Solar steam generation with subsequent steam recondensation has been regarded as one of the most promising techniques to utilize the abundant solar energy and sea water or other unpurified water through water purification, desalination, and distillation. Although tremendous efforts have been dedicated to developing high-efficiency solar steam generation devices, challenges remain in terms of the relatively low efficiency, complicated fabrications, high cost, and inability to scale up. Here, inspired by the water transpiration behavior of trees, the use of carbon nanotube (CNT)-modified flexible wood membrane (F-Wood/CNTs) is demonstrated as a flexible, portable, recyclable, and efficient solar steam generation device for low-cost and scalable solar steam generation applications. Benefiting from the unique structural merits of the F-Wood/CNTs membrane—a black CNT-coated hair-like surface with excellent light absorbability, wood matrix with low thermal conductivity, hierarchical micro- and nanochannels for water pumping and escaping, solar steam generation device based on the F-Wood/CNTs membrane demonstrates a high efficiency of 81% at 10 kW cm\(^{-2}\), representing one of the highest values ever-reported. The nature-inspired design concept in this study is straightforward and easily scalable, representing one of the most promising solutions for renewable and portable solar energy generation and other related phase-change applications.
thermal management, water transportation, and evaporation, the F-Wood/CNTs membrane steam-generation device demonstrates a high efficiency and excellent stability, holding great promise for portable and scalable solar steam generation applications. Moreover, the developed highly flexible and biodegradable mesoporous wood membrane would find a range of applications beyond steam generations, such as flexible electronics,[19,20] wearable energy storage devices,[21–23] and biosensors for health monitoring.[24,25]

Trees are one of the most abundant resources on earth and widely used in structural materials,[26] cellulose manufacturing,[27–29] flexible electronics,[30] and energy storage applications.[31–33] The transpiration of water inside a tree through xylem vessels and lumina and the absorption of sunlight are two major activities that are vital for the metabolism and photosynthesis of trees.[34] Interestingly, when we look at the solar steam generation devices, it is not hard to discover that water transpiration and sunlight absorption are also two vital efficiency-determining factors.[6,12,15,16] This has inspired us to develop a natural wood-based solar steam generation device by taking advantage of the unique nature-made porous and interconnected-channeling structure of wood. Moreover, to optimize the wood structure to be more suitable for solar steam generation, we have made three modifications: (i) cutting the natural wood blocks with an electric saw to create a rough hair-like surface with numerous flower-like microsheets, enhancing the light absorbability by increasing the surface area, and elongating the optical path for multiple scattering; (ii) chemically treating the natural wood to make it flexible, suitable for portable applications; and (iii) coating the hair-like surface with CNTs to improve the photothermal conversion efficiency (Figure S1, Supporting Information). As illustrated in Figure 1, when the sunlight illuminates the F-Wood/CNTs membrane, the rough black hair-like surface will absorb the sunlight and generate localized heat at the water–air interface. Then, the local temperature will go up and water evaporates, escaping to the atmosphere. As the upper water continuously evaporates, water from the bottom will be pumped up simultaneously through the vessels and other nature-made interconnected-channels in wood such as connected lumen, ensuring the continuous supply of water for evaporation. The mechanism of this water upflow is similar to water transpiration in trees,[35] i.e., the negative pressure at the top of the F-Wood/CNTs membrane due to water evaporation can induce very large capillary force inside the F-Wood/CNTs membrane channels that have smaller diameters than vessels. Note that as wood itself is a good thermal insulator, the majority of the generated heat will be localized mainly on the surface of the F-Wood/CNTs membrane, good thermal management thus can be realized. Due to the systematic optimization of light absorption, thermal management, water transportation and evaporation, high efficiency is expected for the F-Wood/CNTs membrane-based solar steam generation device.

Balsa wood was used as the starting material for fabricating the F-Wood membrane due to the unique multichanneled structure with ultrathin channel walls (cell walls) and low density (≈0.17 g cm\(^{-3}\)).[36] After chemically treating the natural Balsa wood membrane through a simple, one-step soak in NaOH/Na\(_2\)SO\(_3\) solution for a few hours, the F-Wood membrane can be obtained. Scanning electron microscopy (SEM)
images of the natural Balsa wood show direct channels and rough hair-like surface with numerous microsheets (Figure S2, Supporting Information). Chemical treatment broke some tracheid cell walls to form large channels through connecting adjacent lumen both vertically and tangentially for potentially transpiring water (Figure S3, Supporting Information). The unique multichanneled structure and rough hair-like surface is well maintained after the chemical treatment (Figure S4, Supporting Information), while the softness of the cell walls is significantly increased, resulting in an excellent flexibility of the F-Wood membrane. Meanwhile, the chemical treatment leads to a weight loss of around 20% due to the partial removal of hemicellulose and lignin (Figures S5 and S6, Supporting Information). It is worth noting that there exist nanopores between the aligned cellulose fibrils due to the partial removal of hemicellulose and lignin, which would improve the water transportation capability of the wood matrix through capillarity (Figure S7, Supporting Information). To improve the light absorbability, we coat the F-Wood membrane surface with CNTs (Figure 2a). The mass percentage of the coated CNTs is as low as 0.3–0.5 wt%, thus the cost of the F-Wood/CNTs membrane will be very low (only small increase compared to the original F-Wood). The F-Wood/CNTs membrane inherits the excellent flexibility of the F-Wood membrane as well, demonstrated by repeated bending/releasing without obvious damage to the structure. Both the structure of the F-Wood matrix and the coated CNTs can be well maintained after repeated bending. SEM images show that the rough hair-like surface and vessel channels along with tracheids is preserved after CNT coating (Figure 2b,c,e and Figure S8, Supporting Information). More magnified SEM images show that the hair-like surface is uniformly coated with a layer of CNTs, while the inside channels remain smooth without CNT coating, consistent with the photo image observations (Figure 2d,f and Figure S1b, Supporting Information). Moreover, the F-Wood/CNTs membrane can float in water due to its low density (similar to that of the original Balsa wood) (Figure S9, Supporting Information). Side-view photo images show that the water contacts with the wood matrix, forming a water–wood interface, which is close to the CNT-coated top surface (Figure S10, Supporting Information).

The optical properties of the F-Wood and F-Wood/CNTs membranes were measured by a UV–vis Spectrometer Lambda 35 from 300–1200 nm with an integrated sphere. The F-Wood/CNTs membrane shows both extremely low transmittance (<1%) and reflectance (~2%) in the visible and infrared (IR) regions, resulting in an ultrahigh absorption of ~98% (Figures S11 and S12, Supporting Information, and Figure 3b). In contrast, the F-Wood membrane without CNT coating shows a relatively higher transmittance of 8.6% and much higher reflectance of 70%, contributing to a lower absorption of only ~21% in the same wavelength range. The distinct absorbability of the two samples are highly dependent on their unique structures (Figure 3a). For the uncoated F-Wood membrane, although the hair-like surface can elongate the light path length for increased scattering thus lowering the transmittance, the reflectance is still too high due to the intrinsically high-reflectivity wood surface. By coating the surface of the F-Wood membrane with a layer of continuously connected CNTs, the surface

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**Figure 2.** Morphology and structure characterization of the flexible wood/CNTs membrane. a) Photo images of the original F-Wood, F-Wood/CNTs, and flexed F-Wood/CNTs membranes. b) Schematic illustration of the F-Wood/CNTs membrane with hair-like surface (top) and direct channels (cross-section). c) Top-view SEM image of the F-Wood/CNTs membrane that shows the hair-like surface with numerous flower-like microsheets. d) Magnified image of c showing that numerous CNTs are uniformly coated on the surface of the microsheets. e,f) Cross-section-view images that show the multichannels.
will become less reflective (the sunlight cannot be reflected so it looks very black) due to the excellent light absorbability of the CNTs. Both the elongation of optical path for multiple scattering and reduced reflectance enabled by the unique CNT-coated rough hair-like surface contribute to the ultrahigh broadband light absorbability of the F-Wood/CNTs membrane.

Thermal management in the solar steam generation device, on the other hand, is also very important for efficient steam generation. Here the static temperatures of the solar steam generation device under various solar illuminations from 1–4 Sun are recorded by an IR camera. As shown in Figure 3c, the heat is mainly localized on the surface (water–air interface) of the F-Wood/CNTs membrane, suggesting excellent thermal management in the steam generation device. As the illumination intensity increases from 1, 2, 3 to 4 Sun, the maximum local temperature goes up quickly from 36.2, 40.1, 49.7 to 59.8 °C, respectively (Figure 3d). This heat localization effect can be further supported by our thermal analysis results. As shown in Figure S13 (Supporting Information), when incident light of 4 Sun illuminates the surface of an F-Wood/CNTs membrane floating in a beaker filled with water, the temperature of the top surface reaches as high as ≈59 °C, while the temperature below the surface remains close to room temperature. Even under a stronger light illumination of 10 Sun, the temperature of the bulk water does not increase significantly, suggesting a high proportion of heat localization. The temperature distribution profile of the CNT-coated wood block from the top surface and along the thickness direction under 9 Sun illumination shows that the light-to-thermal converted heat is mainly localized on the top surface (Figure S14, Supporting Information). The highly efficient thermal management is attributed to the low intrinsic thermal conductivity of the F-Wood that acts as thermal barrier in the steam-generation system. To validate this, we have set up a homemade thermal conductivity measurement device consisting of light simulator, IR camera, metal heat sink, and two pieces of Al blocks. As illustrated in Figure 3e, the sample is placed between the two pieces of Al blocks so that as the light coming from the light simulator heats up the upper Al block, thermal (temperature) distributions in this system can be recorded by the IR camera. Figure 3f shows...
that almost all the heat is blocked by the F-Wood and F-Wood/CNTs membranes, suggesting the excellent thermal insulation properties for both samples. According to the thermal distribution results, the thermal conductivities of the F-Wood and F-Wood/CNTs membranes can be calculated to be ≈0.17 and ≈0.21 W m⁻¹ K⁻¹ (see the Experimental Section for measurement details), both of which are considerably low, comparable to the previous reported steam-generation materials.⁶⁻¹⁻¹⁻¹⁸⁻³⁷

Even in a wet state, the thermal conductivities of the two samples are still low enough, ≈0.36 W m⁻¹ K⁻¹ for wet F-Wood and ≈0.4 W m⁻¹ K⁻¹ for wet F-Wood/CNTs (Figure S15, Supporting Information). It is worth noting that coating the high thermal conductivity CNTs (≈3000 W m⁻¹ K⁻¹) onto the surface of the F-Wood membrane does not enhance the thermal conductivity of the F-Wood/CNTs membrane significantly due to the use of only a trace amount of CNTs.

The CNT-coated flexible wood membrane with a hair-like surface and multichannels along the tree-growth direction (Figure 4a) was then evaluated for its solar steam generation performance using a homemade steam-generation device with a solar simulator as light source, F-Wood/CNTs membrane as light absorber and beaker with water as steam source (Figure 4b). Upon irradiation, the temperature of the surface of the F-Wood/CNTs membrane rapidly increases due to the local heat generation on the surface by photothermal conversion, as recorded by the thermal sensor (Figure S16, Supporting Information). Consequently, steam will generate and get bigger and bigger as the irradiation intensity increases (Figure 4c). The evaporation rate (E.R.) of the solar steam generation device recorded by the electronic balance under various illuminations (C_opt, defined as 1 kW cm⁻²) as a function of time is plotted in Figure 4d and Figure S17 (Supporting Information). The common trends in all curves show that the weight loss increases rapidly within the initial 5 min and then slowly reaches a maximum value, indicating rapid steam generation. The evaporation rates under different illuminations of 1, 3, 5, 7, and 10 Sun are 0.95, 2.88, 5.14, 7.65, and 11.22 kg m⁻² h⁻¹, respectively (Figure 4e). This can be further confirmed by the mass change versus time curves of the steam-generation system (Figure S18, Supporting Information). As a comparison, we have also evaluated the steam-generation performance of pure water under the same conditions. Due to the absence of the F-Wood/CNTs absorber, much lower values of 0.50, 0.83, 1.24, 1.79, and 2.48 kg m⁻² h⁻¹ are obtained under...
1, 3, 5, 7, nd 10 Sun, respectively (Figure 4e and Figure S19 and S20, Supporting Information). The F-Wood/CNTs membrane shows significant enhancement of the evaporation rate in contrast to pure water by a factor of two times under 1 Sun, which rises to 4.5 times under 10 Sun (Figure 4f). The steam-generation efficiency can be calculated based on the following relationship[6]

$$ \eta = \frac{m h_{LV}}{C_{opt} P_0} $$(1)

where \( \eta \) refers to the mass flux (E.R.), \( h_{LV} \) to the total liquid–vapor phase change enthalpy including the sensible heat, \( P_0 \) is the nominal solar irradiation value of 1 kW m\(^{-2} \) and \( C_{opt} \) represents the optical concentration. Accordingly, the thermal efficiencies of the F-Wood/CNTs membrane under various illuminations are calculated to be 65%, 67%, 72%, and 77% at 1, 3, 5, and 7 Sun (Figure 4g, see the Supporting Information for detailed heat loss analysis). More impressively, when the illumination increases to 10 Sun, the thermal efficiency reaches a maximum value of 81%, representing one of the highest values for all reported solar generation devices.[6–38–41]

The remarkable steam-generation efficiency of the F-Wood/CNTs membrane-based solar steam generation device should be attributed to the unique nature-inspired structure design, which enables systematic optimizations of the light absorption, thermal management, and water transpiration. First, almost 100% of the incident light can be absorbed by the rough hair-like CNT-coated surface for high efficient light-to-thermal conversion, enabling an excellent broadband light absorption. Second, the thermally insulating wood matrix can effectively trap the photothermally generated heat at the water–air interface (surface), contributing to an efficient thermal management. Finally, the hierarchical micro-/nanochannels and inherent hydrophilic nature of the cellulose-based wood enables efficient water transport for bulk to the evaporative surface via capillary and nanocavitation effects.

Stability of the solar steam generation devices is of great importance for practical applications. In this context, we have also evaluated the structure and performance stability of the F-Wood/CNTs membrane. F-Wood/CNTs membrane was immersed in water and subjected to various actions of folding and twisting and then released (Figure 5a). Remarkably, the original form can be fully recovered without losing CNTs, even after shaking vigorously in water (Movie S1, Supporting Information), suggesting the excellent flexibility and structure stability of the F-Wood/CNTs membrane. Figure 5b graphically illustrates the strong interactions between the surface coated CNTs and the F-Wood matrix. Strong interactions and connections between CNTs and F-Wood matrix are expected due to the abundant –OH and –COOH groups on the surface of CNTs and –OH groups on cellulose.[42,43] This can be further evidenced by the Fourier transform infrared spectroscopy (FT-IR) results, demonstrating the existence of abundant –OH groups in unprocessed wood, F-Wood and F-Wood/CNTs and additional signals of –COOH in F-Wood/CNTs (Figure 5c). More impressively, even under harsh (acid, alkaline, and high temperature) conditions, no disruption or CNT leakage occurred even with vigorous shaking or soaking for 24 h, suggesting the excellent structure stability of the F-Wood/CNTs membrane (Figure S21, Supporting Information). This can be further supported by the transmission electron microscopy (TEM) observations of the F-Wood/CNTs composite, which show that CNTs are stably adhered on the surface of the F-Wood matrix even after being vigorously shaken (Figure S22, Supporting Information). The excellent structural stability of the F-Wood/CNTs benefits the cycling stability of the steam-generation performance. As shown in Figure 5d, the F-Wood/CNTs membrane-based solar steam generation device exhibits stable evaporation rates for 20 cycles, suggesting the outstanding cycling stability of the device. The super flexibility and stability of the F-Wood/CNTs membrane gives it great potential for scalable, low-cost, portable and recyclable steam-generation applications.

In summary, we have demonstrated the nature-inspired structure design of a flexible and portable CNT-modified wood-based solar steam generation device with facile and scalable fabrication. The F-Wood/CNTs membrane, using natural Balsa wood as starting material, optimized by electric saw cutting, chemical treatment and coating with CNTs, shows a high solar thermal efficiency of 81% with an evaporation rate of 11.22 kg m\(^{-2} \) h\(^{-1} \) at 10 kW m\(^{-2} \). This high efficiency is attributed to the systematic optimizations of light absorbability, thermal management and water transpiration enabled by the unique structure consisting of a hair-like CNT-coated surface as light absorber, insulating wood matrix as thermal blocker and hierarchical micro/nanochannels as water transpiration path. The demonstrated approach towards high-efficiency steam-generation devices is renewable, scalable and cost-effective, representing one promising direction for large-scale, recyclable and portable solar steam generation applications. The nature-inspired design enabling efficient light utilization, water supply and thermal management also provides a guideline for many other applications beyond solar steam generations.

**Experimental Section**

**Chemical Treatment of the Flexible Wood Membrane:** Natural Balsa wood was used as the starting material to fabricate the flexible wood membrane. First, the precut wood slices were immersed into a mixed aqueous solution containing NaOH and Na\(_2\)SO\(_3\), then transferred into a vacuum chamber and vacuum treated for 1 h to let the mixed solution go into the channels of the wood membrane. The treated wood membranes were then washed with deionised water several times to remove the residual chemicals. After freeze drying for 2 d, the flexible wood membranes were obtained.

**Synthesis of F-Wood/CNTs Membrane:** Commercial CNT powder was dispersed in acetone to make the CNT solution. Then, the flexible wood membrane was immersed into the solution and taken out to allow to dry in air. This process was repeated several times to coat CNTs layer-by-layer on the surface of the flexible wood membrane, resulting in the final product of CNT-coated flexible wood membrane.

**Characterizations:** The morphology and structure of the samples were characterized by SEM (SEM, Hitachi SU-70) and TEM (JEOL 2100F field-emission TEM). FT-IR spectrum was carried out on a Thermo Nicolet NEXUS 670 FT-IR. Optical measurements were carried out on a UV–vis Spectrometer Lambda 35 from 300 to 1200 nm (PerkinElmer, USA) with an integrated sphere for reflected light collection. An forward looking infrared (FLIR) Merlin MID IR camera was used to measure the temperature distributions of the samples. Compositional analysis of unprocessed wood and chemical-treated wood membranes was carried out on a high-performance liquid chromatography (Ultimate 3000, Thermo Scientific, USA).
Thermal Conductivity Measurements: The thermal conductivity was measured based on the steady state method using a homemade device shown in Figure 3e. The samples were sandwiched between two standard Al blocks with a calibrated thermal conductivity of 206 W m⁻¹ K⁻¹. A light simulator was used as heating source and metal matrix in the bottom as heat sink. An FLIR Merlin MID IR camera with a resolution of 320 × 256 pixels was used to record the resulting temperature distribution along the side surfaces.

Solar Steam Generation Performance: A custom optical measurement system comprising of a multifunctional solar simulator (Newport Oriel 69907) and optical components (Newport Oriel 67005) was used to test the solar steam generation performance. The F-Wood/CNTs membrane was placed in a beaker filled with water. A properly calibrated electronic balance (Citizen CX301) with an accuracy of 0.1 mg was utilized to measure the evaporation rates, which was recorded in real-time with a digital video camera. Two thermometers (Omega HH74K) were used to measure the maximum temperature of the F-Wood/CNTs membrane under various solar concentrations.

Figure 5. Stability of the F-Wood/CNTs membrane-based steam-generation device. a) Photo images of the F-Wood/CNTs membrane upon various actions in water showing good flexibility and stability. b) Graphical illustration of the interaction between the coating CNTs and the flexible wood matrix. c) FT-IR spectra of the unprocessed wood, F-Wood, and F-Wood/CNTs membranes. d) Cycling performance of F-Wood/CNTs under a solar concentration of 7 Sun.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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