Effect of Porous Silica on the Thermal Performance of Epoxy-Based Transparent Wood

Tayma Hadi

Thalzurai@gmail.com

Mentor: Dr. Yipeng Chen

Yipeng.chen@kaust.edu.sa

Prof. Qiaoqiang Gan

Qiaoqiang.gan@kaust.edu.sa

June 30th - August 24, 2026

Abstract

Transparent wood is a promising alternative to conventional glazing due to its lightweight, renewable structure and optical transparency; however, epoxy infiltration replaces the air-filled pores of natural wood and creates a continuous pathway for heat transfer, limiting its thermal insulation. This study investigated the use of porous silica as a filler to improve the thermal performance of epoxy-based transparent wood while maintaining its optical properties. Delignified balsa wood was infiltrated with epoxy containing 0, 0.25, and 0.5 wt% porous silica. The resulting composites were characterized using scanning electron microscopy, UV–Vis spectroscopy, and thermal conductivity measurements to evaluate their morphology, optical transmittance, and thermal behavior. SEM confirmed successful silica incorporation, with particles remaining distributed as isolated inclusions within the epoxy matrix. Increasing silica content reduced visible transmittance, while thermal conductivity showed no concentration-dependent reduction. These results indicate that the low silica loadings investigated were insufficient to substantially disrupt the dominant heat-transfer pathway within the wood–epoxy structure. The findings highlight the importance of filler architecture and pore accessibility in designing transparent wood for improved thermal management.

Contents

1. Introduction 4

1.1. Background 4

1.2. Transparent Wood 5

1.3. Porous Silica as a Thermal-Insulating Filler 5

1.4. Research Objective 6

2. Methodology 7

2.1. Materials 7

2.1.1. Wood Scaffold 7

2.1.2. Epoxy Resin 7

2.1.3. Porous Silica 7

2.1.4. Chemicals Used for Wood Treatment 7

2.2. Experimental 8

2.3. Characterization 9

2.3.1. Scanning Electron Microscopy (SEM) 9

2.3.2. UV–Vis Spectroscopy 9

2.3.3. Thermal Conductivity 9

3. Results and Discussion 10

3.1. Morphological Characterization of the Wood Scaffold 10

3.2. Silica Distribution in Transparent Wood 11

3.3. Optical Properties 12

3.4. Thermal Conductivity 13

3.5. Discussion of the Thermal Behavior 14

3.6. Relationship Between Thermal and Optical Performance 14

3.7. Potential Direction for Further Development 14

4. Conclusion 15

5. References 16

1. Introduction

1.1. Background

Energy consumption associated with cooling buildings is a significant concern, particularly in hot and arid climates. Building windows represent an important pathway for both solar heat gain and conductive heat transfer, making the development of glazing materials with improved thermal performance an important area of research.

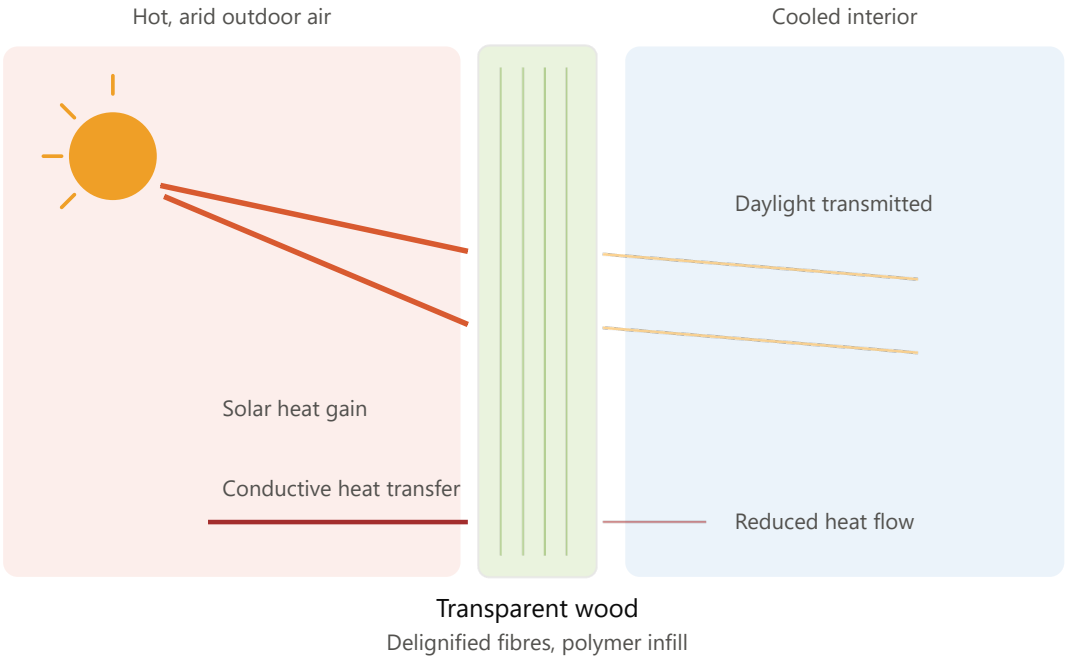


Figure1 . Illustration of proposed qualities of transparent wood

Conventional transparent materials, including glass, low-emissivity glass, polymer glazing, and silica aerogel-based systems, each present different advantages and limitations in terms of optical transparency, thermal insulation, mechanical properties, and structural stability. Transparent wood has emerged as a promising alternative because it combines the lightweight and renewable structure of natural wood with optical transparency and the potential for functional thermal management.

1.2. Transparent Wood

Natural wood consists of an interconnected cellular structure containing air-filled lumens, which contribute to its relatively low thermal conductivity. To produce transparent wood, lignin can be removed from the wood while maintaining the aligned cellulose framework, producing a porous cellulose scaffold. The scaffold can then be infiltrated with a polymer such as epoxy to reduce the refractive-index mismatch between the cellulose structure and the surrounding medium, thereby reducing light scattering and enabling optical transparency. However, replacing the air-filled lumens with epoxy also introduces a continuous polymer phase through the wood structure, which can create a more continuous pathway for heat transfer and consequently reduce the thermal insulation provided by the original wood structure.

1.3. Porous Silica as a Thermal-Insulating Filler

To address the thermal trade-off associated with epoxy infiltration, porous silica was investigated as a filler within the epoxy matrix. Porous silica possesses a highly porous structure and intrinsically low thermal conductivity, making it a potential means of introducing additional low-conductivity regions into the transparent wood composite. Incorporating porous silica into the epoxy could therefore provide a route to partially compensate for the thermal insulation lost when the natural air-filled lumens are replaced by polymer.

1.4. Research Objective

The objective of this study was to investigate whether incorporating porous silica into epoxy-based transparent wood could reduce thermal conductivity while maintaining acceptable optical transparency.

The effect of porous silica loading on the structure, optical properties, and thermal conductivity of the resulting transparent wood composites was investigated at 0, 0.25, and 0.5 wt% silica.

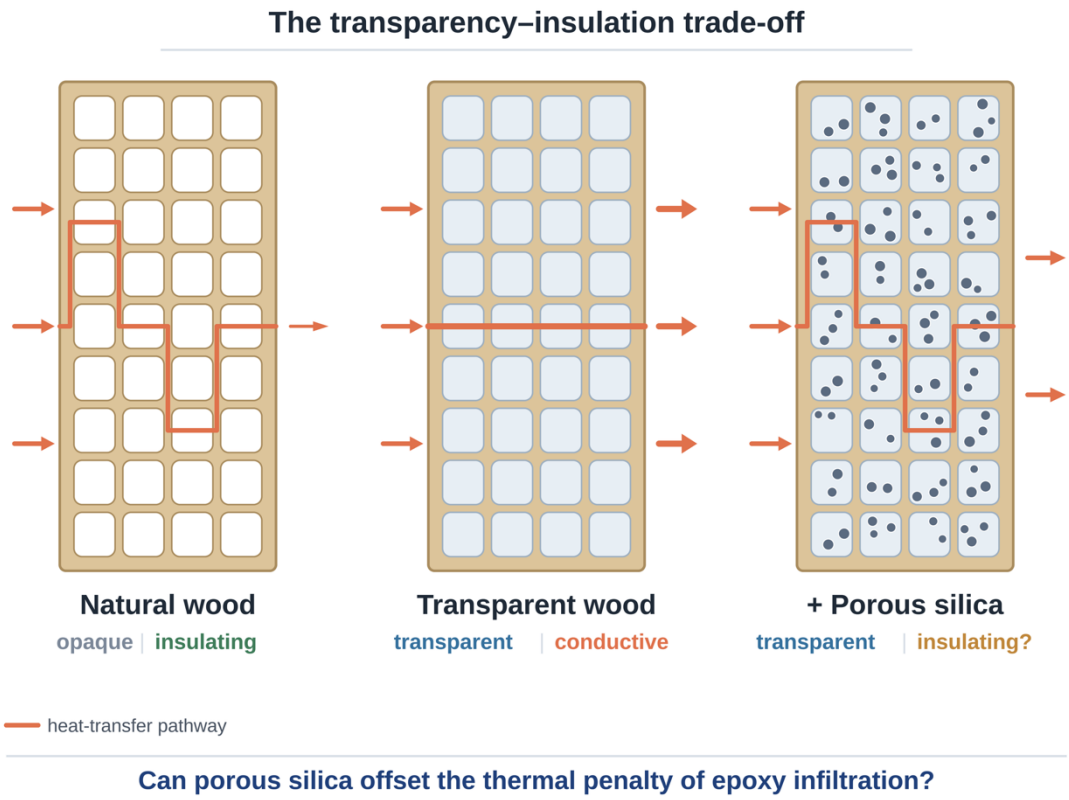


Figure 2 . Comparison between natural wood, transparent wood, and transparent wood with silica

2. Methodology

2.1. Materials

2.1.1. Wood Scaffold

Balsa wood was used as the cellulose scaffold for the fabrication of transparent wood. Wood samples with different dimensions were prepared, with thicknesses ranging from **1 mm to 1 cm** and a fixed length of approximately **2 cm**, depending on the subsequent fabrication and characterization requirements.

2.1.2. Epoxy Resin

Epoxy resin was used to infiltrate the delignified wood scaffold and produce the transparent wood.

2.1.3. Porous Silica

Porous silica was incorporated into the epoxy matrix at different loadings to investigate its effect on the thermal and optical properties of transparent wood. Three silica concentrations were investigated: 0, 0.25, and 0.5 wt%, with the silica-free formulation serving as the control

2.1.4. Chemicals Used for Wood Treatment

A 1:1 solution of hydrogen peroxide (H_2O_2) and acetic acid was used to bleach the balsa wood samples. The samples were immersed in the bleaching solution and placed in a hot bath at 80 °C under continuous stirring for 6 h. Following bleaching, the samples were thoroughly rinsed with deionized (DI) water, followed by immersion in ethanol for 12 h and subsequently in acetone for 12 h to remove residual water and facilitate solvent exchange.

2.2. Experimental

Balsa wood samples with dimensions ranging from 1 mm to 1 cm in thickness and approximately 2 cm in length were prepared for the fabrication process. The samples were immersed in a 1:1 mixture of H_2O_2 and acetic acid and placed in a hot bath maintained at 80 °C under continuous stirring for 6 h. Following the bleaching treatment, the samples were rinsed with DI water, immersed in ethanol for 12 h, and then immersed in acetone for 12 h.

Porous silica was dispersed in epoxy at three different loadings: 0, 0.25, and 0.5 wt%. The silica-free epoxy formulation was used as the control.

The silica–epoxy mixtures were infiltrated into the delignified balsa wood scaffold. Epoxy infiltration filled the wood lumens and reduced optical scattering, resulting in transparent wood.

The resulting transparent wood samples were prepared for structural, optical, and thermal characterization.

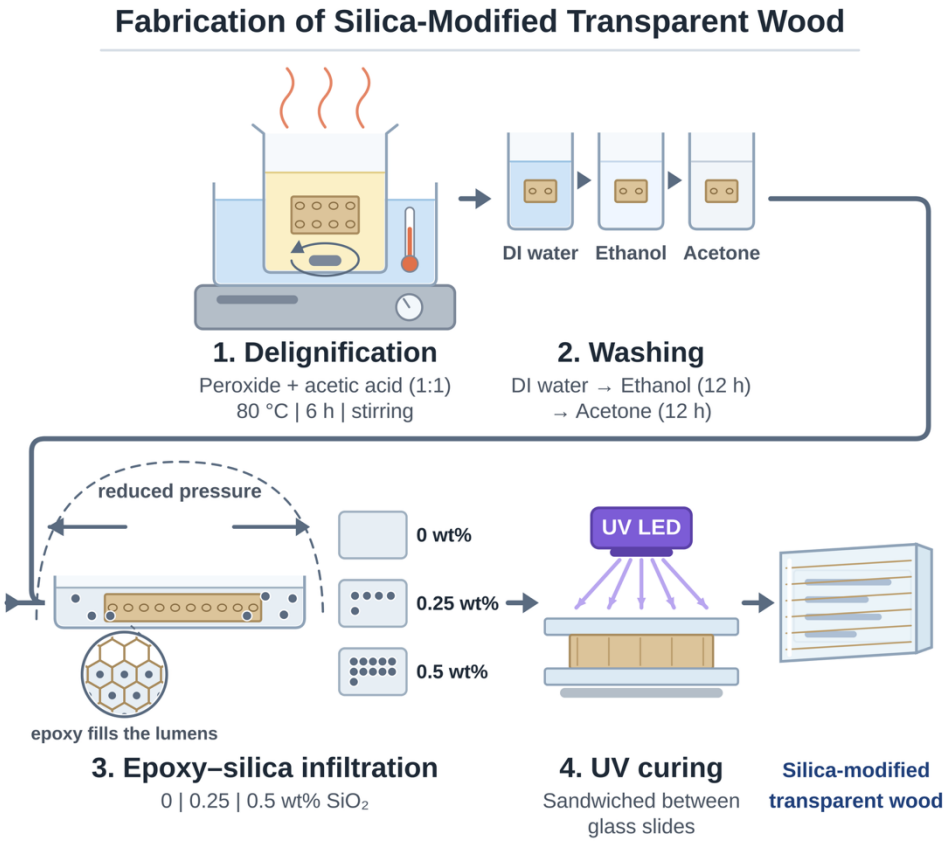


Figure3 . Schematic overview of the fabrication and characterization process for silica-modified transparent wood.

2.3. Characterization

2.3.1. Scanning Electron Microscopy (SEM)

Scanning electron microscopy was used to examine the morphology of the wood scaffold and the cured transparent wood. Natural and bleached balsa wood were examined to evaluate preservation of the cellular structure following delignification, while transparent wood samples containing 0, 0.25, and 0.5 wt% silica were examined to evaluate silica distribution, particle aggregation, and the wood–epoxy structure. The SEM images showed that silica particles were incorporated into the epoxy matrix and remained as isolated inclusions rather than forming a continuous network.

2.3.2. UV–Vis Spectroscopy

UV–Vis spectroscopy was used to evaluate the optical transmittance of transparent wood containing different silica loadings. Visible transmittance was compared across the 0, 0.25, and 0.5 wt% silica samples.

2.3.3. Thermal Conductivity

Through-plane thermal conductivity measurements were performed on all three silica loadings, with each sample compared with the silica-free control under the same measurement conditions.

3. Results and Discussion

3.1. Morphological Characterization of the Wood Scaffold

SEM images of natural balsa wood showed the original open cellular structure and air-filled lumens. Following delignification, the aligned cellulose structure and open lumens remained intact, indicating that the chemical treatment removed lignin while preserving the porous architecture required for subsequent polymer infiltration.

First, the porosity is continuous and interconnected, so it forms an uninterrupted low-conductivity path through the material rather than a scatter of separate cavities. Second, it is entirely air-filled, and that air is why untreated wood conducts heat so poorly — still air sits near 0.026 W $m^{-1}K^{-1}$ against roughly 0.2 for cured epoxy.

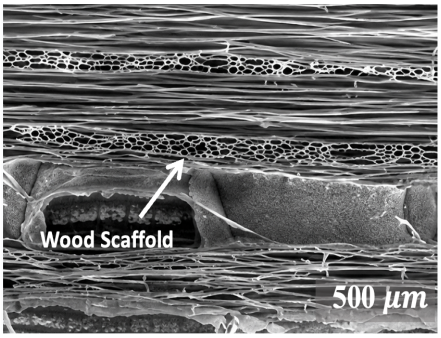


Figure4 NATURAL BALSA WOOD

The same architecture survives the chemical treatment. Fibres remain aligned and parallel, the cell walls are unbroken, and the lumens are still open, bleaching stripped the lignin without collapsing the scaffold, which is the single requirement this step has to meet.

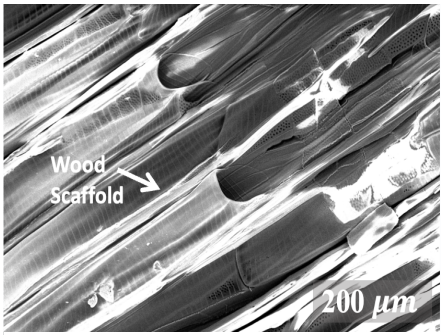


Figure5 DELIGNIFIED WOOD

After infiltration and curing the open cavities are gone. The fracture surface is continuous and resin-covered, with cell walls encased rather than exposed, evidence that epoxy reached the lumen interiors and bonded to them. The arrow marks a filled lumen. Equally important is what is absent: not one bright particle appears anywhere in the field. The absence of bright particles in the control supports their identification as silica particles in the subsequent images.

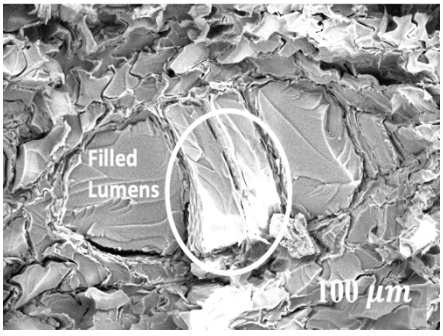


Figure6 0 wt% SILICA

Bright spheres now appear across the epoxy-rich region, ranging from well under a micron to a few microns and separated from one another by tens of microns of clean resin. The circled feature is the largest cluster in the field, just two touching particles, so there is no sign of the coarse agglomerates or settled bands that would indicate poor mixing.

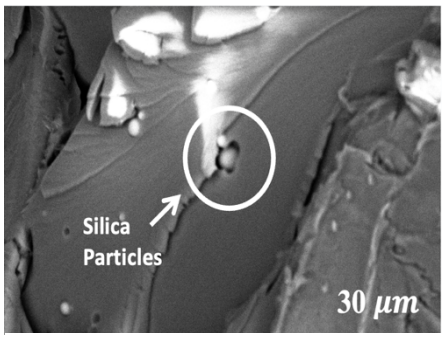


Figure7 0.25 wt% SILICA

More particles per field, spanning a wider size range from sub-micron up to roughly ten microns, confirming that the intended composition reached the sample and that the powder is polydisperse. Note the magnification differs from the 0.25 wt% frame, a 20 µm scale bar against 30 µm, so number densities cannot be compared quantitatively between them. Qualitatively the arrangement is unchanged: discrete inclusions in continuous resin, occasional touching pairs, and nowhere a chain spanning the field. The minor phase never percolates, so epoxy sets the heat path.

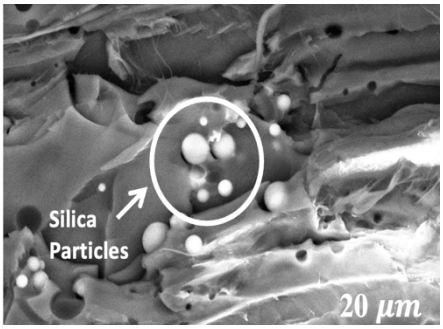


Figure8 0.5 wt% SILICA

3.2. Silica Distribution in Transparent Wood

SEM confirmed the successful incorporation of porous silica into the epoxy matrix. The 0 wt% sample served as the silica-free control, while the 0.25 wt% sample showed sparse, separated silica particles. The 0.5 wt% sample contained a greater number of particles, but the particles remained predominantly isolated. No obvious continuous silica network or large-scale agglomeration was observed. This isolated distribution indicates that the epoxy remained the dominant continuous phase through which heat could be transferred.

3.3. Optical Properties

Increasing silica loading resulted in a decrease in visible transmittance, while haze increased with increasing silica content. These results demonstrate an optical trade-off associated with increasing the silica concentration, as the incorporation of additional particles introduces greater light scattering within the composite.

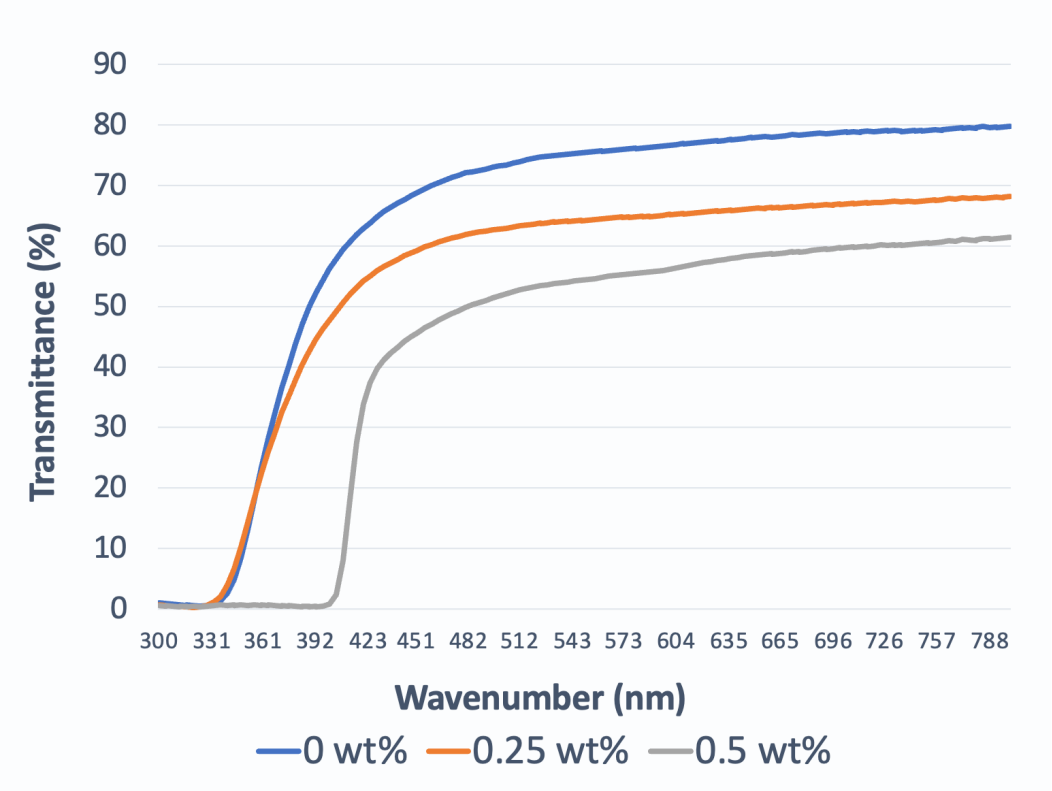


Figure9 UV-VIS SPECTROSCOPY

3.4. Thermal Conductivity

The measured thermal conductivity values were approximately 0.2642 W m^{-1} K^{-1} for the 0 wt% sample, 0.2601 W m^{-1} K^{-1} for the 0.25 wt% sample, and 0.2878 W m^{-1} K^{-1} for the 0.5 wt% sample. No concentration-dependent decrease in thermal conductivity was observed. The 0.25 wt% sample showed only a small difference from the control, whereas the 0.5 wt% sample exhibited a higher thermal conductivity. Because replicate measurements and associated uncertainties were not evaluated in this study, the small difference between the 0 and 0.25 wt% samples should not be interpreted as a significant reduction.

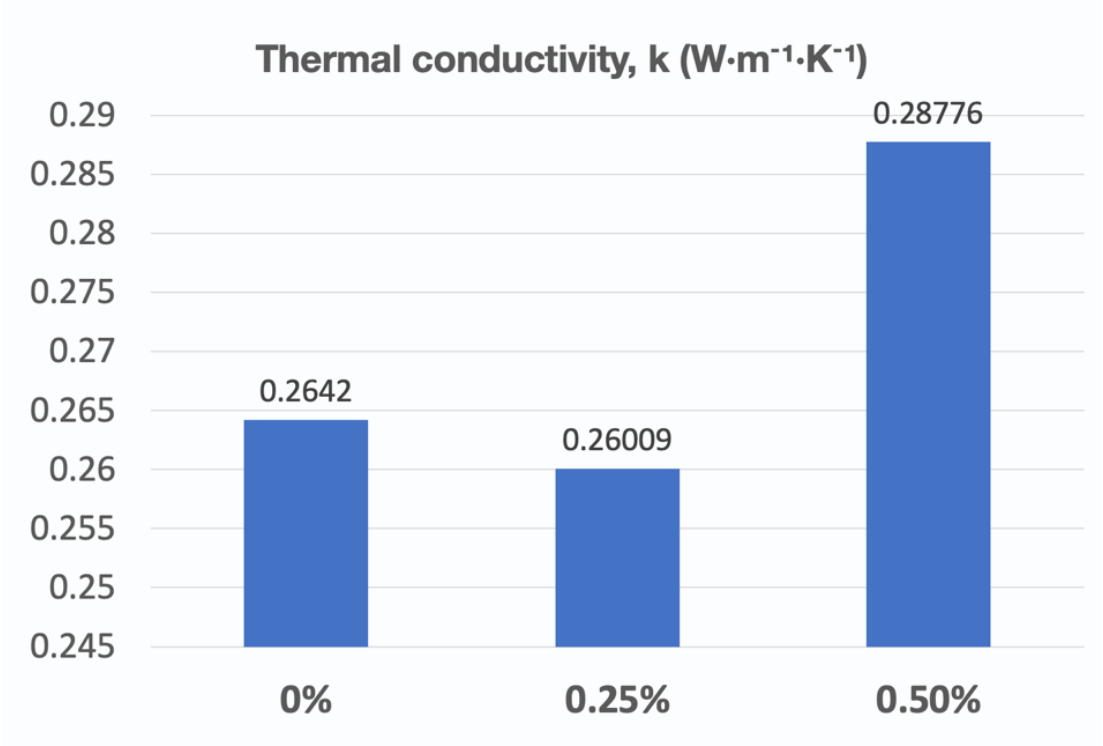


Figure10 THERMAL CONDUCTIVITY

3.5. Discussion of the Thermal Behavior

The lack of improvement in thermal conductivity can be related to the composite structure observed by SEM. Natural wood contains interconnected air-filled lumens that interrupt heat transfer, whereas epoxy infiltration replaces this air and creates a more continuous heat-transfer pathway. Although porous silica has intrinsically low thermal conductivity, the low silica loading and isolated particle distribution may be insufficient to substantially disrupt the continuous epoxy matrix. In addition, the porous network of silica may be accessible to the epoxy during infiltration. If epoxy penetrates the pores, the air responsible for the silica's low thermal conductivity can be replaced by a more conductive solid phase. Therefore, the intrinsic thermal properties of porous silica may not be directly translated into the thermal performance of the final composite.

3.6. Relationship Between Thermal and Optical Performance

Increasing silica content did not provide the intended thermal benefit while simultaneously reducing optical transmittance and increasing haze. Therefore, simply increasing the silica concentration does not appear to be an effective strategy for simultaneously improving thermal insulation and maintaining transparency. The results suggest that silica morphology, pore accessibility, spatial distribution, and the silica–epoxy interface may be more important than filler loading alone.

3.7. Potential Direction for Further Development

The continuous wood–epoxy structure may alternatively be explored for controlled heat spreading rather than thermal insulation. The present results suggest that the thermal behavior of the material could potentially be tuned through its spatial structure and heat-transfer pathways.

4. Conclusion

This study investigated the effect of porous silica incorporation on the thermal performance of epoxy-based transparent wood at 0, 0.25, and 0.5 wt% silica loading. SEM confirmed preservation of the wood scaffold after delignification and successful incorporation of silica into the epoxy matrix, with the particles remaining largely isolated. Increasing silica loading reduced optical transmittance and increased haze, while no concentration-dependent reduction in thermal conductivity was observed.

The results indicate that the investigated silica loadings were insufficient to disrupt the dominant heat-transfer pathway within the wood–epoxy composite. The findings also suggest that preservation of silica porosity and control over filler architecture may be more important than simply increasing silica content. Future work should therefore investigate strategies for maintaining accessible low-conductivity pores and controlling silica distribution within the transparent wood structure.

5. References

- Liu, X., Li, M.-C., Lu, Y., Li, Z., Liu, C., Liu, Z., Mei, C., & Wu, Q. (2024). Cellulose nanofiber- coated delignified wood as an efficient filter for microplastic removal. *Progress in Natural Science: Materials International*, *34*(1), 162–171. https://doi.org/10.1016/j.pnsc.2024.02.010
- Li, Z., Zhang, Z., Huang, H., Liu, Y., Wu, Y., Pan, Z., Qing, Y., Tian, L., Li, Z., Zhao, X., & Wu, Y. (2026). Sustainable transparent bamboo/W-VO2 composites for solar modulation and energy-efficient buildings. *Journal of Bioresources and Bioproducts*, *11*(1), 100225. https://doi.org/10.1016/j.jobab.2025.11.001
- Mi, R., Li, T., Dalgo, D., Chen, C., Kuang, Y., He, S., Zhao, X., Xie, W., Gan, W., Zhu, J., Srebric, J., Yang, R., & Hu, L. (2019). A Clear, Strong, and Thermally Insulated Transparent Wood for Energy Efficient Windows. *Advanced Functional Materials*, *30*(1). https://doi.org/10.1002/adfm.201907511
- Chen, K., Yue, K., Qian, J., Song, X., Wu, P., & Li, Q. (2026). Innovative fabrication of high- performance transparent wood from fast-growing poplar: Enhancing optical and mechanical properties. *Polymer Testing*, *158*, 109186. https://doi.org/10.1016/j.polymertesting.2026.109186
- Ram, F., Höglund, M., Liao, M., Hallberg, T., Jonsson, M. P., Berglund, L. A., & Shanker, R. (2025). Transparent Wood for Passive Radiative Cooling of Solar Absorbers. *Nano Letters*, *25*(38), 14025– 14031. https://doi.org/10.1021/acs.nanolett.5c02994
- Chen, F., Ritter, M., Xu, Y., Tu, K., Koch, S. M., Yan, W., Bian, H., Ding, Y., Sun, J., & Burgert, I. (2024). Lightweight, Strong, and Transparent Wood Films Produced by Capillary Driven Self- Densification. *Small*. https://doi.org/10.1002/smll.202311966
- Li, Y., Fu, Q., Yu, S., Yan, M., & Berglund, L. (2016). Optically Transparent Wood from a Nanoporous Cellulosic Template: Combining Functional and Structural Performance. *Biomacromolecules*, *17*(4), 1358–1364. https://doi.org/10.1021/acs.biomac.6b00145

- Frey, M., Widner, D., Segmehl, J. S., Casdorff, K., Keplinger, T., & Burgert, I. (2018). Delignified and Densified Cellulose Bulk Materials with Excellent Tensile Properties for Sustainable Engineering. *ACS Applied Materials &Amp; Interfaces*, *10*(5), 5030–5037. https://doi.org/10.1021/acsami.7b18646
- Wang, S., Li, L., Zha, L., Koskela, S., Berglund, L. A., & Zhou, Q. (2023). Wood xerogel for fabrication of high-performance transparent wood. *Nature Communications*, *14*(1). https://doi.org/10.1038/s41467-023-38481-x
- Li, Y., Yang, X., Fu, Q., Rojas, R., Yan, M., & Berglund, L. (2018). Towards centimeter thick transparent wood through interface manipulation. *Journal of Materials Chemistry A*, *6*(3), 1094–1101. https://doi.org/10.1039/c7ta09973h
- Jele, T. B., Andrew, J., John, M., & Sithole, B. (2023). Engineered transparent wood composites: a review. *Cellulose*, *30*(9), 5447–5471. https://doi.org/10.1007/s10570-023-05239-z