

The promise of transparent wood as a multifunctional energy material

Giulio Malucelli, Alberto Mariani & Daniele Nuvoli



Transparent wood has potential not only as a sustainable substitute for glass, but also as a multifunctional energy material whose value lies in the integration of diffuse light management, thermal insulation, mechanical load bearing and sustainability. Its widespread adoption will require application-driven design, realistic durability assessments and alignment with standards.

Partially or completely removing lignin from wood and then infiltrating it with monomers that are polymerized or cured in situ results in a type of composite that combines optical transparency, mechanical strength and eco-friendly sourcing^{1–4}: transparent wood. Its properties make it a potential environmentally friendly alternative to glass in buildings and a reliable base for photonic and optoelectronic devices.

Nonetheless, as studies in this field progress, it is increasingly evident that considering transparent wood just as a substitute for glass is too simplistic. This perspective conceals the features that provide transparent wood with distinct value, such as its diffuse light transmission, direction-dependent optical properties, limited heat conduction and strength under applied mechanical stresses^{5–9}. In this Comment, we argue that transparent wood ought to be redefined as an advanced energy material, emphasizing its remarkable optical, thermal and mechanical properties and its sustainability rather than just its transparency. For instance, it exhibits even better thermal insulation properties than low-emissivity conventional glasses. In addition, it is generally characterized by high haze, thus allowing for homogeneous distribution of the transmitted light, which results in more comfortable ambient illumination, especially for glazing applications.

Main applications

The defining optical feature of transparent wood is not its absolute transparency, but rather its high optical haze^{7,8}. Early research showed that wood treated to remove lignin and add polymers lets plenty of visible light pass through. Still, further findings revealed that its natural cell structure scatters light intensely owing to directional grain patterns. Hence, sunlight spreads evenly without harsh brightness. At comparable transmittance, transparent wood panels distribute light more homogeneously than glass, improving indoor visual comfort and potentially reducing the demand for artificial lighting⁵. The directional nature of scattering, arising from the aligned wood microstructure, also enables optical design strategies that integrate load-bearing capacity and light management within a single material. This scattering constitutes a structurally encoded optical function rather than a secondary

effect. Because the scattering is anisotropic, light is preferentially redistributed along the fibre axis. This increases the internal optical path length while maintaining high transmittance. This behaviour enables applications in passive daylighting, photovoltaic light management, privacy glazing and optomechanical sensing⁷. Transparent wood emerges as a multifunctional, structurally programmable photonic material that couples mechanical strength with anisotropic light control, rather than merely being a sustainable alternative to glass.

Because of their cellular composition, inherited from natural wood, transparent wood composites typically exhibit lower thermal conductivity than glass⁶, which might minimize heat loss through building exteriors (such as windows and other light-transmitting glass parts).

The performance of transparent wood is strongly determined by wood species because the anatomical template governs optical, mechanical and thermal behaviour. Low-density species, such as balsa, provide higher transmittance and stronger directional scattering, which favours daylighting and photovoltaic applications. Denser woods, such as birch, enhance mechanical strength for structural applications, and softwoods with pronounced growth rings, such as pine, have advantageous anisotropic thermal properties.

Finally, its optical diffusion, mechanical durability and suitability for large-area applications make transparent wood suitable for optoelectronic and photonic uses, such as substrates for solid-state lighting, luminescent panels and hybrid photovoltaic systems^{1–4}. Rather than enabling high-precision optoelectronics, transparent wood is suited to roles in which light management and mechanical support are equally important, such as diffusive substrates for devices operating at low temperatures and structurally integrated lighting elements.

Challenges

Despite its potential for applications, several obstacles restrict the practical utilization of transparent wood. One important challenge is durability. Eliminating lignin raises vulnerability to photodegradation, and infiltrated polymers may discolour, become brittle or deteriorate at the interface when subjected to ultraviolet radiation, moisture fluctuations and thermal stresses. Although protective coatings and chemical stabilization methods can enhance performance, they introduce complexity and frequently compromise the sustainability of the final material.

Processing and scalability pose equally important challenges. The production of transparent wood requires several chemical processes, such as delignification, thorough washing, monomer infiltration and in situ polymerization or curing^{2–4}. These processes are time-consuming and may be difficult to scale up without losing uniformity, especially for thick or large wood specimens.

Also, the limited diffusion and anisotropic transport in wood hinder process control and introduce concerns regarding reproducibility and costs that are mostly overlooked in the academic literature.

Although sustainability is frequently mentioned as the primary advantage of transparent wood, this topic is more complex than generally recognized. Although the cellulose scaffold is renewable, delignification requires chemicals – which might be fossil-based and non-biodegradable – water and energy. Life-cycle assessments show that transparent wood may be more sustainable than glass in specific impact areas with optimistic assumptions, yet the findings are very dependent on system boundaries and energy inputs¹⁰. Additionally, the hybrid characteristics of transparent wood make recycling and end-of-life management more complex, leaving circularity largely unaddressed.

Ultimately, important regulatory and standardization obstacles persist. As an example, for use in buildings, transparent wood must satisfy stringent standards concerning fire safety, mechanical integrity, visual uniformity and enduring durability. These issues can also limit the potential applications in optoelectronics, a sector in which standards for qualification and reliability are strictly enforced. At present, the lack of standardized testing procedures and certification routes constitutes a substantial obstacle to real-world implementation.

Outlook

The future of transparent wood will hinge not on its ability to substitute glass, but instead on its promise to transform the design opportunities of multifunctional energy materials. To accomplish this goal, we need to redirect our attention from individual-property standards to optimization tailored for specific applications. This means considering diffuse light transmission, thermal behaviour, structural performance and environmental impact together.

Advancement requires improvements in processing chemistry, including the creation of more sustainable delignification methods and bio-derived or recyclable polymer systems. It also relies on design strategies focused on durability, emphasizing long-term functionality in actual service conditions. Integrating transparent wood into hybrid material systems is equally crucial, as its distinct combination of properties enhances established materials rather than competing with them.

Transparent wood exemplifies the potential and limitations of bio-based engineered materials amid the shift in energy sources.

Its path highlights the necessity for truthful evaluations of performance, cross-disciplinary cooperation and proactive involvement with standards and policy structures.

Giulio Malucelli ¹, **Alberto Mariani** ²✉ & **Daniele Nuvoli** ²

¹Department of Applied Science and Technology, Politecnico di Torino, Torino, Italy. ²Department of Chemical, Physical, Mathematical, and Natural Sciences, University of Sassari, Sassari, Italy.

✉ e-mail: mariani@uniss.it

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References

1. Zhu, M. et al. Transparent and haze wood composites for highly efficient broadband light management in solar cells. *Nano Energy* **26**, 332–339 (2016).
2. Zhu, S. et al. Transparent wood-based functional materials via a top-down approach. *Prog. Mater. Sci.* **132**, 101025 (2023).
3. Li, Y., Fu, Q., Yang, X. & Berglund, L. Transparent wood for functional and structural applications. *Phil. Trans. A Math. Phys. Eng. Sci.* **376**, 20170182 (2018).
4. Zhu, M. et al. Highly anisotropic, highly transparent wood composites. *Adv. Mater.* **28**, 5181–5187 (2016).
5. Li, T. et al. Wood composite as an energy efficient building material: guided sunlight transmittance and effective thermal insulation. *Adv. Energy Mater.* **6**, 1601122 (2016).
6. Bisht, P., Pandey, K. K. & Srinivas, G. Physicochemical characterization and thermal behaviour of transparent wood composite. *Mater. Today Commun.* **31**, 103767 (2022).
7. Montanari, C., Li, Y., Chen, H., Yan, M. & Berglund, L. A. Transparent wood for thermal energy storage and reversible optical transmittance. *ACS Appl. Mater. Interfaces* **11**, 20465–20472 (2019).
8. Mi, R. et al. Scalable aesthetic transparent wood for energy efficient buildings. *Nat. Commun.* **11**, 3836 (2020).
9. Song, J. et al. Processing bulk natural wood into a high-performance structural material. *Nature* **554**, 224–228 (2018).
10. Jiang, F. et al. Wood-based nanotechnologies toward sustainability. *Adv. Mater.* **30**, 1703453 (2018).

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Competing interests

The authors declare no competing interests.