Transparent Wood or Bamboo Composites as a Suitable Topic for College-level Education, Research, and Outreach Activities in the Next Decade

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Due to societal interest in reducing carbon emissions, transparent wood has attracted increasing attention since 2016. Research on transparent wood composites has become a hot spot in the forest product field. Many challenges and limitations still need to be addressed, involving large-dimensional manufacturing, weak interfacial bonding, difficult three-dimensional tunable, and insufficient optical transmittance. A series of student-led projects is proposed in this editorial to address these barriers. A further goal in transparent wood composite development is to replace single-use plastics (*e.g.* polyethylene terephthalate food containers). It is proposed to Integrate transparent wood composite research into the education and outreach activities of wood science and forestry university programs.

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Challenges and Limitations of Transparent Wood (Bamboo) Composites

Wood and plastic composites (WPCs) have become well-developed over the past two decades for diverse industrial applications because of their light weight, dimensional stability, and cost-competitiveness. However, WPCs have intrinsic limitations in mechanical properties due to poor compatibility of heterogenous wood flour, additives, and polymer matrix. In addition, fire-retardant properties of WPCs are often achieved at the cost of mechanical properties.

As an advanced form of wood-plastic composites, transparent wood was initially discovered by Fink (1992). Owing to its high transmittance and excellent mechanical properties, this novel concept has been rapidly developing since 2016. Due to its unique pore structures remaining after de-lignification, such wood can be impregnated with resin to prepare high-performance transparent wood-based composite materials. Transparent wood composite development so far has been mainly limited to small dimensions. When delignification has been applied to large-dimensional wood veneers, there has been a reduction of tissue adhesion of vascular bundles and parenchyma cells. As a result, the delignified wood is vulnerable to cracking and breakage of wood cellular structure. Additionally, de-lignification of thick wood usually requires tedious protocols that have low efficiency due to the slow diffusion of chemicals *via* wood channels into secondary walls (S1, S2, and S3) of wood cells. More than 80% lignin, hemicellulose, and extractions are initially present in the secondary wall, and approximate 20% of them are stored in the primary wall and middle lamella (Shmulsky *et al.* 2011). The primary challenge currently is a lack of effective methods to manufacture large dimensional and thickness controllable transparent woods. Looking back to the microstructures of wood cells, the abundant hydroxyl groups on cell walls with exposure to the lumen and middle lamella can contribute to the physically and chemically cross-linking reactions *via* covalent, dynamic covalent, and even supramolecular interactions. These pre-cross-linking treatments as binders make it possible to mediate the cellulose backbone disintegration during the de-lignification process and to maintain the integration of large-dimensions of de-lignin woods. Additionally, inspired by the plywood manufacturing (Shmulsky *et al.* 2011), it is possible to obtain sufficient thickness of transparent wood by wood veneer rotatory cutting and subsequent hot-press lamination. As another barrier of developing transparent wood composites, the interfacial compatibility and bonding are not satisfactory for robust mechanical applications. For instance, the well-matched refractive index of impregnated hydrophobic poly (methyl methacrylate) or epoxy resin does not adhere well to hydrophilic delignified wood cells. The delignification process followed by post-treatments *via* surface activations of wood cells (*e.g*., aldehyde groups) sounds interesting as a way to enhance the interfacial adhesives or interactions. Optimization of impregnation with waterborne epoxy and polyurethane is another feasible solution, enhancing interfacial interactions of transparent wood composites. As another limitations, high-performance transparent wood composites usually work on shape-manageable applications at two dimensions, while conventional WPCs can be manageable in three dimensions *via* tunable extrusion dies during melting compounding. Thus, developing transparent wood composites with shape-ability and three-dimensional (3D) manageable are highly desirable. Thanks to the shape-memory polymers and shape-memory traits of dynamic-covalent crosslinked vitrimer (*e.g*., epoxy resin and transparent polyurethane), there are viable ways to achieve the manufacturing of 3D transparent wood composites. These transparent woods with editable dimensions and thickness along with tunable shapes have promising applications in the sustainable building glass and smart agricultures. Among the greatest challenges to implementation of such technologies is a lack of suitable equipment. Wood scientists need to think about its development during the next decade. Finally, tuning optical haze and transmittance of transparent wood composites is a long-term task for high-resolution transparent wood composite development. Post-modification *via* surface coating of transparent or non-color materials with similar refractive index matching that of wood walls of delignified wood is a promising approach to manage the optical haze effects.

Transparent bamboo-based composites are another promising goal for research and education, despite their lack of development. Such efforts can benefit from some unique traits of bamboo, involving short harvestable maturity (3 to 5 years) and annual selective harvesting without the need of replantation (Shmulsky *et al.* 2011). The delignified bamboo-based materials are an ideal natural template for advanced transparent bamboo-based composite material development. Compared to the conventional bamboo and plastic composites *via* melting extrusion manufacturing, transparent bamboo-based composites made by impregnation of bamboo templates with thermoplastics provide new insights for wood science fields.

Potentials of Transparent Wood (Bamboo) Composite Packaging Materials

The global packaging industry is undergoing a significant shift as regulations increasingly limit the use of single-use plastics due to environmental concerns. Cellulose- or cellulose nanofiber-based sustainable packaging materials are being developed to replace food packaging plastics (*e.g.*, polyethylene terephthalate or polypropylene food containers). All-cellulose composite materials that can be called “single polymer composites” have attracted significant interest in academia. The nature template of delignified wood with impregnated cellulose, cellulose nanofibers or derivatives (*e.g.*, ethyl cellulose and cellulose acetate) holds promise for advanced transparent wood-based sustainable packaging materials. Due to its mechanical flexibility and thermoformable nature, diverse transparent wood-based single polymer composites can be produced *via* thermoforming and hot-press molding for tableware, food containers, or drinking straws, along with cups. These are exciting alternatives to single-use plastics. Antioxidant and anti-microbial active functional packaging can be achieved by doping with active additives; such materials can be further manufactured for functional food packaging material applications (*e.g.*, shell-life extension). Owing to unique temperature-, pH- or pressure-sensitive properties of hydroxypropyl cellulose and chitosan cholesteric liquid crystals, these chiral nematic liquid crystal solutions impregnated into de-lignin wood can produce intelligent transparent wood composite packaging as indictors or sensors to monitor the qualities of packaging materials. Additionally, transparent wood-based single polymer composites with room temperature phosphorescence and fluorescence properties are interesting for anti-counterfeiting packaging material applications, especially with circularly polarized luminescence recognitions.

Inspired by cellulose aerogels or foams, delignification of wood or bamboo provides a promising path for further developing into transparent wood foams *via* supercritical CO_2 or freeze-drying protocols. Due to the well-preserved wood cell structures after delignification process, these de-lignin wood or bamboo foams or transparent wood-based single polymer foams have been found to maintain outstanding mechanical properties and energy absorbance capacities. They have potential for cushioning and insulating foam packaging material applications in the extreme environments. For instance, they could be used in parachute-free airdrops by the US Army. By their further integration with phase-change particles, these transparent wood-based foam packaging materials have potential to be used in cold-chain transportation in regions such as the Amazon. As another example, they could maintain food quality during its long-term transportation, for instance, seafoods from southern Florida and Louisiana to Western Arizona and California, US.

Integration of Research on Transparent Wood-based Composite Materials into Interdisciplinary Education of Wood Science and Forestry Products

Research and education are becoming increasingly interrelated and mutually reinforced in modern university curricula. It is desirable to think about the research on transparent wood-based composites as a suitable topic for students’ training in STEM educational programs. As the transparent wood-based projects for junior-level students at their second-semester studies and senior-level students for capstone bachelor’s degree need to make use of both polymer chemistry course knowledge and wood anatomy knowledge, they need to master interdisciplinary knowledge. Especially, for the four-year students, whose interests are continuously pursuing Ph.D. programs, the capstone project research experience of “transparent wood” can enrich their personal statements and/or diversity statements and enhance their curriculum vitae in applications of graduate school programs. Most importantly, these valuable project experience can enhance their application opportunities successfully for U.S. National Science Foundation Graduate

Research Fellowships and National Graduate Fellowships of U.S. Department Agriculture and the National Institute of Food and Agriculture. To equip undergraduate students majoring in wood science with interdisciplinary knowledge, chemistry and chemical engineering related courses are suggested to construct students' unique interdisciplinary knowledge structure and foster problem-solved capacities from diverse perspectives along with team collaborations. For the details, the course in terms of wood anatomy knowledge can be taken for sophomore students during their first semester of 2nd year studies. Additionally, the courses regarding Polymer Chemistry along with Principle of Polymer Engineering can be taught for junior students in their second semester of 3rd year studies or senior students at their first semester of fourth year studies as they need to have enough knowledge in Introductory to Organic Chemistry and Physical Chemistry along with General Chemistry, which are usually completed during their second- to early third-year studies. The goal of interdisciplinary course studies is to help students become confident in carrying out a research project successfully as they are equipped with solid knowledge in wood science and technology and chemistry along with polymer engineering. For instance, students will need to draw upon their knowledge of such topics as condensation polymerization (polymer chemistry) and microstructures of wood cells and lignin and hemicellulose compositions and distributions in wood cells (wood science and forestry products), when they work on a research project, which might be called "synthetic epoxy resin vitrimer impregnating de-lignin transparent wood composites". Skills in project communications and effective teamwork can be developed in the course of such a project. PowerPoint presentations and chalk talks by students in wood science classes and team projects are effective ways to train students in critical thinking and logical expression. Such practices are conductive to train students to be able to work under pressure for adaptable real work scenarios in society. According to the education psychology analysis, the presentation of group project results can enhance students' confidence. Students also can gain experience in discussing their findings, writing reports, and communicating their work logically, thereby developing their readiness of a career. Efforts to teach tricky concepts at the undergraduate level can benefit from internships, field trips, and hand-on practices. For instance, students can be challenged to come up with alternatives for toxic isocyanate-based adhesive alternatives from oriented strand board practices. Most importantly, the overarching goal of research and education is to serve society. Outreach activities such as a science day with the theme about "delignified transparent wood" and "waterborne polyurethane vitrimer synthesis" are the needs for high-school student and workshop for the middle school teachers.

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