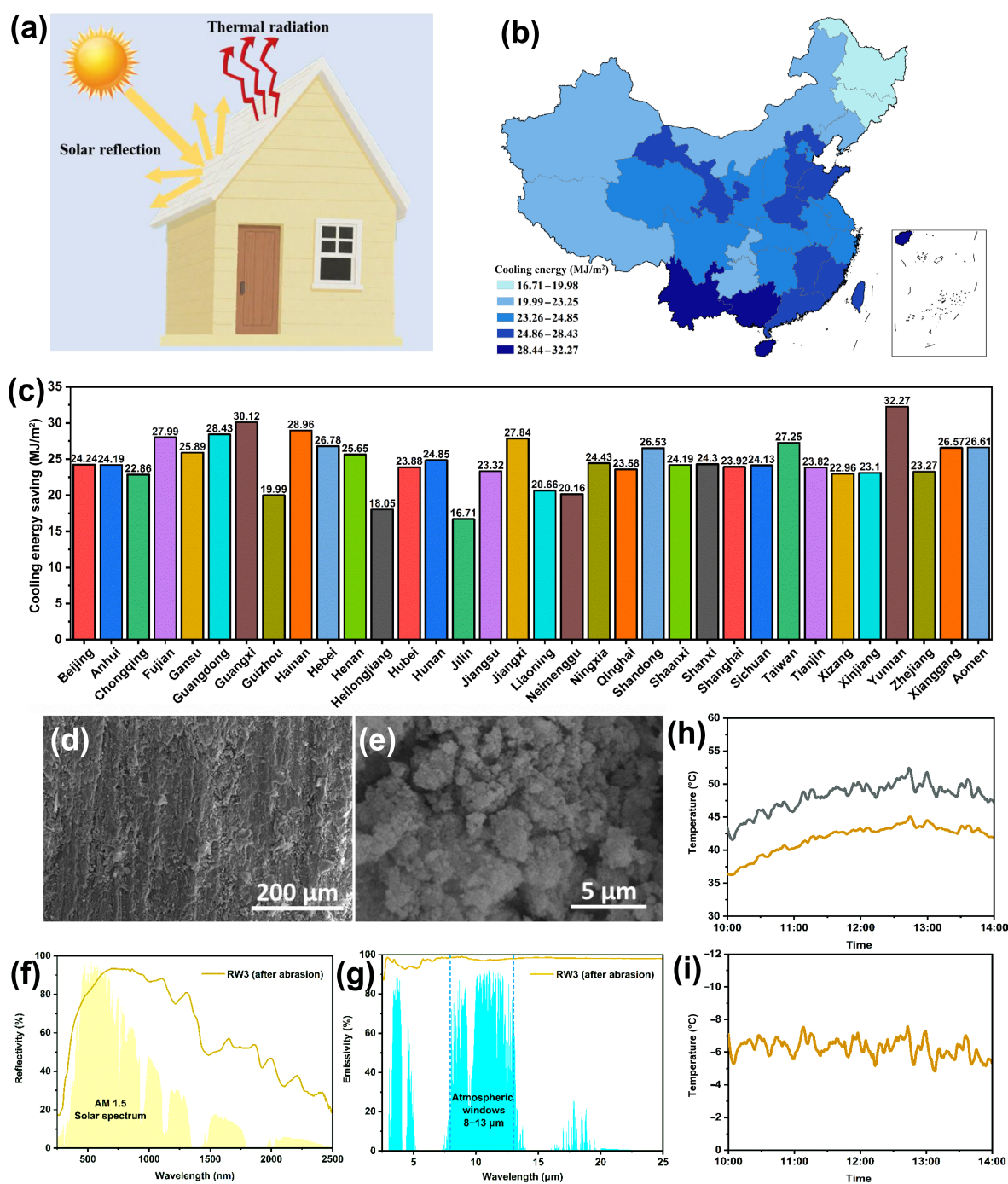


Figure 6 Building energy consumption simulation and long-term application: (a) schematic diagram of energy saving building; (b) visualized map of China for cooling energy savings; (c) detailed data of cooling energy saving; (d) and (e) SEM images of RW3 surface after sandpaper abrasion; (f) and (g) solar light reflectance and infrared emissivity of RW3 sample after sandpaper abrasion; (h) and (i) real-time temperature and temperature difference of RW3 sample after sandpaper abrasion.

nanocomposites were developed by filling porous copolymers and SiO₂ nanoparticles. Thanks to the integrated wood cellulose skeleton, highly porous organic-inorganic hybrid structure, dual functional groups of low-surface-energy and strong infrared emission, the wood-based nanocomposite exhibited robust superhydrophobicity and long-lasting radiative cooling performance. The wood-based nanocomposite demonstrated outstanding optical properties, achieving a solar reflectance of 91.29% in the visible spectrum and an infrared emittance of 98.77% in the atmospheric window, resulting in a significant cooling effect

of 8.36 °C. In China's hottest regions, this material can reduce cooling energy consumption by 32.27 MJ/m². Remarkably, even after rigorous environmental testing, such as 3000 cycles of sandpaper abrasion, water jetting, immersion in acidic/alkaline solutions and organic solvents, and extreme temperature cycling, the wood-based nanocomposite retained exceptional superhydrophobicity. The bulk superhydrophobicity of wood-based nanocomposite contributed to the long-term effectiveness of radiation cooling. Even if the surface was severely worn, it could still maintain a high cooling capacity.

Electronic Supplementary Material: Supplementary material (including materials, methods, and characterization data, spectra, results) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94908522>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (Nos. 32301516 and 32401674), Project funded by China Postdoctoral Science Foundation (No. 2024M761431), and Research Start-up Funding of Nanjing Forestry University (Nos. 163020538 and 163020823).

Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

K. L. W.: Conceptualization, methodology, data curation, writing – original draft, project administration, funding acquisition. Y. J. Z.: Methodology, formal analysis. C. Z.: Methodology, data curation. M. Z.: Methodology, formal analysis, data curation, writing – original draft. Y. C. C.: Investigation, formal analysis, data curation. Y. Q. W.: Investigation, formal analysis, data curation. Y. M. D.: Formal analysis, data curation. J. W.: Methodology, writing – review & editing. D. T.: Writing – review & editing. X. R. L.: Conceptualization, project administration, funding acquisition. J. Z. L.: Project administration, funding acquisition.

Use of AI statement

None.

References

- [1] Bijarniya, J. P.; Sarkar, J.; Maiti, P. Review on passive daytime radiative cooling: Fundamentals, recent researches, challenges and opportunities. *Renew. Sustain. Energy Rev.* **2020**, *133*, 110263.
- [2] Li, L.; Zhang, Q.; Liu, G.; Shi, R.; Zhao, H.; Huang, K.; Zang, Y.; Xu, Y.; Li, C.; Wu, L. et al. Advanced passive daytime radiative cooling: From material selection and structural design to application towards multifunctional integration. *Adv. Compos. Hybrid Mater.* **2025**, *8*, 97.
- [3] Chen, H.; Liu, X. J.; Liu, J. C.; Wang, F. Q.; Wang, C. H. Radiative cooling applications toward enhanced energy efficiency: System designs, achievements, and perspectives. *Innovation* **2025**, *6*, 100999.
- [4] Liang, J.; Wu, J. W.; Guo, J.; Li, H. G.; Zhou, X. J.; Liang, S.; Qiu, C. W.; Tao, G. M. Radiative cooling for passive thermal management towards sustainable carbon neutrality. *Natl. Sci. Rev.* **2023**, *10*, nwac208.
- [5] Wang, C.; Chen, H.; Wang, F. Passive daytime radiative cooling materials toward real-world applications. *Prog. Mater. Sci.* **2024**, *144*, 101276.
- [6] Hou, X. Y.; Zhang, K. Y.; Lai, X. T.; Hu, L. W.; Vogelbacher, F.; Song, Y. L.; Jiang, L.; Li, M. Z. Brilliant colorful daytime radiative cooling coating mimicking scarab beetle. *Matter* **2025**, *8*, 101898.
- [7] Suhendri, S.; Hu, M.; Dan, Y.; Su, Y.; Zhao, B.; Saffa, R. Building energy-saving potential of a dual-functional solar heating and radiative cooling system. *Energy Build.* **2024**, *303*, 113764.
- [8] Wei, X. K.; Wang, F.; Wu, D. X.; Zhang, C. Y.; Zhu, H. T. Radiative cooling of outdoor electronic devices by polyimide fiber films fabricated via an electrospinning-electrospray process. *ACS Appl. Mater. Interfaces* **2025**, *17*, 21313–21322.
- [9] Chen, Y. F.; Mo, Q. Y.; Dai, Y. T.; Yang, D. Y.; Yue, X. J.; Qiu, F. X.; Zhang, T. Reversible thermochromic cellulose-based agricultural film with radiation cooling for agricultural cultivation. *Int. J. Biol. Macromol.* **2025**, *306*, 141628.
- [10] Liu, R. N.; Zhao, S. M.; Wu, X. K.; Zhao, Z. J.; Wang, K. K.; Guo, Z. Y.; Xi, A. K.; Lan, F.; Li, R.; Liu, R. H. et al. Radiative cooling meta-fabric integrated with knitting perspiration-wicking and coating heat conduction. *ACS Nano* **2025**, *19*, 826–836.
- [11] Bahramipour, S. S.; Askarpour, A. N. One-dimensional photonic crystal with tilted termination and its angular filtering properties for radiative cooling. *Opt. Express* **2024**, *32*, 5191–5205.
- [12] Jin, Y.; Jeong, Y.; Yu, K. Infrared-reflective transparent hyperbolic metamaterials for use in radiative cooling windows. *Adv. Funct. Mater.* **2023**, *33*, 2207940.
- [13] Feng, S. J.; Yao, L.; Feng, M. X.; Cai, H. R.; He, X.; Bu, X. H.; Huang, Y. Z.; Zhou, Y. M.; He, M. Superamphiphobic interface-enhanced inorganic coating for multi-environments tolerant and zero-energy building radiative cooling. *Chem. Eng. J.* **2023**, *475*, 146191.
- [14] Zhang, Y. T.; Sun, J. H.; Wang, Y. F.; Wu, Y. C.; Huang, C.; Zhang, C.; Liu, T. X. A radiative-cooling hierarchical aligned porous poly(vinylidene fluoride) film by freeze-thaw-promoted nonsolvent-induced phase separation. *Chin. J. Polym. Sci.* **2024**, *42*, 976–983.
- [15] Cheng, N. B.; Wang, Z. H.; Lin, Y. Y.; Li, X. Q.; Zhang, Y. F.; Ding, C. F.; Wang, C.; Tan, J.; Sun, F. F.; Wang, X. F. et al. Breathable dual-mode leather-like nanotextile for efficient daytime radiative cooling and heating. *Adv. Mater.* **2024**, *36*, 2403223.
- [16] Li, T.; Zhai, Y.; He, S. M.; Gan, W. T.; Wei, Z. Y.; Heidarinejad, M.; Dalgo, D.; Mi, R. Y.; Zhao, X. P.; Song, J. W. et al. A radiative cooling structural material. *Science* **2019**, *364*, 760–763.
- [17] Cai, C. Y.; Zhao, X.; Miao, C.; Tian, X. Y.; Xie, F. Y.; Luo, F. M.; Zhang, M.; Wu, X. D.; Liu, J.; Jiang, B. W. et al. Bioinspired durable daytime radiative cooling wood: Realizing outdoor longtime use. *Nano Lett.* **2025**, *25*, 4369–4378.
- [18] Ram, F.; Höglund, M.; Liao, M. N.; Hallberg, T.; Jonsson, M. P.; Berglund, L. A.; Shanker, R. Transparent wood for passive radiative cooling of solar absorbers. *Nano Lett.* **2025**, *25*, 14025–14031.
- [19] Yu, Y.; Wei, L. Y.; Pang, Z. W.; Wu, J. F.; Dong, Y. M.; Pan, X. H.; Hu, J. D.; Qu, J. F.; Li, J. Z.; Tian, D. et al. Multifunctional wood composite aerogel with integrated radiant cooling and fog-water harvesting for all-day building energy conservation. *Adv. Funct. Mater.* **2025**, *35*, 2414590.
- [20] She, Y. N.; Xu, H. C.; Tian, F. Y.; Wu, Q. L.; Xu, X. W. Optimizing wood's thermal performance: Lignin modification for energy-efficient buildings. *ACS Sustain. Chem. Eng.* **2025**, *13*, 6249–6257.
- [21] Shanker, R.; Anusuyadevi, P. R.; Gamage, S.; Hallberg, T.; Kariis, H.; Banerjee, D.; Svagan, A. J.; Jonsson, M. P. Structurally colored cellulose nanocrystal films as transreflective radiative coolers. *ACS Nano* **2022**, *16*, 10156–10162.
- [22] Song, J. W.; Chen, C. J.; Yang, Z.; Kuang, Y. D.; Li, T.; Li, Y. J.; Huang, H.; Kierzewski, I.; Liu, B. Y.; He, S. M. et al. Highly compressible, anisotropic aerogel with aligned cellulose nanofibers. *ACS Nano* **2018**, *12*, 140–147.
- [23] Guan, H.; Cheng, Z. Y.; Wang, X. Q. Highly compressible wood sponges with a spring-like lamellar structure as effective and reusable oil absorbents. *ACS Nano* **2018**, *12*, 10365–10373.

- [24] Chen, C. J.; Kuang, Y. D.; Zhu, S. Z.; Burgert, I.; Keplinger, T.; Gong, A.; Li, T.; Berglund, L.; Eichhorn, S. J.; Hu, L. B. Structure-property-function relationships of natural and engineered wood. *Nat. Rev. Mater.* **2020**, *5*, 642–666.
- [25] Fu, Z. Y.; Lu, Y.; Wu, G. F.; Bai, L.; Barker-Rothschild, D.; Lyu, J.; Liu, S. X.; Rojas, O. J. Wood elasticity and compressible wood-based materials: Functional design and applications. *Prog. Mater. Sci.* **2025**, *147*, 101354.
- [26] Chang, A. J.; Xue, C. H.; Sun, J. J.; Cheng, J.; Huang, M. C.; Liu, B. Y.; Wang, H. D.; Guo, X. J.; Ma, C. Q.; Wan, L. et al. A superhydrophobic wood aerogel for radiative cooling and sound absorption. *J. Mater. Chem. A* **2025**, *13*, 6440–6450.
- [27] Yang, X. T.; Hong, H. Q.; Zhang, H. Y.; Hong, X. B. Highly spectrally selective dual-layer cellulose-based composite material for daytime radiative cooling. *Express Polym. Lett.* **2022**, *16*, 665–676.
- [28] Hu, W. W.; Tan, X. Y.; Yang, X. B.; Qi, G. G.; Chen, S. Y.; Li, S. S.; Wang, Y. Q.; Zhang, F. T.; Yan, K.; Kang, Z. A superhydrophobic transparent radiative cooling film exhibits excellent resistance to acid and alkali as well as remarkable robustness. *Opt. Mater.* **2024**, *149*, 114995.
- [29] Luo, J.; Guo, Z. G. Recent advances in biomimetic superhydrophobic surfaces: Focusing on abrasion resistance, self-healing and anti-icing. *Nanoscale* **2024**, *16*, 16404–16419.
- [30] Vazirinasab, E.; Jafari, R.; Momen, G. Application of superhydrophobic coatings as a corrosion barrier: A review. *Surf. Coat. Technol.* **2018**, *341*, 40–56.
- [31] Wang, S. L.; Zhao, Z. M.; Yu, Q.; Li, P. F.; Zhou, F.; Xu, C.; Zhao, X. F.; Teng, Y. C. Superdurable full-life superhydrophobic composite block. *Adv. Mater.* **2024**, *36*, 2403853.
- [32] Moghadam, S. G.; Parsimehr, H.; Ehsani, A. Multifunctional superhydrophobic surfaces. *Adv. Colloid Interface Sci.* **2021**, *290*, 102397.
- [33] Zhang, W. L.; Wang, D. H.; Sun, Z. N.; Song, J. N.; Deng, X. Robust superhydrophobicity: Mechanisms and strategies. *Chem. Soc. Rev.* **2021**, *50*, 4031–4061.
- [34] Ellinas, K.; Tserpi, A.; Gogolides, E. Durable superhydrophobic and superamphiphobic polymeric surfaces and their applications: A review. *Adv. Colloid Interface Sci.* **2017**, *250*, 132–157.
- [35] Dyett, B. P.; Wu, A. H.; Lamb, R. N. Mechanical stability of surface architecture-consequences for superhydrophobicity. *ACS Appl. Mater. Interfaces* **2014**, *6*, 18380–18394.
- [36] Li, X. J.; Gao, L. K.; Wang, M.; Lv, D.; He, P. Y.; Xie, Y. J.; Zhan, X. X.; Li, J.; Lin, Z. Q. Recent development and emerging applications of robust biomimetic superhydrophobic wood. *J. Mater. Chem. A* **2023**, *11*, 6772–6795.
- [37] Shah, S. M.; Zulfiqar, U.; Hussain, S. Z.; Ahmad, I.; Habib-ur-Rehman; Hussain, I.; Subhani, T. A durable superhydrophobic coating for the protection of wood materials. *Mater. Lett.* **2017**, *203*, 17–20.
- [38] Wiedenhoef, A. C.; Miller, R. B. Structure and function of wood. In *Handbook of Wood Chemistry and Wood Composites*. Rowell, R. M., Ed.; CRC Press: Boca Raton, 2005; pp 9–33.
- [39] Cosgrove, D. J. Growth of the plant cell wall. *Nat. Rev. Mol. Cell Biol.* **2005**, *6*, 850–861.
- [40] Wei, S.; Lu, D. X.; Sun, J.; He, Y.; Zhu, L. F.; Zhang, Y. L.; Xiao, F. S. Solvothermal synthesis of highly porous polymers and their controllable transition from macro/mesoporosity to meso/microporosity. *Colloids Surf. A: Physicochem. Eng. Asp.* **2012**, *414*, 327–332.
- [41] Li, Y.; Zhang, Z. Z.; Ge, B.; Men, X. H.; Xue, Q. J. One-pot, template-free synthesis of a robust superhydrophobic polymer monolith with an adjustable hierarchical porous structure. *Green Chem.* **2016**, *18*, 5266–5272.
- [42] Lin, X. X.; Tan, B.; Peng, L.; Wu, Z. F.; Xie, Z. L. Ionothermal synthesis of microporous and mesoporous carbon aerogels from fructose as electrode materials for supercapacitors. *J. Mater. Chem. A* **2016**, *4*, 4497–4505.
- [43] Singh, B. K.; Xu, D. D.; Han, L.; Ding, J.; Wang, Y. M.; Che, S. N. Synthesis of single-crystalline mesoporous ZSM-5 with three-dimensional pores via the self-assembly of a designed triply branched cationic surfactant. *Chem. Mater.* **2014**, *26*, 7183–7188.
- [44] Keplinger, T.; Wittel, F. K.; Rüggeberg, M.; Burgert, I. Wood derived cellulose scaffolds-processing and mechanics. *Adv. Mater.* **2021**, *33*, 2001375.
- [45] Kumar, A.; Jyske, T.; Petrič, M. Delignified wood from understanding the hierarchically aligned cellulosic structures to creating novel functional materials: A review. *Adv. Sustain. Syst.* **2021**, *5*, 2000251.
- [46] Wang, K. L.; Liu, X. R.; Tan, Y.; Zhang, W.; Zhang, S. F.; Li, J. Z. Two-dimensional membrane and three-dimensional bulk aerogel materials via top-down wood nanotechnology for multibehavioral and reusable oil/water separation. *Chem. Eng. J.* **2019**, *371*, 769–780.
- [47] Wu, J. M.; Wu, Y.; Yang, F.; Tang, C. Y.; Huang, Q. T.; Zhang, J. L. Impact of delignification on morphological, optical and mechanical properties of transparent wood. *Compos. Part A: Appl. Sci. Manuf.* **2019**, *117*, 324–331.
- [48] Fu, Q. L.; Ansari, F.; Zhou, Q.; Berglund, L. A. Wood nanotechnology for strong, mesoporous, and hydrophobic biocomposites for selective separation of oil/water mixtures. *ACS Nano* **2018**, *12*, 2222–2230.
- [49] Cai, Y. H.; Yu, Y.; Wu, J. F.; Wang, K. L.; Dong, Y. M.; Qu, J. F.; Hu, J. D.; Zhang, L. W.; Fu, Q. L.; Li, J. Z. et al. Durable, flexible, and super-hydrophobic wood membrane with nanopore by molecular cross-linking for efficient separation of stabilized water/oil emulsions. *EcoMat* **2022**, *4*, e12255.
- [50] Lepré, X.; Ehrmann, P.; Menapace, J.; Lotscher, J.; Shin, S.; Meissner, R.; Baxamusa, S. Ultralow stress, thermally stable cross-linked polymer films of polydivinylbenzene (PDVB). *Langmuir* **2017**, *33*, 5204–5212.
- [51] Fang, X. Y.; Liao, R. J.; Wang, K. J.; Zheng, M.; Li, H. J.; Wang, R.; Liu, X. R.; Dong, Y. M.; Wang, K. L.; Li, J. Z. Fabrication of bulk superhydrophobic wood by grafting porous poly(divinylbenzene) to wood structure using isocyanatoethyl methacrylate. *RSC Adv.* **2024**, *14*, 15201–15208.
- [52] Hayakawa, S.; Hench, L. L. AM1 study on infra-red spectra of silica clusters modified by fluorine. *J. Non-Cryst. Solids* **2000**, *262*, 264–270.
- [53] Wang, K. L.; Liu, X. R.; Tan, Y.; Zhang, W.; Zhang, S. F.; Li, J. Z.; Huang, A. M. Highly fluorinated and hierarchical HNTs/SiO₂ hybrid particles for substrate-independent superamphiphobic coatings. *Chem. Eng. J.* **2019**, *359*, 626–640.
- [54] Liu, R.; Wang, N.; Zhou, X.; Kang, H. J.; Liu, X. R.; Wang, K. L.; Dong, Y. M.; Li, J. Z. *In situ* synthesis of thymol@ZIF-90 with bamboo structures: Evaluation of long-term antimildew and physical-mechanical properties. *Constr. Build. Mater.* **2025**, *477*, 141328.
- [55] Qu, M. N.; Ma, X. R.; He, J. M.; Feng, J.; Liu, S. S.; Yao, Y. L.; Hou, L. G.; Liu, X. R. Facile selective and diverse fabrication of superhydrophobic, superoleophobic-superhydrophilic and superamphiphobic materials from kaolin. *ACS Appl. Mater. Interfaces* **2017**, *9*, 1011–1020.
- [56] Li, Y. H.; Fan, Y. G.; Ma, J. B. The thermal properties of porous polydivinylbenzene beads. *React. Funct. Polym.* **2002**, *50*, 57–65.
- [57] Bai, H. Y.; Zhao, T. H.; Cao, M. Y. Interfacial fluid manipulation with bioinspired strategies: Special wettability and asymmetric structures. *Chem. Soc. Rev.* **2025**, *54*, 1733–1784.
- [58] Ahmed, N.; Xiong, X. H.; Zhang, L. Z.; Sattar, F.; Chen, B.; Jing, T.; Cui, J. X. Designing the future of cooling: Superhydrophobic passive daytime radiative cooling systems. *ACS Appl. Mater. Interfaces* **2025**, *17*, 27629–27650.
- [59] Meng, X.; Chen, Z. C.; Qian, C. L.; Li, Q.; Chen, X. M. Durable and

- mechanically robust superhydrophobic radiative cooling coating. *Chem. Eng. J.* **2023**, *478*, 147341.
- [60] Xie, F.; Jin, W. L.; Nolen, J. R.; Pan, H.; Yi, N. Q.; An, Y.; Zhang, Z. Y.; Kong, X. T.; Zhu, F.; Jiang, K. et al. Subambient daytime radiative cooling of vertical surfaces. *Science* **2024**, *386*, 788–794.
- [61] Liu, R.; Wang, S. C.; Zhou, Z. G.; Zhang, K. Y.; Wang, G. Y.; Chen, C. Y.; Long, Y. Materials in radiative cooling technologies. *Adv. Mater.* **2025**, *37*, 2401577.
- [62] Xu, J. N.; Xie, W.; Han, H. X.; Xiao, C. Y.; Li, J.; Zhang, Y. F.; Chen, S. W.; Zhao, B. Y.; Zhang, D.; Zhou, H. Radiative cooling materials for extreme environmental applications. *Nano-Micro Lett.* **2025**, *17*, 324.
- [63] Hanif, M.; Mahlia, T. M. I.; Zare, A.; Saksahdan, T. J.; Metselaar, H. S. C. Potential energy savings by radiative cooling system for a building in tropical climate. *Renew. Sustain. Energy Rev.* **2014**, *32*, 642–650.
- [64] Lin, C. J.; Li, K. Q.; Li, M.; Doppoopho, B.; Zheng, J. Z.; Wang, J. Z.; Du, S. S.; Li, Y.; Huang, B. L. Pushing radiative cooling technology to real applications. *Adv. Mater.* **2025**, *37*, 2409738.
- [65] Nie, S. J.; Bai, L. Z.; Lin, G. P.; Guo, Y. D.; Yuan, K.; Zhang, Y. F.; Lan, H. X.; Su, S.; Qi, G. G.; Wang, M. Y. High-thermal-conductivity radiative cooling films for enhanced passive daytime cooling. *ACS Appl. Mater. Interfaces* **2025**, *17*, 51335–51347.
- [66] Zhu, M.; Chen, H.; Wang, L.; Shi, Y.; He, Y. Y.; Cui, T. K. Radiative cooling performance analysis of cooling wood with three delignification processes for building applications. *Energy Build.* **2024**, *312*, 114185.



This is an open access article under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0, <https://creativecommons.org/licenses/by/4.0/>).

© The Author(s) 2026. Published by Tsinghua University Press.



清华大学出版社
Tsinghua University Press

SciOpen