CHAPTER 14

GREEN FABRICATION TECHNIQUES FOR TRANSPARENT WOOD COMPOSITES: PIONEERING SUSTAINABLE MATERIALS FOR THE FUTURE

NONTOBEKO P. SIMELANE,[1]
OLATUNDE S. OLATUNJI,[1]
MAYA J. J.[2] AND ANDREW J.[2]
[1]DEPARTMENT OF CHEMISTRY, FACULTY OF SCIENCE,
UNIVERSITY OF KWAZULU NATAL, PRIVATE BAG X01, 175
UNIVERSITY RD, WESTVILLE, 3630, SOUTH AFRICA.
[2]BIOREFINERY INDUSTRY DEVELOPMENT FACILITY (BIDF),
COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH (CSIR),
DURBAN, SOUTH AFRICA.

Abstract

As the world battles with environmental challenges and the need for sustainable alternatives to conventional building materials such as glass, transparent wood composites have emerged as a promising solution. Transparent wood composites, derived from renewable and abundant wood resources, offer a unique combination of strength, thermal insulation, and optical transparency.

This chapter explores the latest progress in transparent wood composites, focusing on innovative and eco-friendly fabrication techniques that pave the way for widespread adoption in various applications. It highlights using sustainable wood sources, such as fast-growing trees, and reducing energy-intensive processing steps.

The chapter also explores other emerging technologies, including nanocellulose reinforcements and bio-based polymers, that have the potential to revolutionize the fabrication of transparent wood composites.

Through a comprehensive review of recent advancements and prospects, this chapter aims to provide researchers with valuable insights into the exciting world of transparent wood composites. Focusing on green fabrication techniques underscores the critical role transparent wood composites can play in building a more sustainable and environmentally responsible future.

Keywords: Transparent wood, Bio-based polymers, Sustainability, Green fabrication techniques.

14.1 Introduction

Green fabrication techniques for transparent wood composites represent an innovative approach to producing sustainable materials for the building and construction sector. This emerging field combines traditional wood engineered with other transparent biopolymers to create a new class of eco-friendly, energy-efficient, and aesthetically pleasing building materials (Wachter, Rantuch and Štefko 2023; Zhu, Biswas, Qiu, Yue *et al.* 2022; Akpan, Wetzel and Friedrich 2021). Wood has been a fundamental construction material for centuries due to its abundance, renewability, and structural properties (Ding, Pang, Lan, Yao *et al.* 2022; Chen and Hu 2021). However, its use in transparent applications, such as windows and facades, has been limited because of its inherent opacity.

Wood is primarily composed of lignin, cellulose, and the hemicelluloses. Transparent wood is a recent innovation that involves removing or modifying lignin (the light-absorbing component) while preserving its wood ultrastructure. This process renders wood partially or fully transparent, depending on the lignin removal or modification degree. Sustainable construction practices using transparent wood can significantly improve energy efficiency, reducing carbon emissions and combating climate change (Li, Zhu, Yang, Song *et al.* 2016; Lehmann 2013).

Buildings significantly contribute to greenhouse gas emissions due to their energy consumption for heating, cooling, lighting, and other functions. This is mainly due to transparent materials, such as glass and plastic, used extensively in construction. These materials have drawbacks, such as high energy consumption during production, limited sustainability, and concerns over their environmental impact (Hussain and Kamal 2015; Blengini, Busto, Fantoni and Fino 2012). This chapter aims to comprehensively explore and elucidate the latest green fabrication techniques and sustainable methodologies employed in developing transparent wood composites. This chapter aims to comprehensively understand the innovative approaches and eco-friendly materials in transparent wood fabrication. It also highlights their environmental impact and potential applications. Through a systematic review of innovative research and practical case studies, this chapter seeks to contribute to advancing sustainable materials and technologies in transparent wood composites.

14.2 Transparent Wood

14.2.1 What is Transparent Wood?

Transparent wood is a material made from wood engineered to have the optical properties of glass while retaining the mechanical properties of wood. This is done by removing or modifying lignin, a component in the wood that gives it its characteristic brown and opaque appearance, and replacing it with a transparent polymer that matches the refractive index of the wood scaffold. This process allows light to pass through the wood, making it transparent. Transparent wood was first reported in 1992 by Siegfried Fink (Fink 1992) but it was studies conducted recently that sparked the rush of interest in functional transparent wood composites and coatings (Li, Fu, Yu, Yan *et al.* 2016; Zhu, Song, Li, Gong *et al*. 2016).

14.2.2 Wood Anatomy

Wood is the most-used bio-based, renewable material in buildings, furniture, and many other applications (Guzel 2020; Woodard and Milner 2016). It is sustainable, biodegradable, and environmentally friendly. The structure of natural wood is shown in Figure 14.1. A typical tree trunk consists of the pith, heartwood, sapwood (secondary xylem), and bark (secondary phloem and cork). Understanding wood anatomy is crucial for assessing the quality and properties of wood for various uses, including transparent wood fabrication.

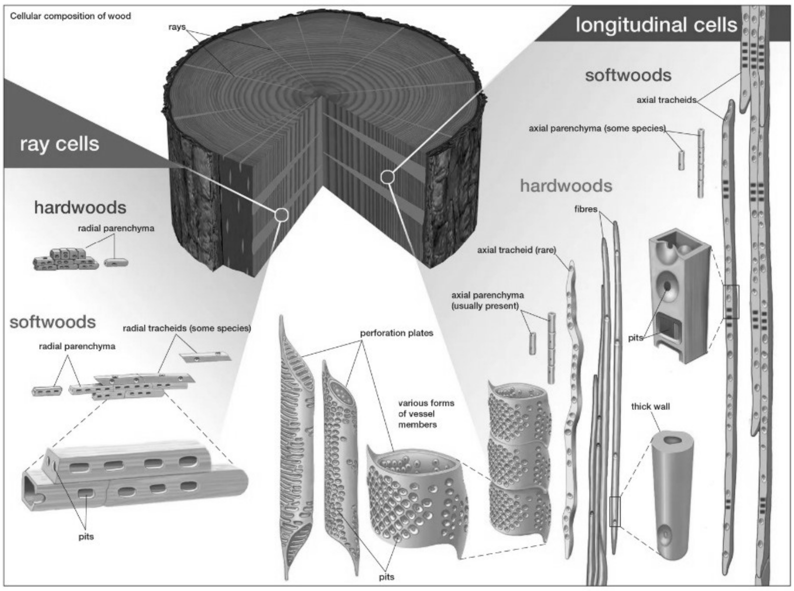

Figure 14.1 Diagram depicting the types of cells present in hardwoods and softwoods. Source: Encyclopædia Britannica, Inc.

14.2.3 Cell Types

Wood consists of different cell types called tracheids, fibres, parenchyma, and vessel elements (Sjostrom 2013; Stokke and Gardner 2003).

Softwoods are comprised of tracheids and parenchyma, while hardwoods comprise vessel members, fibers, and parenchyma. Tracheids are also found in a few hardwood species but they are uncommon. Tracheids are the most common cell type in softwood. They are elongated, tapering cells with thick cell walls that provide structural support to the tree. Parenchyma cells are smaller and less elongated. They have various functions, including the storage of nutrients and water. Fibers are long, slender cells found in wood. They are responsible for most of the mechanical strength of wood. Vessel elements are responsible for conducting water. They are larger and more open than tracheids.

14.2.4 Growth Rings

Wood also consists of growth rings, which are concentric circles visible on a cross-section of a tree. They represent a year's growth and are formed because of seasonal variations in temperature and moisture. Earlywood (springwood) is the portion of the growth ring formed in the spring and is usually lighter in color and less dense. Latewood (summerwood) is formed in the summer and is denser and darker. Some trees have distinctive growth patterns, such as spiral grain, which affects the direction in which the wood fibers run and can impact wood's stability and workability.

14.2.5 Heartwood and Sapwood

Heartwood is the older, non-living central part of the tree trunk. It is often darker and more complex than sapwood and may contain resins and extractives.

Sapwood is the younger, living outer portion of the tree, responsible for transporting water and nutrients.

14.2.6 Medullary Rays

Medullary rays are radial sheets, or ribbons of cells extending from the tree's pith (center) to the bark. They play a role in the lateral transport of nutrients and are visible on the surface of some wood types as rays.

14.2.7 Pores

Pores, or vessels are the openings formed by vessel elements in hardwoods. They are responsible for conducting water. The arrangement of vessels can vary and is often used in wood identification.

14.2.8 Bark

Bark is the protective outer covering of a tree. It consists of multiple layers, including the inner phloem and the outer cork layer.

14.3 Chemical Composition of Wood

Lignocellulosic biomass, such as wood, contains three primary components: lignin, responsible for the wood's brown color, cellulose and hemicellulose (Sugiarto, Pong, Tan, Leow *et al.*, 2022; Pinkert, Goeke, Marsh and Pang, 2011), all of which are polymeric. The exact chemical composition of wood can vary depending on the type of wood, its age, and its source. The following is a general overview of the major chemical components found in wood:

Cellulose: is the most abundant organic polymer in wood. It consists of long chains of glucose molecules linked together. Cellulose is found in the secondary cell wall of wood cells and plays a crucial role in providing rigidity and strength to the cell. This component makes up about 40-50% of the dry weight of wood.

Hemicellulose: is another biopolymer found in wood but it is more branched and less ordered than cellulose. Hemicellulose typically makes up about 20-30% of the dry weight of wood. It is a filler material in the wood's cell walls and contributes to its strength and flexibility.

Lignin: is a complex, amorphous, and highly cross-linked polymer that provides rigidity and resistance to decay to the wood. It makes up about 20-30% of the dry weight of wood. Lignin is responsible for the dark color of many blocks of wood and is a significant contributor to the density and hardness of wood.

Other components found in the wood cells include extractives, moisture, and ash. Wood contains various extractive compounds, including resins, oils, tannins, and other substances. These compounds can affect the wood's color and odor, and resistance to decay. The types and amounts of extractives vary widely depending on the tree species. Moreover, freshly harvested wood contains a significant amount of water, which needs to be removed through drying to make the wood suitable for various applications. Wood also contains small amounts of inorganic materials, such as minerals, left behind when the wood is burned. The percentage of ash in wood is generally low and varies with the wood type.

Wood's specific composition and properties can vary significantly from one species to another. Different types of wood have different cellulose-to-lignin ratios, extractive contents, and physical properties. Additionally, the age of the wood, growth conditions, and the part of the tree from which the wood is obtained can all influence its chemical composition.

The chemical composition of wood is of great importance in transparent wood fabrication, as it determines the wood's suitability for this application.

14.4 Applications and Potential Benefits of Transparent Wood

Although it is a relatively new material, transparent wood has the potential to revolutionize various industries due to its unique properties

(Figure 14.2). This material can be incorporated into energy-efficient buildings for building windows and facades as a substitute for glass (Li, Fu, Yang and Berglund 2018). This is because it provides thermal insulation while letting in natural light, lowering the need for artificial lighting and heating. It can also be used as a substrate for solar panels, combining the benefits of transparency with energy generation (Zhu, Li, Davis, Yao *et al.* 2016). It can also make solar panels more aesthetically pleasing and integrate them into various architectural designs. Many furniture pieces, such as tables, chairs, and shelves, can also be crafted from transparent wood, adding a touch of natural elegance to interior spaces (Zhou and Xu 2022; Li, Fu, Rojas, Yan *et al.* 2017).

Additionally, transparent wood has the potential to be utilized in touchscreens and flexible screens for electronic gadgets such as cell phones and tablets (Tang, Fang, Wang, Zou *et al.* 2018; Zhu, Song, Li, Gong *et al.* 2016). It presents an intriguing alternative to display technology due to its transparency and versatility. In the automotive and aerospace sectors, transparent wood can be used to make solid and lightweight materials for windows, cabins, and interior components (Akhil, Radhika, Saleh, Krishna *et al.* 2023; Tang, Zou, Gao, Chang *et al.* 2021).

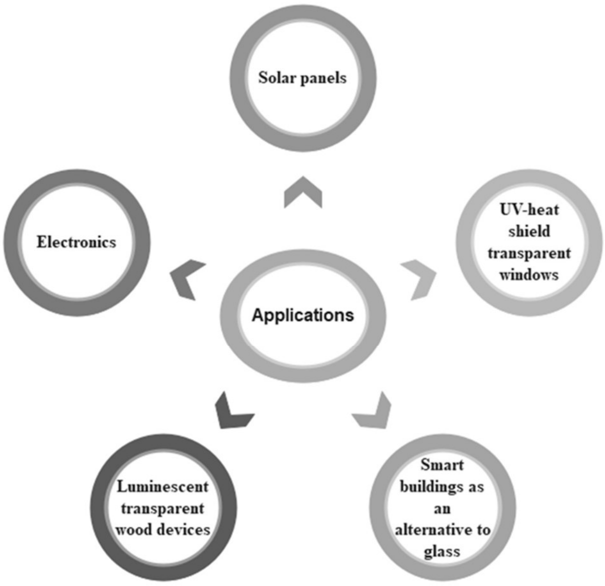

Figure 14.2 Illustration of different applications of transparent wood.

14.5 Sustainable Materials for Transparent Wood Composites

14.5.1 Renewable Resources

When fabricating transparent wood composites, it is essential to consider the type of wood used. Typically, fast-growing hardwoods like basswood and poplar, as well as softwoods like pine, are chosen due to their delicate, uniform grain structure and lower lignin content (Chutturi, Gillela, Yadav, Wibowo *et al.* 2023; Wu, Zhou, Huang, Yang *et al.* 2020). These trees are also advantageous because they have a shorter growth cycle, which helps to reduce the environmental impact of harvesting wood.

14.5.2 Polymers

Polymethyl methacrylate (PMMA) and epoxy resin are the commonly used transparent polymers used to impregnate the wood during transparent wood fabrication (Gan, Xiao, Gao L., Gao R. *et al.* 2017; Bisht, Pandey, and Barshilia 2021). While these synthetic polymers have successfully made transparent wood, they come with certain disadvantages and limitations, including that they are not biodegradable and can contribute to plastic pollution when disposed of improperly. These polymers are also not sustainable, are non-renewable, and can cause yellowing and UV degradation on transparent wood.

Manufacturing transparent wood using eco-friendly polymers is a crucial step in ensuring the sustainability of this innovative material. Eco-friendly polymers are derived from renewable resources and are biodegradable, or have a minimal environmental impact during production and disposal. Although they are still being researched, some of these polymers that can be considered for fabricating transparent wood include cellulose-based polymers, polylactic acid (PLA), as well as polyhydroxyalkanoates (PHAs) (Nanda, Patra, Patel, Bakos *et al.* 2022).

Using bio-based polymers as alternatives to conventionally used synthetic polymers (polymethyl methacrylate or epoxy resin) for transparent wood manufacturing is an innovative and environmentally friendly approach. Bio-based polymers can produce transparent wood by impregnating the wood structure with them after delignification instead of using synthetic polymers (Montanari, Ogawa, Olsén and Berglund 2021). These biopolymers can be extracted from plant and animal waste. Some examples from plant biomass include D-limonene and limonene acrylate from citrus waste, and sawdust polylactic acid (PLA) from renewable resources like corn starch or sugarcane. (Madhu, Praveenkumara, Sanjay, Siengchin *et al.* 2022; Iwata, 2015).

Biopolymers are derived from renewable resources, making them more favorable than synthetic polymers due to their environmental friendliness, sustainability and biodegradability. However, challenges remain in terms of cost, durability and scalability. It is, therefore, essential to continue to explore and develop new formulations and manufacturing processes to improve the properties of transparent wood made with bio-based polymers to make them more competitive than traditional materials like PMMA or epoxy resin.

14.6 Green Fabrication Techniques

The fabrication of transparent wood involves several techniques to remove lignin from natural wood and infuse it with a transparent material, typically a polymer (Figure 14.3). In other cases, the lignin is not removed but modified by removing the lignin structure's chromophores. These processes are not always environmentally friendly due to the nature of the polymers and the chemicals used. Recently, scientists have started looking into sustainable techniques to produce transparent wood. Green or sustainable fabrication techniques for transparent wood aim to minimize the environmental impact of the manufacturing process. These techniques prioritize using renewable materials, reduced energy consumption, and minimal waste generation. Below are some green fabrication techniques for transparent wood:

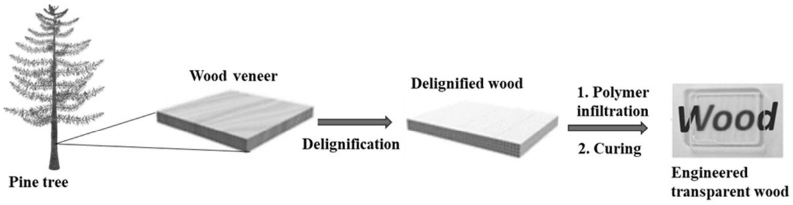

Figure 14.3 An illustration of the transparent wood fabrication process.

14.6.1 Green Approaches for Lignin Removal in Biomass

14.6.1.1 Enzymatic Delignification

Enzymatic delignification is a procedure used to remove lignin from lignocellulosic biomass and is commonly practiced in the pulp and paper industry (references) and in the production of biofuels (references). This involves dissolving and removing lignin from the lignocellulosic material using enzymes, specifically ligninolytic enzymes produced by certain fungi and bacteria (Suryadi, Judono, Putri, Eclessia *et al.* 2022; Kumar and Chandra 2020). Examples of these enzymes include lignin peroxidases, manganese peroxidases, and laccases. This approach has some advantages, which include lower environmental impact, reduced energy consumption, and the potential for higher product yields (Figure 14.4).

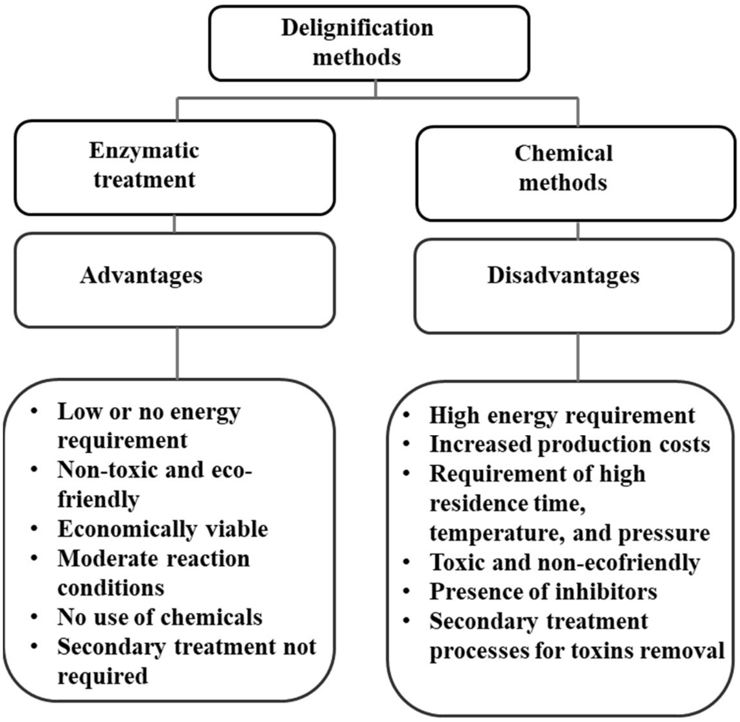

Figure 14.4 Advantages of enzymatic delignification methods over conventional chemical methods, adapted from Malhotra and Suman 2021.

Enzymatic delignification often begins with pre-treating lignocellulosic biomass to increase enzyme accessibility (figure 14.5). Processes like acid hydrolysis or steam explosion alkali treatment are used to accomplish this step (Kruyeniski, Ferreira, Carvalho, Vallejos *et al.* 2019). Applying enzymes to the biomass in the following phase allows them to catalyze the oxidation cleavage of lignin molecules, breaking them down into smaller fragments. After this stage, the lignin fragments are more water soluble and can be separated from the biomass using separation techniques. Enzymic hydrolysis would next be carried out on the leftover cellulose and hemicellulose components following the delignification. Enzymatic delignification has several benefits over conventional chemical delignification methods, which typically involve strong acids or bases. However, this method is not without drawbacks, including the high cost of producing the enzymes and the requirement for carefully monitored conditions.

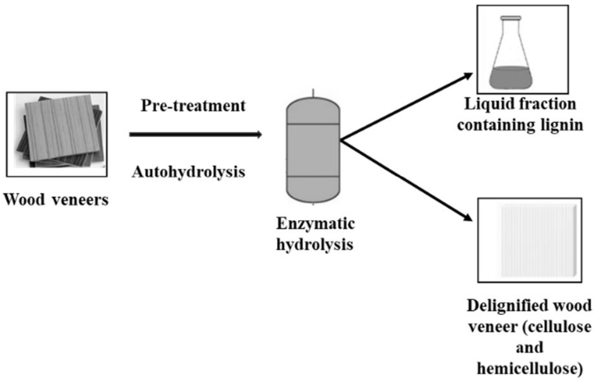

Figure 14.5 An illustration of the enzymatic delignification process, adapted from Wahlström and Suurnäkki 2015.

14.6.1.2 Delignification Using Ionic Liquids

Another method for removing lignin from biomass is dissolution in ionic liquids (ILs). Ionic liquids are salts in a liquid state at relatively low temperatures, typically below 100°C (Anthony, Brennecke, Holbrey and Maginn *et al.* 2006). They are composed of cations and anions, and their unique properties make them suitable for delignification processes. They are considered green solvents because they are non-volatile and, therefore, can be used to dissolve lignin, making it easier to separate it from biomass. Some advantages of using ILs for delignification include selectivity, low volatility, and reusability. Ionic liquids can selectively dissolve lignin while leaving cellulose and hemicellulose largely intact. This selectivity is crucial for maintaining the quality of the cellulose, which can then be used to fabricate transparent wood. Their low vapor pressures are crucial in reducing emissions risk and making them safer than some traditional organic solvents used in delignification processes**.** Additionally, many ILs can be regenerated and reused in multiple cycles, making the process more economically viable. They are also more environmentally friendly than traditional organic solvents.

The delignification process using ionic liquids generally involves the following steps:

1. *Pre-treatment:* The lignocellulosic biomass is typically pretreated to remove impurities, such as minerals or extractives, which may interfere with the IL-based delignification process.
2. *Mixing:* The pretreated biomass is mixed with the chosen ionic liquid. The IL penetrates the cell walls and dissolves the lignin.
3. *Separation:* After sufficient delignification, the mixture is separated into solid and liquid phases. The solid phase contains the cellulose and hemicellulose, while the liquid phase contains the dissolved lignin.
4. *Recovery:* The separated ionic liquid can be regenerated through various processes, including precipitation or extraction, and then reused in subsequent cycles.

14.7 Incorporating Nanotechnology

Incorporating nanotechnology into transparent wood fabrication is a promising approach for manufacturing advanced materials with a wide range of applications in construction, transportation, electronics, and more (Zhu, Biswas, Qiu, Yue, *et al.* 2022) (Li, Fu, Yang and Berglund 2018). This is because nanotechnology offers several possibilities for enhancing the properties and expanding the potential applications of transparent wood. Nanotechnology can be applied at various stages of transparent wood fabrication to functionalize it and improve its transparency, strength, durability, and other vital characteristics. Nanomaterials such as cellulose nanofibres (CNFs) and cellulose nanocrystals (CNCs), carbon nanotubes, graphene, and many others can be incorporated into transparent wood to reinforce the wood structure at the nanoscale, increasing its mechanical strength and transparency (Tayeb, Amini, Ghasemi and Tajvidi 2018). Figure 14.6 is an example of transparent wood fabricated using nanoparticles of silver and gold.

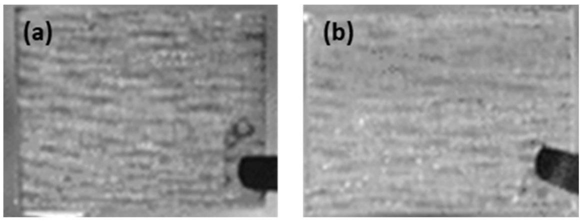

Figure 14.6: 7 Transparent wood composites made with plasmonic nanoparticles of (a) silver and (b) gold. Source: Hoglund, Garemark, Nero, Willhammar *et al.* 2021.

14.7.1 Waste Reduction and Recycling

Green fabrication techniques for transparent wood production also consider waste reduction and recycling for environmental sustainability and cost-effectiveness. Transparent wood production involves using natural resources, minimizing waste, and efficiently utilizing materials is therefore crucial. The following are some of the strategies that can be implemented to reduce waste and promote recycling in the transparent wood fabrication process.

14.7.2 Optimized Wood Sourcing

This involves using sustainably sourced wood to minimize the environmental impact of harvesting. The use of wood that may be considered waste or by-products from other industries, such as sawmill residues or wood from construction sites, may also be considered.

14.7.3 Efficient Lignin Extraction

The lignin extraction process can be optimized to maximize the yield of transparent wood. This can be done by removing lignin while preserving the structural integrity of the wood (Xia, Chen, Yao, He et al., 2021). The extracted lignin can be recovered and reused in applications in various industries, including adhesives, chemicals, and bioenergy.

14.7.4 Precise Manufacturing

Precision manufacturing techniques can be implemented to minimize material waste during the processing and shaping of transparent wood. This includes optimizing cutting and shaping processes to reduce offcuts and scrap.

14.7.5 Recycling of Failures and Offcuts

Collect and recycle offcuts and trimmings generated during the manufacturing process. Failed or suboptimal transparent wood pieces can be repurposed or recycled into other wood-based products or used as feedstock for energy production.

14.8 Economic Importance of the Green Fabrication Techniques

Besides being beneficial for the environment, green fabrication techniques offer numerous economic benefits. Below are some of the critical economic advantages of green fabrication techniques:

- *Cost savings:* Green fabrication involves improving energy efficiency, reducing waste, and optimizing resource utilization. These measures can significantly reduce operating costs and raw material, energy, and waste disposal costs. These measures may eventually help organizations become more profitable.
- *Innovation and technological advancements:* Achieving sustainability often necessitates the development of innovative technologies and processes. Therefore, additional revenue streams may be generated from this as it can lead to intellectual property rights, patents, and opportunities for technology licensing.
- *Risk mitigation:* By reducing the environmental impact of manufacturing, companies can mitigate the risks associated with environmental disasters, resource scarcity, and volatile energy prices. This can help to protect a company's finances and long-term sustainability.
- *Compliance with regulations:* To reduce negative environmental impacts, governments and regulatory organizations are imposing more environmental standards and regulations on industries (Song, Wang and Zhang 2020). Therefore, companies that employ green fabrication methods and processes are more likely to remain in compliance with these rules, avoiding penalties and legal problems that could be economically damaging.

14.9 Future Directions and Challenges

The development of transparent wood is an exciting area of materials science with the potential to revolutionize various industries. This is because it offers several opportunities, including sustainability, energy efficiency, renewable energy, and lightweight structure. However, several challenges still need to be addressed for further advancements in this field, and these include improving transparency and clarity, scaling up production, and cost reduction.

14.10 Conclusion

The manufacturing of transparent wood composites has heralded a path toward a more sustainable and innovative future. Green fabrication techniques for transparent wood aim to align with principles of sustainability and environmental responsibility while maintaining the unique properties of transparent wood. These techniques contribute to developing a more eco-friendly and sustainable building material. Furthermore, the valorization of plant waste to extract biopolymers for inclusion in transparent wood production holds significant promise for sustainable, eco-friendly, and economically viable materials. The adoption of waste reduction and recycling strategies can also help manufacturers minimize the environmental footprint, reduce production costs, and contribute to a more sustainable and circular economy.

References

Akhil, U. V., N. Radhika, Bassiouny Saleh, S. Aravind Krishna, Niveditha Noble and L. Rajeshkumar. 2023. "A comprehensive review on plant-based natural fiber reinforced polymer composites: fabrication, properties, and applications." Polymer Composites.

Akpan, Emmanuel Isaac, Bernd Wetzel and Klaus Friedrich. 2021. "Eco-friendly and sustainable processing of wood-based materials." Green Chemistry 23, no. 6: 2198-2232.

Anthony, Jennifer L., Joan F. Brennecke, John D. Holbrey, Edward, J Maginn, Rob A. Mantz, Robin D. Rogers, Paul C. Trulove, Ann E. Visser and Tom Welton. 2006. "Physicochemical Properties ofIonic Liquids." *Ionic liquids in synthesis*: 41.

Bisht, Priya, Krishna K. Pandey and Harish C. Barshilia. 2021. "Photostable transparent wood composite functionalized with an UV-absorber." Polymer Degradation and Stability 189: 109600.

Blengini, Gian Andrea, Mirko Busto, Moris Fantoni and Debora Fino. 2012. "Eco-efficient waste glass recycling: Integrated waste management and green product development through LCA." Waste management 32, no. 5: 1000-1008.

Chen, Chaoji and Liangbing Hu. 2021. "Nanoscale ion regulation in wood-based structures and their device applications." Advanced Materials 33, no. 28: 2002890.

Chutturi, Mahesh, Swetha Gillela, Sumit Manohar Yadav, Eko Setio Wibowo, Kapil Sihag, Sanjay Mavinkere Rangppa, Prakash Bhuyar *et al.* 2023. "A comprehensive review of the synthesis strategies, properties, and applications of transparent wood as a renewable and sustainable resource." Science of The Total Environment 864: 161067.

Ding, Yu, Zhenqian Pang, Kai Lan, Yuan Yao, Guido Panzarasa, Lin Xu, Marco Lo Ricco *et al.* 2022. "Emerging engineered wood for building applications." Chemical Reviews 123, no. 5: 1843-1888.

Encyclopædia Britannica, Inc. [Online]. Available at: https://www.britannica.com/science/wood-plant-tissue/Microstructure (Accessed on October 16, 2023).

Fink, Siegfried. 1992. "Transparent wood–a new approach in the functional study of wood structure.": 403-408.

Gan, Wentao, Shaoliang Xiao, Likun Gao, Runan Gao, Jian Li and Xianxu Zhan. 2017. "Luminescent and transparent wood composites fabricated by poly (methyl methacrylate) and γ-Fe2O3@ YVO4: Eu3+ nanoparticle impregnation." ACS Sustainable Chemistry & Engineering 5, no. 5: 3855-3862.

Guzel, Tugba Andac. 2020. "Consumer attitudes toward preference and use of wood, woodenware, and furniture: A sample from Kayseri, Turkey." BioResources 15, no. 1: 28-37.

Hoglund, Martin, Jonas Garemark, Mathias Nero, Tom Willhammar, Sergei Popov and Lars A. Berglund. 2021. "Facile processing of transparent wood nanocomposites with structural color from plasmonic nanoparticles." *Chemistry of Materials* 33, no. 10: 3736-3745.

Hussain, Anwar and Mohammad Arif Kamal. 2015. "Energy efficient sustainable building materials: An overview." Key Engineering Materials 650: 38-50.

Iwata, Tadahisa. 2015. "Biodegradable and bio-based polymers: future prospects of eco-friendly plastics." Angewandte Chemie International Edition 54, no. 11: 3210-3215.

Kruyeniski, Julia, Paulo JT Ferreira, Maria da Graça Videira Sousa Carvalho, María E. Vallejos, Fernando E. Felissia and María C. Area. 2019. "Physical and chemical characteristics of pretreated slash pine sawdust influence its enzymatic hydrolysis." Industrial Crops and Products 130: 528-536.

Kumar, Adarsh and Ram Chandra. 2020. "Ligninolytic enzymes and its mechanisms for degradation of lignocellulosic waste in environment." Heliyon 6, no. 2.

Lehmann, Steffen. 2013. "Low carbon construction systems using prefabricated engineered solid wood panels for urban infill to significantly reduce greenhouse gas emissions." Sustainable Cities and Society 6: 57-67.

Li, Tian, Mingwei Zhu, Zhi Yang, Jianwei Song, Jiaqi Dai, Yonggang Yao, Wei Luo, Glenn Pastel, Bao Yang and Liangbing Hu. 2016. "Wood composite as an energy efficient building material: guided sunlight transmittance and effective thermal insulation." Advanced Energy Materials 6, no. 22: 1601122.

Li, Yuanyuan, Qiliang Fu, Ramiro Rojas, Min Yan, Martin Lawoko and Lars Berglund. 2017. "Lignin-retaining transparent wood." ChemSusChem 10, no. 17: 3445-3451.

Li, Yuanyuan, Qiliang Fu, Shun Yu, Min Yan and Lars Berglund. 2016. "Optically transparent wood from a nanoporous cellulosic template: combining functional and structural performance." Biomacromolecules 17, no. 4: 1358-1364.

Li, Yuanyuan, Qiliang Fu, Xuan Yang and Lars Berglund. 2018. "Transparent wood for functional and structural applications." Philosophical Transactions of the Royal Society: Mathematical, Physical and Engineering Sciences 376, no. 2112: 20170182.

Łukawski, Damian, Alina Dudkowiak, Daniel Janczak and Agnieszka Lekawa-Raus. 2019. "Preparation and applications of electrically conductive wood layered composites." Composites Part A: Applied Science and Manufacturing 127: 105656.

Madhu, P., Praveenkumara, J., Sanjay, M. R., Suchart Siengchin and Sergey Gorbatyuk. 2022. "Introduction to bio-based fibers and their composites." In: Advances in Bio-Based Fiber, pp. 1-20. Woodhead Publishing.

Malhotra, Manisha and Sunil Kumar Suman. 2021. "Laccase-mediated delignification and detoxification of lignocellulosic biomass: removing obstacles in energy generation." Environmental Science and Pollution Research 28: 58929-58944.

Montanari, Céline, Yu Ogawa, Peter Olsén and Lars A. Berglund. 2021. "High performance, fully bio-based, and optically transparent wood biocomposites." Advanced Science 8, no. 12: 2100559.

Nanda, Sonil, Biswa R. Patra, Ravi Patel, Jamie Bakos and Ajay K. Dalai. 2022. "Innovations in applications and prospects of bioplastics and biopolymers: A review." Environmental Chemistry Letters 20, no. 1: 379-395.

Pinkert, André, Dagmar F. Goeke, Kenneth N. Marsh and Shusheng Pang. 2011. "Extracting wood lignin without dissolving or degrading cellulose: investigations on the use of food additive-derived ionic liquids." Green Chemistry 13, no. 11: 3124-3136.

Sjostrom, Eero. 2013. Wood chemistry: fundamentals and applications. Elsevier.

Song, Malin, Shuhong Wang and Hongyan Zhang. 2020. "Could environmental regulation and R&D tax incentives affect green product innovation?" Journal of Cleaner Production 258: 120849.

Stokke, Douglas D. and Gardner, Douglas J. 2003. "Fundamental aspects of wood as a component of thermoplastic composites." Journal of Vinyl and Additive Technology 9, no. 2: 96-104.

Sugiarto, S., Pong, R. R., Tan, Y. C., Leow, Y., Sathasivam, T., Zhu, Q., Loh, X. J. and Kai, D. 2022. "Advances in sustainable polymeric materials from lignocellulosic biomass." Materials Today Chemistry 26: 101022.

Suryadi, Herman, Jessica J. Judono, Merianda R. Putri, Alma D. Eclessia, Jiihan M. Ulhaq, Dinar N. Agustina and Triyani Sumiati. 2022. "Biodelignification of lignocellulose using ligninolytic enzymes from white-rot fungi." Heliyon.

Tang, Qiheng, Lu Fang, YunFei Wang, Miao Zou and Wenjing Guo. 2018. "Anisotropic flexible transparent films from remaining wood microstructures for screen protection and AgNW conductive substrate." Nanoscale 10, no. 9: 4344-4353.

Tang, Qiheng, Miao Zou, Kezheng Gao, Liang Chang, Li Gao and Wenjing Guo. 2021. "Laminating delignified wood veneers toward high-strength, flame-retardant composites for structural applications." ACS Sustainable Chemistry & Engineering 9, no. 32: 10717-10726.

Tayeb, Ali H., Ezatollah Amini, Shokoofeh Ghasemi and Mehdi Tajvidi 2018. "Cellulose nanomaterials—Binding properties and applications: A review." *Molecules* 23, no. 10: 2684.

Wachter, Igor, Peter Rantuch and Tomáš Štefko. 2023. "Smart Windows." In Transparent Wood Materials: Properties, Applications, and Fire Behaviour, pp. 71-85. Cham: Springer Nature Switzerland.

Wahlström, R. M. and Suurnäkki, A. 2015. "Enzymatic hydrolysis of lignocellulosic polysaccharides in the presence of ionic liquids." Green Chemistry 17, no. 2: 694-714.

Woodard, A. C. and Milner, H. R. 2016. "Sustainability of timber and wood in construction." In Sustainability of construction materials, pp. 129-157. Woodhead Publishing.

Wu, Yan, Jichun Zhou, Qiongtao Huang, Feng Yang, Yajing Wang, Xinmu Liang and Jinzhu Li. 2020. "Study on the colorimetry properties of transparent wood prepared from six wood species." ACS omega 5, no. 4: 1782-1788.

Xia, Qinqin, Chaoji Chen, Yonggang Yao, Shuaiming He, Xizheng Wang, Jianguo Li, Jinlong Gao *et al*. 2021. "In situ lignin modification toward photonic wood." Advanced Materials 33, no. 8: 2001588.

Zhou, Jichun and Wei Xu. 2022. "Toward interface optimization of transparent wood with wood color and texture by silane coupling agent." Journal of Materials Science 57, no. 10: 5825-5838.

Zhu, Hongli, Wei Luo, Peter N. Ciesielski, Zhiqiang Fang, J. Y. Zhu, Gunnar Henriksson, Michael E. Himmel and Liangbing Hu. 2016. "Wood-derived materials for green electronics, biological devices, and energy applications." Chemical reviews 116, no. 16: 9305-9374.

Zhu, Mingwei, Jianwei Song, Tian Li, Amy Gong, Yanbin Wang, Jiaqi Dai, Yonggang Yao, Wei Luo, Doug Henderson and Liangbing Hu. 2016. "Highly anisotropic, highly transparent wood composites." Advanced materials 28, no. 26: 5181-5187.

Zhu, Mingwei, Tian Li, Chelsea S. Davis, Yonggang Yao, Jiaqi Dai, Yanbin Wang, Feras AlQatari, Jeffrey W. Gilman and Liangbing Hu. 2016. "Transparent and haze wood composites for highly efficient broadband light management in solar cells." Nano Energy 26: 332-339.

Zhu, Sailing, Subir Kumar Biswas, Zhe Qiu, Yiying Yue, Qiliang Fu, Feng Jiang and Jingquan Han. 2022. "Transparent wood-based functional materials via a top-down approach." Progress in Materials Science: 101025.