

Unlocking the hidden power of lignin in woody solar evaporators: Lowering enthalpy and boosting photothermal conversion

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Solar-driven interfacial evaporation has emerged as a promising solution to the escalating global freshwater crisis, owing to its ability to localize thermal energy at the air-water interface while minimizing heat dissipation to the bulk liquid. Among various material platforms, woody biomass, distinguished by its abundance, renewability, and intrinsically hierarchical porous architecture (enabling efficient capillary-driven water transport), has emerged as an attractive candidate for decentralized solar desalination systems [1].

Despite these advantages, the performance of wood-based evaporators remains fundamentally limited by two interrelated challenges. First, water confined within biomass matrices predominantly exists as strongly hydrogen-bonded bound water or bulk-like free water, both of which are associated with high evaporation enthalpies that impose an intrinsic thermodynamic barrier to efficient vapor generation [2]. Second, natural wood exhibits insufficient solar absorption, necessitating external photothermal coatings (such as plasmonic metal nanoparticles and semiconductor inks) that often compromise structural integrity, environmental sustainability, or scalability [1].

To overcome these limitations, previous efforts have largely focused on aggressive delignification to enhance hydrophilicity and accelerate water transport. For example, Gu et al. developed a fully wood-based evaporator through complete delignification, achieving a solar-to-vapor conversion efficiency of 91.74% and an evaporation rate of 1.93 kg·m⁻²·h⁻¹ [3]. Shen et al. integrated deep eutectic solvent delignification with a polypyrrole photothermal coating to realize efficient solar evaporation (1.94 kg·m⁻²·h⁻¹), along with outstanding self-cleaning capability and long-term desalination stability [4]. However, these approaches generally regarded lignin as a structural obstacle rather than a functional mediator, overlooking its multifunctional contributions and

consequently disrupting the delicate balance among water transport, thermal management, and mechanical robustness. These limitations raise a fundamental question: can lignin be re-engineered from a passive structural component into an active functional mediator for water and energy transport?

In a recent *Nature Communications* study, Wang et al. provide an affirmative answer through a dual-functional lignin engineering strategy [5]. By partially removing lignin within the balsa wood in an alcohol-based solution at 150 °C (denoted as W-150), they regulate hydrogen-bonding networks and promote the formation of intermediate water, a metastable state with reduced bonding strength and lower evaporation enthalpy, thereby accelerating water evaporation while preserving efficient capillary transport (Fig. 1(a)). Subsequently, the lignin extracted from the delignification process is redeposited onto the wood surface and transformed via laser-induced graphitization into a hierarchically porous graphene/graphitic carbon layer that exhibits strong broadband solar absorption and efficient heat localization. The obtained evaporator is denoted as E-150. The integration of water-state regulation and photothermal conversion thus establishes a synergistic platform that overcomes the conventional trade-offs among water transport, energy efficiency, and structural stability in biomass-based evaporators.

To investigate the influence of lignin on the water states and the evaporation enthalpy of water within woody biomass frameworks, low-field nuclear magnetic resonance (LF-NMR) and dark evaporation experiments are systematically conducted. The LF-NMR technique is initially employed to investigate spin proton relaxation, offering information regarding the nuclear mobility of bound and free water [6]. In the 1D LF-NMR spectrum, water strongly bound to the cell wall matrix (such as bound water) exhibits a shorter transverse relaxation time (T_2), whereas highly mobile free water displays much longer T_2 [6]. Accordingly, the relaxation domains at $T_2 < 1$ ms (T_{21}) and ~ 1000 ms (T_{24}) are assigned to bound water and free water, respectively, while signals in the intermediate relaxation region might be attributed to intermediate water in the large-diameter channels (T_{22}) and capillary water confined within fine channels (T_{23} , with a relaxation peak near 45 ms) [7]. The wood with lignin all removed (W-A)

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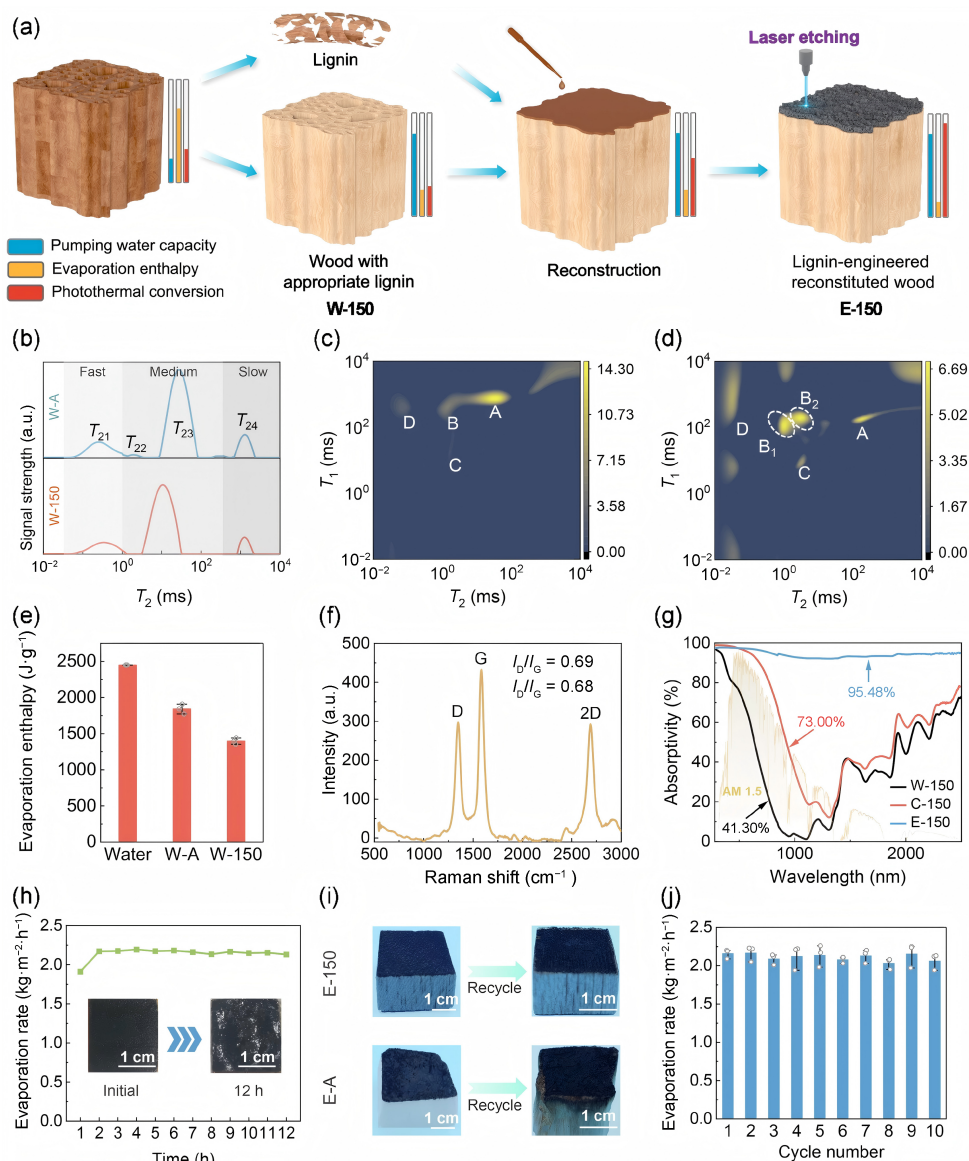


Figure 1 Lignin-enabled water-state engineering and photothermal interface construction for efficient solar desalination. (a) Illustration of the dual-functional lignin engineering strategy. LF-NMR spectra of evaporators in the fiber saturated state: (b) 1D LF-NMR transverse relaxation time (T_2) profiles of lignin-all-removed W-A and partially delignified W-150, 2D LF-NMR T_1 - T_2 correlation spectra of (c) W-A and (d) W-150. (e) Apparent water evaporation enthalpy of W-A and W-150 derived from dark evaporation measurements. (f) Raman spectrum of the lignin-derived photothermal layer on E-150. (g) Broadband solar absorption characteristics of different woody biomass evaporators together with the air mass 1.5 global (AM 1.5 G) solar spectrum. (h) Long-term seawater desalination performance of E-150 under one-sun illumination for 12 h. The inset shows its evaporation surface after continuous operation, demonstrating negligible salt accumulation. (i) Photographs of E-A and E-150 before and after repeated desalination cycles. (j) Cycling stability of E-150 during 10 consecutive 4-h desalination tests in real seawater under one-sun illumination. Reprinted with permission from Ref. [5], © Wang, B. et al. 2026.

shows a large fraction of both bound water (T_{21}) and free water (T_{24}), whereas the relaxation feature of the T_{22} peak associated with intermediate water is nearly absent (Fig. 1(b)), indicating that excessive lignin removal suppresses the formation of intermediate water. By contrast, the partially delignified W-150 exhibits an overlapping relaxation peak for T_{22} and T_{23} , implying similar properties of intermediate water and capillary water under this condition.

Since 1D LF-NMR has difficulty in distinguishing intermediate water from capillary water and bound water, 2D LF-NMR is further employed to characterize the water states. This approach effectively reduces the interference caused by water overlap and chemical composition. Results show that four main relaxation domains were

identified in the 2D LF-NMR spectra of the different wood samples. Among them, peak D (characterized by the highest T_1/T_2 ratio) is correlated with tightly bound water, while peak A (exhibiting the lowest T_1/T_2 value) corresponds to highly mobile free water. Peaks B and C originate from capillary water, corresponding to the water primarily located in the amorphous region of microfibrils and lignin, respectively [8]. Owing to the complete removal of lignin in W-A, the lignin-associated relaxation feature (peak C) vanished, while the signal related to free water (peak A) is detected (Fig. 1(c)). The relatively weaker peak B and relatively stronger peak A indicate that the property of capillary water in W-A is similar to that of free water.

In contrast, partially delignified W-150 exhibits a dominant peak

B₂, which is further resolved into two subdomains (B₁ and B₂) to better distinguish the capillary water (Fig. 1(d)). The B₂ domain, characterized by a lower T_1/T_2 ratio, corresponds to highly mobile clustered water stabilized by hydrogen bonding, which is energetically unfavorable for evaporation. The B₁ domain is assigned to intermediate water with moderated molecular interactions. Notably, the significantly enhanced B₁ signal observed in W-150 relative to W-A indicates that W-150 contains more intermediate water. This observation suggests that lignin is not merely a structural component but an active regulator of water-state distribution. Overall, appropriate lignin retention favors the generation of intermediate water, particularly within capillary regions, enabling efficient water supply to the evaporation interface while lowering vaporization enthalpy and ultimately enhancing evaporation performance.

To evaluate the influence of lignin content on the evaporation enthalpy of water in the wood, dark evaporation experiments are carried out (Fig. 1(e)). The results indicate that the partially delignified W-150 (1397 J·g⁻¹) exhibits a significantly lower evaporation enthalpy than the fully delignified W-A (1842 J·g⁻¹), which demonstrates that appropriate lignin retention can effectively reduce the energy barrier for vapor generation. This finding is consistent with the above LF-NMR analyses, which show that controlling the lignin content facilitates the formation of intermediate water with a lower evaporation enthalpy.

Having established the role of lignin engineering in regulating water thermodynamics, the authors next turn to the second key challenge in solar evaporation: efficient photothermal conversion. By utilizing the laser-induced graphitization technique, they convert the extracted lignin into a hierarchically porous graphene/graphitic carbon layer. The structural evolution of the lignin-derived carbon layer on the E-150 surface is subsequently examined by Raman spectroscopy (Fig. 1(f)). The Raman spectrum displays characteristic D (~ 1340 cm⁻¹), G (~ 1570 cm⁻¹), and two-dimensional (2D) (~ 2670 cm⁻¹) bands. The D band originates from a defect-activated double-resonance process associated with the breathing vibration of six-membered sp² carbon rings, reflecting structural defects and edge disorder. The G band arises from the in-plane stretching of sp²-hybridized carbon atoms and signifies the development of ordered graphitic domains. The 2D band, generated by a second-order double-resonance scattering process, further suggests the formation of graphene-like structures and enhanced graphitic ordering [9]. Collectively, these spectral features confirm the presence of graphene and graphitic carbon within the lignin-derived photothermal layer.

The coexistence of graphene and graphitic carbon creates a hierarchically organized carbon network favorable for broadband light harvesting and efficient photothermal conversion. Consistent with this structural evolution, E-150 exhibits outstanding absorption across the entire ultraviolet–visible–near-infrared range (300–2500 nm), reaching a solar absorptance of 95.48% (Fig. 1(g)). This pronounced enhancement relative to W-150 and C-150 (a control sample obtained by redepositing the extracted lignin onto partially delignified W-150 without subsequent laser graphitization) highlights the effectiveness of lignin-derived graphitization in constructing a highly efficient solar–thermal conversion interface.

While the formation of intermediate water and the graphitized photothermal interface collectively explain the exceptional evaporation performance of E-150, practical deployment involves additional considerations, such as salt accumulation, performance

decay, and structural degradation. Building upon its benchmark evaporation performance, the long-term desalination capability of E-150 is further evaluated under real seawater conditions. After 12 h of continuous seawater evaporation under one-sun illumination, E-150 still exhibits a stable evaporation rate of 2.16 kg·m⁻²·h⁻¹, and negligible salt accumulation is observed (Fig. 1(h)), which underscores its outstanding long-term operational stability under practical desalination conditions. This remarkable salt resistance stems from the retained interconnected multistage channel network within the partially delignified wood scaffold. Due to the different hydraulic conductivities of the hierarchical channels, an in-plane salt concentration gradient is established during desalination, driving transverse ion transport through the ray cells while promoting ion diffusion from the large-diameter channels back into the bulk solution. This multidirectional mass-transfer process effectively suppresses local salt supersaturation and crystallization, enabling stable desalination while allowing accumulated salt crystals to be readily removed under dark conditions, thereby improving the practicality of E-150 for continuous day-night freshwater production.

Beyond its excellent salt resistance, E-150 also exhibits outstanding structural robustness during repeated desalination cycles. After multiple seawater evaporation–drying cycles, E-150 largely retains its original morphology and structural integrity, whereas E-A (a control evaporator prepared from lignin-all-removed wood followed by lignin redeposition and laser-induced graphitization) undergoes severe volumetric shrinkage accompanied by substantial damage to the photothermal layer (Fig. 1(i)). This striking contrast highlights the critical role of partially retained lignin in reinforcing the woody framework and preserving mechanical stability during cyclic operation.

The enhanced structural resilience translates directly into superior operational durability. Owing to the preserved lignin skeleton, E-150 maintains stable evaporation performance throughout 10 consecutive 4 h desalination cycles with negligible performance degradation (Fig. 1(j)). Such robustness demonstrates that the lignin-engineered architecture can withstand repeated hydration–dehydration and thermal stresses without compromising functionality.

Collectively, these results underscore that the dual-functional lignin engineering strategy delivers benefits extending well beyond improved evaporation thermodynamics and solar harvesting. By simultaneously imparting salt resistance, structural robustness, and long-term operational stability, this design addresses several key barriers that have hindered the practical deployment of biomass-based solar evaporators. As a result, E-150 represents a promising step toward scalable and durable solar desalination technologies capable of sustained operation under realistic conditions.

In summary, Wang et al. present an elegant lignin-engineering strategy to overcome two fundamental bottlenecks in biomass-based solar evaporators: the high evaporation enthalpy associated with confined water and the limited solar absorption of natural wood. By judiciously regulating lignin content within the woody framework, the authors promote the formation of intermediate water with reduced hydrogen-bond strength, thereby lowering the energy barrier for vapor generation while preserving efficient capillary water transport. Simultaneously, the extracted lignin is upcycled through laser-induced graphitization to generate a graphene/graphitic carbon photothermal layer with excellent broadband solar absorption. The resulting evaporator achieves a

rare combination of low-enthalpy evaporation, efficient photothermal conversion, salt resistance, structural robustness, and long-term operational stability within a single biomass platform.

Beyond the impressive device performance, the conceptual significance of this work lies in redefining lignin from a passive structural component to an active functional mediator governing both water thermodynamics and solar-to-thermal energy conversion. This integrated approach challenges the conventional view that lignin should simply be removed to improve water transport, instead demonstrating that controlled lignin regulation can unlock synergistic advantages across multiple performance metrics. More broadly, the study highlights how rational manipulation of biomass chemistry can simultaneously optimize mass transport, energy conversion, and mechanical stability.

Looking forward, several opportunities deserve further exploration. A deeper molecular-level understanding of intermediate water formation and evolution within lignocellulosic frameworks could provide fundamental insights into the interplay among biomass chemistry, hydrogen-bonding networks, and evaporation thermodynamics. Extending the concept of lignin-enabled water-state regulation beyond wood to other abundant biomass resources, such as bamboo, agricultural residues, and cellulose-based composites, may further broaden its applicability. In addition, integrating this platform with advanced functionalities, including selective ion recovery, photocatalytic self-cleaning, antimicrobial activity, and atmospheric water harvesting, could enable multifunctional water-treatment systems capable of addressing increasingly complex environmental challenges. From an engineering perspective, future efforts should establish the operational boundaries of lignin-engineered evaporators under realistic service conditions, including fluctuating solar irradiation, varying salinity, complex water chemistries, biofouling, and long-term outdoor operation, while simultaneously developing scalable manufacturing strategies, cost-effective processing routes, and system-level integration for practical decentralized solar desalination. Finally, integrating molecular simulations with artificial intelligence may enable predictive water-state engineering, allowing biomass composition and evaporation performance to be rationally programmed rather than empirically optimized.

As freshwater scarcity continues to intensify worldwide, this work provides a compelling blueprint for the next generation of solar desalination technologies. By coupling water-state engineering with biomass valorization, it opens a promising pathway toward efficient, durable, scalable, and sustainable solutions for decentralized freshwater production.

Data availability

Not applicable.

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Declaration of competing interest

The authors declare no competing interests in this work.

Author contribution statement

H. C.: Writing – original draft. M. N. Q.: Writing – review & editing. T. L.: Writing – review & editing. Y. Z. L.: Writing – review & editing. X. J. Z.: Writing – review & editing, project administration. All the authors have approved the final manuscript.

Use of AI statement

When preparing this manuscript, the authors used DeepSeek only to assist with identifying and correcting grammatical and spelling errors. The authors thoroughly manually revised the full content to guarantee conceptual accuracy, logical coherence, and scholarly rigor. The authors take full responsibility for the final content and publication integrity.

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