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Engineered transparent wood with cellulose matrix for glass applications: A review

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ABSTRACT

Engineered transparent wood (ETW), derived from the modification of natural wood, presents a sustainable and aesthetically pleasing alternative to traditional glass. This review comprehensively explores the burgeoning field of ETW as a novel material for applications in the glass industry. A comprehensive overview of the various methodologies employed in the engineering of transparent wood, encompassing delignification, polymer infiltration, and other innovative techniques is provided. Additionally, the optical, mechanical, and thermal properties of ETW are systematically examined, highlighting its potential advantages over conventional glass materials. The review also discusses recent advancements, challenges, and future considerations of ETW. Furthermore, the review discusses key applications in the glass industry where ETW has demonstrated promising performance, including windows, facades, and decorative elements. Essentially, this review aims to enhance understanding of ETW's potential in glass applications by critically analyzing current research and advancements. It seeks to pave the way for future developments in this innovative and eco-friendly technology.

1. Introduction

Glass, an ancient yet ever-evolving material, has long been a symbol of transparency, clarity, and versatility in human craftsmanship. From construction in rural areas and modern metropolises to packaging and transportation, the applications of glass span a vast spectrum of industries and daily life. With a daily capacity of more than 500 tons/day, glass products are produced globally by 1141 businesses and groups in 91 countries (Plants.glassglobal.com). Around 209 million tonnes of glass are currently produced annually (International Year of Glass, 2022).

While glass has found applications in diverse fields, it still poses certain environmental challenges which raises concerns. The glass production process is energy-intensive and uses a lot of resources. An estimated 500–700 million GJ of energy is consumed per ton of glass produced (Seo et al., 2020). Moreover, the combustion of fossil fuels during the glass manufacturing process releases carbon dioxide (CO_2) and other greenhouse gases into the atmosphere. This contributes to global warming and a high carbon footprint. The global carbon dioxide emissions from glass production were approximately 95 million metric tons in 2022 (Statista, 2023). Another challenge with glass is that not all of it can be recycled after use. Contaminated glass or certain types of glass products may be challenging to recycle effectively. Therefore, on average, approximately 550 000 tons of waste glass find its way into landfills in South Africa thereby raising safety as well as environmental concerns (Sabinet, 2011).

Due to the challenges associated with glass, there has therefore in recent years been a quest for sustainable and innovative materials to substitute for glass. Researchers have explored novel glass alternatives that blend ecological consciousness with cutting-edge technology. Engineered transparent wood (ETW) has therefore emerged as a captivating contender in this pursuit, offering a unique combination of transparency, strength, and environmental sustainability (Farid et al., 2022; Jele et al., 2023; Lian et al., 2022; Muthoka et al., 2021). Engineered transparent wood is a composite material that combines the mechanical properties of wood with the optical properties of glass. This intriguing material represents a shift from conventional glass, presenting an opportunity to reimagine traditional applications in the glass industry. For example, studies have shown that it has the potential to replace traditional glass windows in buildings, as it offers better

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insulation and is more environmentally friendly (De Luca et al., 2017; Yang et al., 2023; Zhu et al., 2022).

Transparent wood was first mentioned by German scientist Sigfried Fink in his 1992 paper titled "*Transparent Wood – A New Approach in the Functional Study of Wood Structure*" (Fink, 2009). During his research, he made wood samples transparent to better observe unique three-dimensional wood structures. To date, some fascinating features concerning ETW have been uncovered, and its production has been refined over a couple of years of research. The present review summarizes the recent advances in ETW composites and their physicochemical properties (optical, thermal, and mechanical performance). Their prospective applications and challenges associated with them are also discussed. Furthermore, this review also aims to identify ways to improve on present ETW manufacturing processes to enhance its sustainability, performance, scale-up manufacturing, and expand its applications.

2. Wood

2.1. *Types of wood*

There are primarily two kinds of solid wood - hardwood and softwood (Yaddanapudi et al., 2017). Both hardwoods and softwoods can be used to prepare ETW. Research has however shown that the specific characteristics of the chosen wood species play a crucial role in determining the quality and properties of the final ETW. Hardwoods are stronger than softwoods therefore they tend to produce ETW with higher mechanical properties. Softwoods on the other hand have a lower lignin content than hardwoods therefore usually result in ETW with a high transparency (Zhang et al., 2022b).

2.2. *Composition*

Wood is one of the world's most abundant organic polymer resources that is renewable and biodegradable. This material has a naturally multiscale porous structure (micro- and nanoscale) and its lumen space is fully filled with air (refractive index of 1.00). The wood cell wall is composed of cellulose (refractive index of 1.52), hemicellulose (refractive index of 1.53)., and lignin (refractive index of 1.61) (Fig. 1). Cellulose is the main structural polymer in wood cell walls and thus the primary source of the high strength and stiffness of wood (Jakob et al., 2022). The nanoscale arrangement of the wood cell wall as a nano-porous cellulose fibril composite allows for the customized design of advanced wood-based multi-functional materials while maintaining structural performance (Li et al., 2017).

2.3. *The transparency mechanism*

To comprehend the process of producing ETW, it is important to first grasp the transparency mechanism involved in the interaction between light and natural wood which is a solid material. When light interacts with natural wood at the air-cell wall interfaces, there will be an intense scattering and absorption in the visible light range, resulting in color and texture (Jacucci et al., 2021). This is due to the refractive index (RI) contrast between the wood cell walls (1.52–1.61) and the air-filled lumen space (1.00) together with the presence of lignin. Lignin accounts for 80–95 % of the light absorption in wood (Fink, 1992; Li et al., 2017). Therefore, to make wood transparent, both absorption and scattering effects, need to be reduced or eliminated.

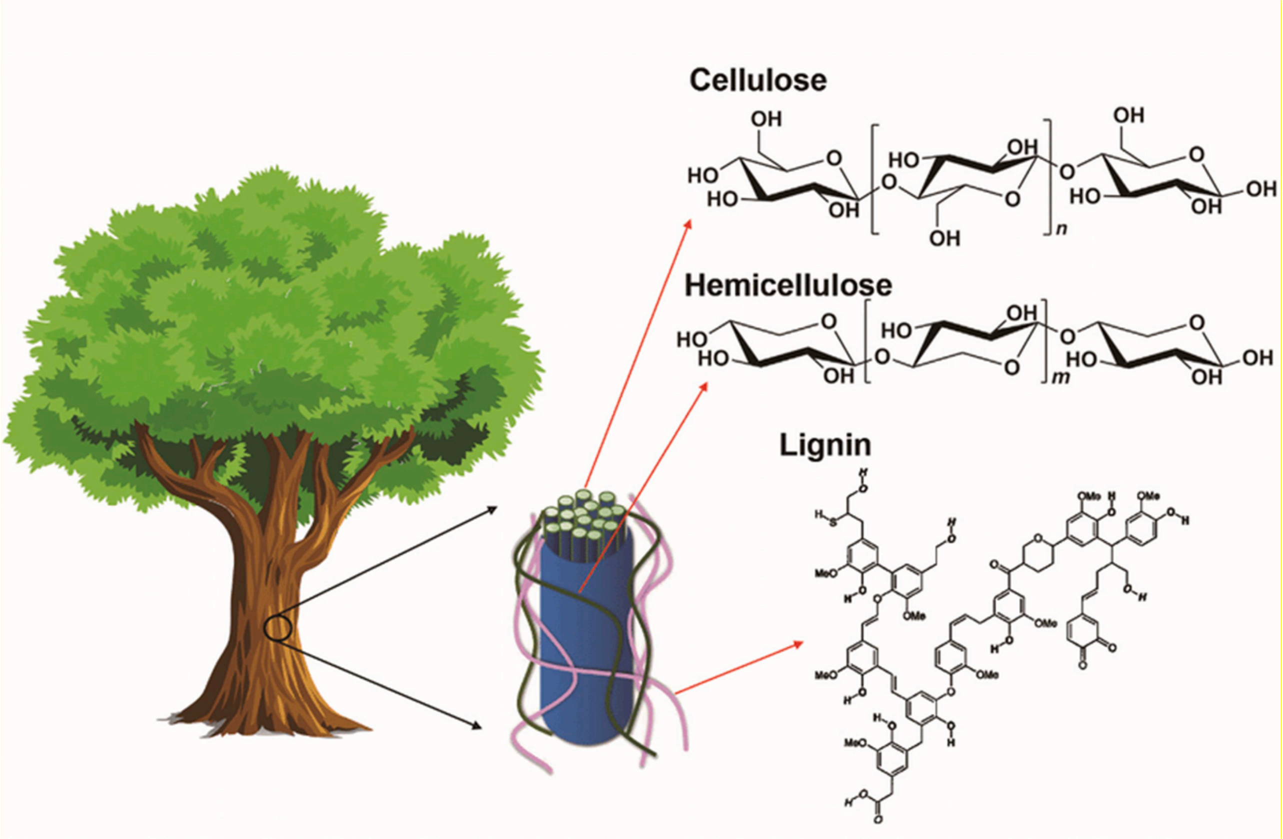

Fig. 1. Diagram showing how the cellulose strands are surrounded by hemicellulose and lignin in wood cell wall, and the corresponding structures of cellulose, hemicellulose, and lignin, Source: (Hu et al., 2021).

3. Fabrication of engineered transparent wood

The process of ETW manufacturing involves two steps which are delignification and polymer impregnation (Fig. 2). Delignification is the removal of the light-absorbing lignin from the cell walls of natural wood using a solution-based immersion method. Polymer impregnation follows right after delignification and it involves infiltrating a refractive index matching polymer into the delignified wood matrix to minimize light absorption and scattering, respectively (Montanari et al., 2021; Shi et al., 2023; Yaddanapudi et al., 2017).

3.1. Lignin removal/modification

The first step during the fabrication of ETW involves removing lignin, a polymer that gives wood its color and strength (Bisht et al., 2021), from the cell walls of the wood. This process is known as delignification and is a crucial step in the production of ETW. Delignification decreases light absorption in wood, and the refractive index mismatch in the cell wall (Chen et al., 2019). This process has an impact on the natural wood's mechanical, thermal and optical attributes, and functions.

During the delignification process, it is important to consider the thickness of the wood samples as this may affect the process. The thickness of the wood samples has an effect on the delignification conditions such as the solution concentrations, reaction times, and temperature (Kumar et al., 2021; Li et al., 2018a). Thicker samples of more than 3 mm tend to require more time (6–12 h) and a higher temperature of around 80–100 °C for delignification to be efficient compared to less thicker ones (Li et al., 2016). The choice of wood species also significantly impacts the delignification process. This is because various hardwood and softwood species differ in lignin content, cell structure, and porosity, affecting the efficiency of delignification. Softwood species usually exhibit superior transparency due to their lower lignin content (Hararak et al., 2023).

Conventional delignification agents include peroxides (Rai et al., 2022; Wachter et al., 2019), sodium chlorite (Geng et al., 2018; Ono et al., 2022; Qiu et al. (2020)), sodium hypochlorite (Costa et al., 2018; Day et al., 2009) and alkaline solutions. These agents work by breaking down lignin bonds, allowing for its extraction from the wood matrix. Although they are effective in delignifying the wood, these substances are harmful to the environment because they require the use of significant amounts of energy, and produce hazardous waste (Rousu et al., 2022; Xia et al., 2021). Environmental concerns and the need for more sustainable processes have therefore driven the development of alternative methods of delignification.

There have therefore been some new developments in this area. For example, some studies have adopted the use of sustainable and eco-friendly substances such as green solvents (ionic liquids) to delignify their wood samples (Moniruzzaman & Goto, 2019; Moniruzzaman & Ono, 2012; Mori et al., 2021). Ionic liquid assisted enzymatic delignification of wood, utilizing lignin-degrading enzymes, represents a promising avenue for green and energy-efficient processing. Furthermore, bio-based solvents and environmentally benign chemicals can be explored as they align with the growing emphasis on sustainability.

Instead of delignification, other studies (Anish et al., 2023; Li et al., 2019; Xia et al., 2021a) have reported lignin modification as a preferred method for whitening the wood samples. This technique involves the use of hydrogen peroxide (H_2O_2), and it works by only completely removing the lignin chromophores. Unlike the conventional delignification chemicals, H_2O_2 is environmentally safe and does not produce harmful waste. Furthermore, it generates samples with better mechanical properties since the lignin which acts as binder in the wood is not removed (Karla, 2020).

The development of sustainable delignification methods is crucial not only for minimizing harm to ecosystems but also for fostering a more sustainable future for industries reliant on wood products. One of the primary considerations in sustainable delignification is the choice of raw materials and reagents. Opting for renewable resources and biodegradable chemicals can significantly reduce the environmental footprint of the process. For instance, using hydrogen peroxide or oxygen as oxidizing agents instead of chlorine-based bleaches eliminates the generation of toxic byproducts such as chlorinated compounds. Furthermore, leveraging enzymatic delignification offers a promising avenue for reducing chemical usage and energy consumption, as enzymes

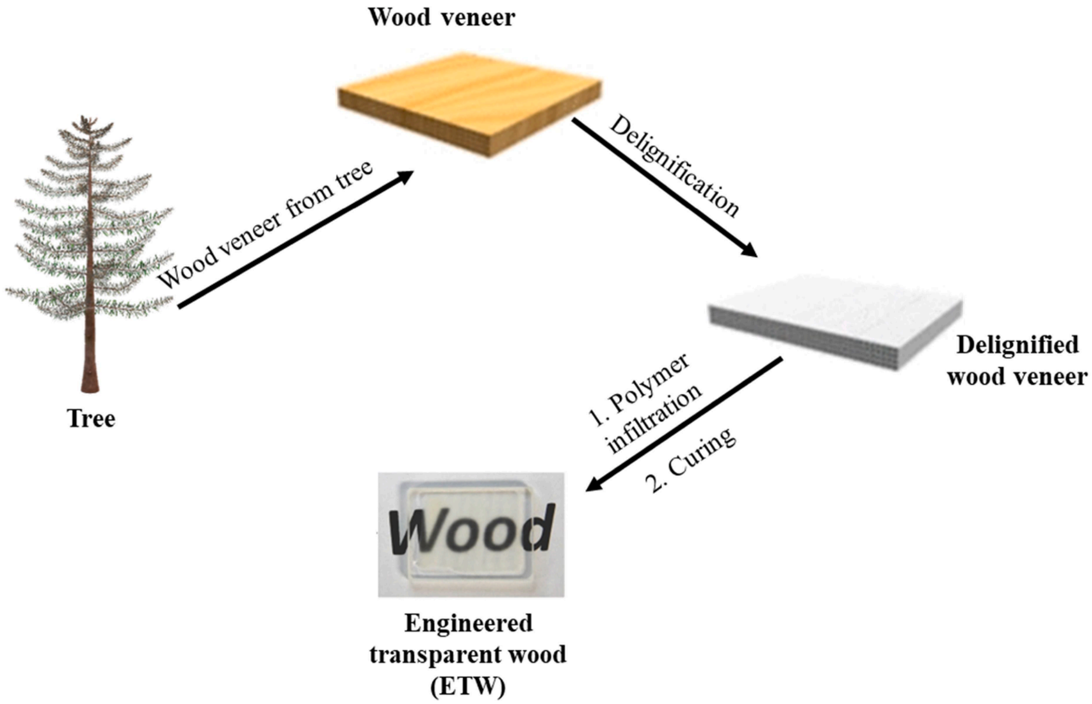

Fig. 2. A schematic representation of the preparation of ETW composites and the subsequent appearance of the transparent wood composite, Adapted from: Jungstedt et al. (2020).

typically operate under mild conditions and are biodegradable.

Another aspect to consider is the energy efficiency of delignification processes. Energy-intensive methods not only contribute to greenhouse gas emissions but also add to the overall cost of production. By incorporating innovative technologies such as microwave-assisted or ultrasound-assisted delignification, it is possible to enhance reaction kinetics and reduce processing times, leading to energy savings and lower environmental impact.

3.2. Polymer infiltration

After the wood is delignified/lignin-modified, its structure becomes weak and porous as the lignin has been removed. The polymer infiltration process then follows immediately after the lignin removal or modification process to provide strength and transparency to the wood. For this process, different transparent polymers such as epoxy resin, poly (methyl methacrylate) (PMMA), poly acrylic acid (PAA) and others have been explored (Bi et al., 2018). The choice of polymer and infiltration method significantly influences the final properties of ETW. This is because different polymers have varying viscosities, refractive indices, and shrinkage qualities which can have an impact on the ETW and its attributes (Li et al., 2018b).

PMMA and epoxy resin are the two most used polymers and they both offer appealing properties such as excellent optical transparency, good mechanical strength, UV resistance, as well as a similar refractive index (Chu et al., 2022; Lin et al., 2020; Wu et al., 2021). The chosen polymer for fabricating ETW will therefore depend on the specific requirements and intended applications. According to literature PMMA is a better option, for example, if obtaining the maximum degree of optical transparency is the main objective. Wang et al. (2018) conducted a study whereby they developed transparent wood from PMMA and wood fibers as a substrate instead of the commonly used approaches which utilizes only the delignified or lignin modified wood structure. Their objective was to efficiently produce large-size transparent wood for practical applications. This resulted in transparent wood fiber composites with a higher light transmittance of 92 ± 2 %, which is comparable to neat PMMA (95 %). However, this study may have some drawbacks because integrating PMMA with wood fibers to produce transparent wood can be technically challenging. Achieving uniform dispersion of PMMA within the wood matrix without compromising optical clarity or mechanical properties requires precise control over processing parameters. Additionally, ensuring strong adhesion between PMMA and wood fibers is crucial for maintaining structural integrity, which may require additional surface modification or adhesion promoters.

Epoxy resin on the other hand, is frequently used when looking for a more robust and durable material because of its capacity to reinforce wood. One major drawback with this polymer though is that it may undergo yellowing or discoloration when exposed to UV radiation or environmental factors such as heat and humidity. This can degrade the optical clarity of transparent wood and diminish its esthetic appeal, particularly in applications where color stability is important. A solution to this would be to use UV-resistant epoxy formulas especially if the ETW application will be subjected to a lot of UV light.

In their study, Bisht et al. (2021) found that transparent wood composites without a UV-absorber was highly sensitive to UV light exposure and exhibited rapid photo-discoloration, chemical degradation, and a decrease in optical transmittance. Incorporation of UV absorber in epoxy resin considerably reduced discoloration and photo-degradation of the composites. While incorporating a UV absorber into epoxy resin can provide UV, it is important to consider that this may introduce compatibility issues or affect the curing process of the resin. Certain UV absorbers may interfere with the crosslinking reactions or chemical stability of the epoxy matrix, leading to processing challenges. Furthermore, some UV absorbers, particularly organic compounds, may pose environmental concerns due to their persistence, bioaccumulation, or toxicity. If released into the environment during manufacturing, use, or disposal of transparent wood products, UV absorbers could potentially contribute to pollution or ecological harm.

Although synthetic polymers are often successful in ETW fabrication, they still have other disadvantages including reduced sustainability and potential issues related to brittleness, thermal expansion, and chemical sensitivity. In that regard, the use of biopolymers to mitigate these disadvantages and improve the overall sustainability of ETW needs to be explored. Biopolymers derived from renewable resources such as cellulose or starch, offer several advantages such as sustainability, biodegradability, renewability, as well as reduced environmental impact. Using biopolymers to infiltrate the delignified wood structure could be an exciting and sustainable approach that would help to replace the less eco-friendly synthetic polymer in making ETW.

A few studies have reported some state-of-the-art developments in this area which include the use of biopolymers derived from plants waste for ETW fabrication instead of the commonly used synthetic polymers. Limonene acrylate monomer, a biopolymer extracted from citrus fruits peels was used by Montanari et al. (2021) to infiltrate the delignified wood structure to produce ETW. The results showed that the produced ETW had excellent optical transmittance of 90 % at 1.2 mm thickness and a low haze of 30 %, with a high mechanical performance (strength 174 MPa, Young's modulus 17 GPa). This bio-based approach is advantageous as it not only harnesses the potential of renewable resources but also offers a creative solution to address environmental challenges associated with conventional materials and processes. The appeal of using Limonene acrylate monomer lies in its origins. Citrus fruit peels, often considered waste in large-scale agricultural operations, are abundant and readily available sources of Limonene—a natural compound found in citrus oils. By repurposing these agricultural byproducts into a valuable raw material for transparent wood fabrication, waste and the reliance on fossil fuels can be reduced. Limonene acrylate monomer's bio-based nature means that it is biodegradable and inherently more environmentally friendly. Unlike petroleum-derived monomers, which contribute to carbon emissions and pollution, this monomer supports the transition towards a more sustainable and circular economy. It represents a tangible step towards reducing our ecological footprint and mitigating the impacts of climate change.

Poly acrylic acid (PAA) is another biopolymer that has recently been used to make transparent wood. PAA is a non-toxic, biocompatible, and biodegradable polymer derived from the polymerization of monomer acrylic acid (Arkaban et al., 2022). It is also an environmentally friendly polymer with high mechanical strength and clarity (Abd Alsaheb et al., 2015; Babiker et al., 2019). Yang et al. (2022) investigated the use of PAA in ETW preparation. During the preparation, the PAA was mixed with Iron (III) chloride to form a flexible $FeCl_3$/polyacrylic acid transparent conductive wood. The results showed that the transparent wood had the best conductivity and tensile strength of up to 6.03 MPa demonstrating potential applications in conductive films, flexible human sensors, and other fields. This study demonstrated a state-of-the-art approach in developing transparent conductive wood using polyacrylic acid combined with a filler. It represents an exciting convergence of sustainability, innovation, and functionality. The synergistic combination of iron ions and polyacrylic acid facilitated the formation of a conductive network within the wood structure while maintaining optical clarity. This novel approach not only expands the functional capabilities of wood but also opens up new possibilities for its use in various applications, from smart windows to flexible electronics.

Despite the limited research on the application of biopolymers in the production of ETW composites, these materials hold great promise as an alternative to synthetic polymers and therefore must be investigated further. Adoption of these materials may, of course, be accompanied with challenges and uncertainties. For example, issues like the high moisture absorption associated with bio-based polymers and cost-effectiveness will need to be addressed.

4. Properties of ETW

As wood transitions from being natural to transparent, its properties change significantly. As a result, ETW has unique optical, mechanical, and thermal properties. Measuring these properties after the ETW fabrication process is essential to confirming that the product satisfies requirements and is safe for its intended application.

4.1. Mechanical properties

Engineered transparent wood exhibits a unique combination of mechanical properties, including strength, stiffness, elasticity, and durability. The removal of lignin and impregnation with polymers can increase the strength and stiffness of wood without significantly compromising its natural flexibility. ETW exhibits enhanced strength and toughness compared to natural untreated wood. Furthermore, the mechanical properties of ETW differ from those of glass, and each material has its own set of advantages and limitations (Table 1).

While ETW shows exceptional mechanical properties, it can be concluded from literature that these properties can be affected by the following factors among others:

4.1.1. Wood species

The mechanical properties of ETW are strongly dependent on the wood species (including their density, cellulose content, cell structure morphology, etc.), and wood structure anisotropy. Different wood species such as balsa (Li et al., 2016), poplar (Gan et al., 2017), and beech (Zhu et al., 2017) impregnated with the same polymer show substantial differences in terms of mechanical properties. This may be due to the interaction between the wood and polymer components, as other species may be more compatible with the polymer than others. Wu et al. (2021) compared the mechanical properties of ETW made from two different wood species (basswood and pinewood). They reported that the hardness of the ETW made from Basswood increased by 14.49 % while that of ETW made from pinewood increased by 11.43 % when compared to their original forms. This could be due to that basswood is relatively stronger than pinewood, hence the higher mechanical strength. However, the choice of wood species will depend on specific project requirements, availability, and desired aesthetics.

Table 1
Summary of the differences in the mechanical properties of ETW and glass (Katunský et al., 2018; Li et al., 2018b).

Characteristic	ETW	Glass
Strength	Reasonable tensile and compressive strength, but it is not as strong as glass. The strength of transparent wood depends on factors, such as the type of wood, the wood-to-polymer ratio, and the processing methods used.	Has high compressive strength, making it suitable for load-bearing applications. However, it is relatively brittle and can shatter upon impact, which can be a safety concern.
Durability	Depends on factors like the type of wood, protective coatings, and exposure to the environment. It may be susceptible to moisture-related issues if not properly sealed.	Highly durable and resistant to environmental factors. It is also less prone to degradation over time.
Flexibility	More flexible than glass. It has the potential to flex to some extent without breaking, which can be an advantage in certain architectural designs.	Rigid and has limited flexibility. It tends to break or crack when subjected to bending stresses.
Weight	Generally lighter than glass, which may be advantageous for reducing the overall weight of building materials and structures.	Denser and heavier than transparent wood, which can impact the design and construction of buildings.

4.1.2. Cutting direction

The cutting direction of the wood samples also have an influence on the mechanical properties of ETW. Wood cut along the fiber (longitudinal) direction tends to be stronger than that which is cut across the fiber (transverse direction). This is due to that in the longitudinal direction, the fiber alignment is preserved and reinforcement and bonding between fibers is easier. Furthermore, the longitudinal direction corresponds to the natural orientation of the wood fibers along the tree's growth axis. This orientation reflects the structural adaptation of the tree to resist gravitational and environmental forces, further contributing to the strength of wood in this direction. These factors collectively enhance the wood's ability to withstand applied loads and stresses along the grain direction. This was in correlation with the results obtained by Xia et al. (2021) where they reported that ETW cut along longitudinal direction exhibited excellent mechanical properties compared to that which was cut across the fiber. A high tensile strength of 24.5 MPa was obtained along the longitudinal direction as compared to the lower tensile strength of 0.7 MPa along the transverse direction.

4.1.3. Wood thickness

In terms of thickness, thicker wood sections tend to be stronger than thinner ones (Li et al., 2018a; Zou et al., 2022). However, excessively thick sections may become challenging to delignify and impregnate evenly, leading to inconsistent transparency and mechanical properties. To overcome this limitation, Wang et al. (2018) developed a new different approach to fabricate ETW with a larger thickness. This was achieved by infiltrating the polymer (PMMA) into wood fibers rather than the commonly used intact wood templates. The fabricated transparent fiber wood demonstrated exceptional mechanical properties, outperforming both natural wood and neat PMMA in terms of rupture strength and modulus, which reached 46.8 MPa and 2.2 GPa, respectively. This could be due to the strong interfacial bonding between the wood fibers and the polymer matrix which facilitated efficient load transfer and stress distribution. Another reason could be due to the longer wood fibers that were used (2–5 mm) to make the transparent wood. Furthermore, the wood fibers could have been aligned in the direction of loading since that can also contribute to enhanced strength and stiffness of the transparent wood. While this approach may have been successful in producing thicker transparent wood with good mechanical properties, a few factors need to be taken into consideration. Firstly, intact wood is typically more durable and resistant to damage compared to wood fibers. Using wood fibers may therefore compromise the structural integrity and longevity of the final product, potentially leading to issues such as warping, cracking, or breakage over time. Furthermore, processing wood fibers separately from intact wood may require additional energy and resources, potentially increasing the environmental footprint of the manufacturing process. Intact wood templates on the other hand offers a more sustainable option by utilizing the entire wood piece efficiently.

4.2. Optical properties

The optical properties of engineered transparent wood, including transparency, haze, refractive index, light transmission, and scattering, play a crucial role in determining its suitability for various applications. Studies have demonstrated that ETW can achieve high levels of transparency (>90 %) while maintaining low levels of haze (Fu et al., 2018; Jia et al., 2019; Mi et al., 2020a; Zhu et al., 2016b). The refractive index of transparent wood can be tailored by selecting appropriate polymer matrices, leading to improved light transmission and optical clarity. Strategies to reduce light scattering, such as optimizing processing conditions and surface treatments, have been investigated to further enhance the optical performance of transparent wood. The optical properties of ETW are tested in accordance with ASTM D1003 ("Standard method for haze and light transmittance of transparent plastics") (ASTM International, 2013; Mi et al., 2020a, b) using a UV–visible spectrophotometer. Transmittance and haze of transparent wood are calculated using the following formulas:

$$\text{Transmittance} = \frac{T2}{T1} \times 100\ \% \tag{1}$$

$$\text{Haze} = \frac{T4}{T2} - \frac{T3}{T1}\ \text{x}\ 100\ \% \tag{2}$$

Where T1 is the incident light, T2 is the transmitted light of the sample, T3 is the scattering light of the instrument, and T4 is the scattered light of the instrument and the sample.

Compared to glass, ETW typically has a lower optical transmittance. However, to achieve a higher optical transmittance, it is important to choose a polymer that has a refractive index which matches that of wood cellulose. As mentioned in Section 3.2, polymers with a refractive index close to wood cellulose such as PMMA and epoxy resin have been utilized to fabricate ETW. This is because the matching refractive indexes minimize light scattering at the interface between the polymer and wood, improving transparency.

The optical properties of ETW are also be affected by the thickness of the wood section. For example, thinner wood sections tend to result in ETW with a higher optical transmittance than thicker ones. Li et al. (2018a) observed the highest transmittance of 92 % for thinner wood samples as compared to thicker ones which gave an optical transmission of around 60 %. This is in correlation to other studies (Chen et al., 2019, 2016; Li et al., 2019b; Zhu et al., 2022). The reason for these observations could be that, unlike thicker sections, thinner sections allow light to penetrate more effectively through the wood matrix. In thicker wood sections, there is an increase in the number of polymer/wood contacts, which leads to light scattering. Basically, thicker wood sections have longer light pathways which results in increased light attenuation whereas shorter light pathway reduces light attenuation, hence smaller thickness results in better optical transmittance.

Concerning haze, the opposite is observed: thicker wood sections result in higher haze. This quality can be particularly beneficial in settings where privacy is important, such as in residential windows or office partitions. This is because increased haze provides a level of privacy by obscuring direct visibility through the material while still allowing light to pass through. However, since high haze diminish the clarity of transparent wood, it makes it less suitable for applications where maximum visibility and transparency are desired, such as in display cases, museum exhibits, or storefronts. The reduced clarity may detract from the overall esthetic or functionality of the material in such settings. Furthermore, excessive haze can potentially reduce the effectiveness of ETW in providing natural daylighting or solar heat gain in architectural applications. This limitation may necessitate additional artificial lighting or compromise energy efficiency goals.

4.3. Thermal properties

The thermal properties of ETW, such as thermal conductivity and thermal stability, are essential considerations for applications in building materials and thermal management systems. Wood naturally exhibits low thermal conductivity and anisotropic thermal transport due to its high porosity, low levels of crystalline biopolymeric components and structural anisotropy at various length scales. Glass on the other hand has a higher thermal conductivity. At room temperature, the thermal conductivity of glass extends from 1.38 W/(m K) (pure quartz glass) to about 0.5 W/(m K) (high lead containing glasses) (Schottglass.com). Values for the commonly used silicate glasses ranges from 0.9 to 1.2 W/(m K).

Compared to glass, ETW has a lower thermal conductivity since it is made from wood. Literature has reported the thermal conductivity of ETW to be as low as 0.20 W/(m K). Jia et al. (2019) reported that their transparent wood exhibited an excellent thermal insulation property with a low thermal conductivity of 0.35 W/(m K) (one-third of ordinary glass). This is in correlation to other studies which have also reported lower thermal conductivities of their developed ETW (Mi et al., 2020a; Wang et al., 2020; Zhang et al., 2020). The significance of ETW with lower thermal conductivity lies in its ability to bridge the gap between aesthetics and functionality. Traditionally, windows and glass facades, often compromise thermal performance, leading to energy loss and increased heating or cooling costs. However, with ETW boasting improved thermal insulation properties, there is now a solution that marries beauty with efficiency. Its thermal stability means it can effectively regulate heat transfer, helping to maintain comfortable indoor temperatures year-round while reducing reliance on artificial heating and cooling systems. The lower thermal conductivities of the ETW makes it a favorable material especially in energy-saving buildings. This is because it has a significantly lower carbon footprint compared to conventional building materials like glass or plastics. Traditional glass windows often pose challenges in terms of insulation and energy efficiency, but ETW presents a promising solution.

5. Functionalization of ETW

Transparent wood functionalization holds significant importance in advancing its practical applications across various industries. Functionalization helps to enhance the ETW properties such as thermal insulation, flame resistance, mechanical strength, electrochromism, UV protection, etc. The specific functionalization method chosen depends on the intended application and desired properties. A photostable transparent wood composite functionalized with an UV-absorber (2-(2H-benzotriazol-2-yl)-4, 6-di-tert-pentylphenol) was developed by Bisht et al. (2021). Findings showed that before functionalization, the transparent wood composite (TWC) was extremely sensitive to UV light exposure and exhibited rapid photo-discoloration, chemical degradation, and a decrease in optical transmittance (Fig. 3). Incorporation of the UV absorber considerably reduced discolouration and photo-degradation of the TWC and the pure epoxy. From a sustainability standpoint, the use of UV absorbers to functionalize transparent wood composites aligns perfectly with the sustainability goals. This is because the UV absorbers extend the lifespan of the products, thereby reducing the need for frequent replacements and minimize waste generation.

Table 2 summarizes some of the different materials from literature that have been employed to functionalize ETW composites.

While functionalizing ETW offers numerous benefits, it also comes with its own set of limitations and challenges. Functionalizing ETW often involves complex chemical treatments or deposition processes, which can be technically challenging and require specialized equipment and expertise. This complexity can increase production costs and limit scalability, particularly for large-scale applications. Furthermore, some functionalization methods may involve the use of chemicals or additives that pose environmental risks or generate hazardous by-products. Minimizing the environmental footprint of functionalization processes and ensuring the safety of end products is a critical consideration for sustainable development.

6. Applications of ETW

ETW offers some unique advantages such as flexibility, reduced weight, improved thermal insulation, high optical transmittance (over 80 %) as well as a distinctive appearance. These properties make it appealing for various applications including smart buildings, load-bearing structures, solar cells as well as electronic devices and displays (Zhu et al., 2016b). The following sections discusses some of the different ETW applications.

6.1. Building material

ETW has been considered for architectural applications, such as windows and panels. Its optical clarity allows for the passage of natural

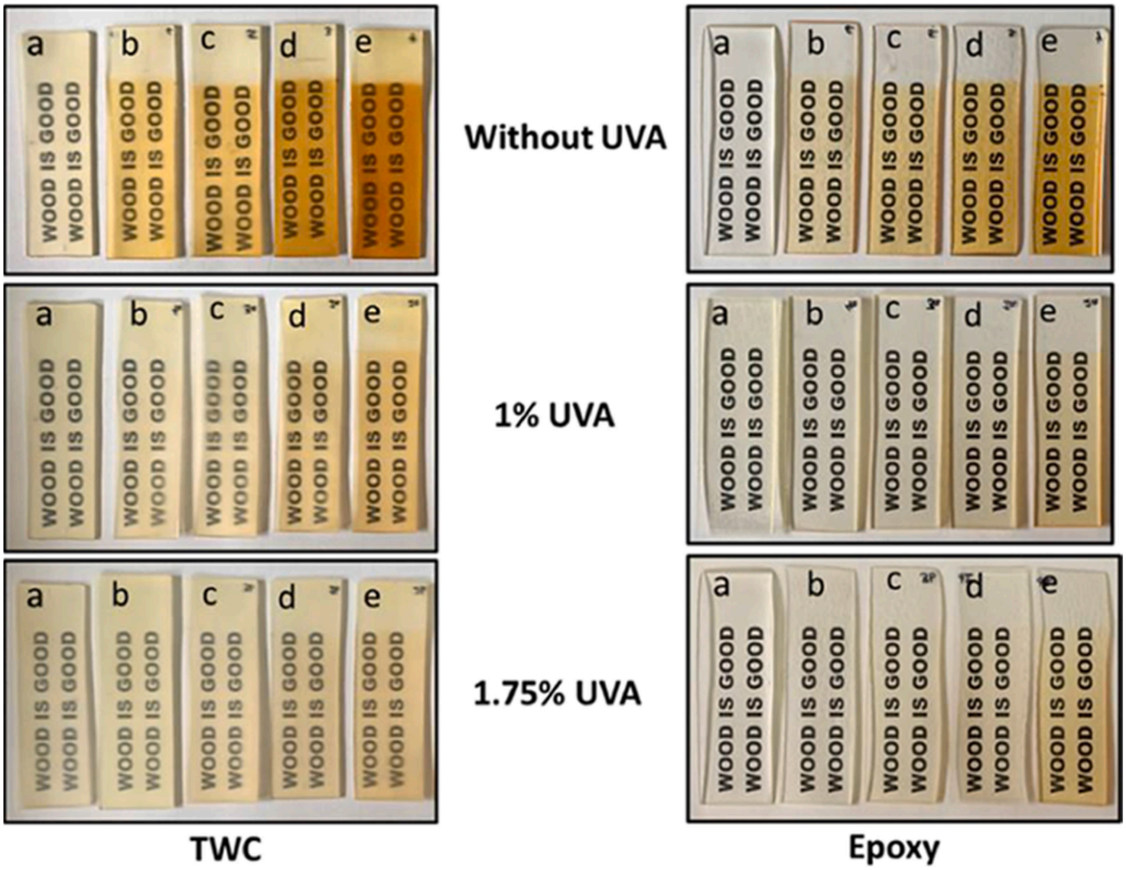

Fig. 3. The effect of light irradiation on TWC without and with UVA (Conc. 1.0 % and 1.75 %), and epoxy resin, Source: (Bisht et al., 2021).

Table 2
Different ETW functionalization approaches from literature and their effects.

Wood species	Polymer	Functionalization material	Effect	Reference
Basswood	methyl methacrylate (MMA)	photoluminescent lanthanide-doped aluminum strontium oxide ($SrAl_2O_4:Eu^{2+}$, Dy^{3+}; ASOED) pigment	The ETW exhibited improved UV protection and superhydrophobic activity. It also showed fast and reversible photochromic responses to UV light without fatigue.	Al-Qahtani et al., 2021
Balsa wood	poly(acrylic acid) (PAA)	multiple-color-emission carbon dots (CDs)	The ETW showed white light emission under ultraviolet light excitation and enhanced mechanical tensile strength (60.92 MPa).	Bi et al., 2018
Poplar wood	Epoxy resin	UV absorber (1 % and 1.75 % w/v) of 2-(2H-Benzotriazol-2-yl)-4, 6- di-tert-pentylphenol (Btz)	ETW with a reduced discolouration and photo-degradation. Water uptake was also drastically reduced in the ETW.	Bisht et al. 2021
Poplar wood	poly(methyl methacrylate) (PMMA)	luminescent γ-Fe_2O_3@ $YVO_4:Eu^{3+}$ nanoparticles	The ETW showed excellent thermal properties, dimensional stability, and mechanical properties. It also displayed a high optical transmittance in a broad wavelength range between 350 and 800 nm, magnetic responsiveness, and brightly colored photoluminescence under UV excitation at 254 nm.	Gan et al., 2017

light while providing thermal insulation and reducing glare. Gao et al. (2022) fabricated ETW for smart building applications. The prepared ETW showed excellent thermal insulation, sound absorption and energy absorption properties. These properties make ETW an ideal building material since it can effectively reduce the energy consumption for cooling and heating buildings. Several other studies (Jia et al., 2019; Katunský et al., 2018; Mi et al., 2020a) have also reported on the application of ETW in smart buildings and construction as a solution to the high energy consumption associated with glass. By integrating ETW into buildings, carbon emissions can be reduced, and climate change can be mitigated. This can then create healthier and more resilient communities for future generations.

The unique esthetic qualities of ETW, including its natural grain and texture, make it appealing for design and decorative purposes (Yang et al., 2023). It provides a novel and sustainable alternative to traditional materials in furniture, interior design, and art installations.

6.2. Electronic and photovoltaic devices

The high transparency and mechanical flexibility of ETW makes it an ideal candidate for flexible electronic devices, enabling lightweight and bendable displays, sensors, and wearable technologies. It can be integrated into optoelectronic devices, such as light-emitting diodes (LEDs), photodetectors, and optical sensors. Its optical transparency and light-scattering properties make it suitable for enhancing light extraction and distribution in these devices, improving efficiency and performance. Bi et al. (2021) developed a transparent wood film as encapsulating material for white Light-Emitting Diodes (LEDs). From a thermal standpoint, this innovation is appealing since the thermal insulation properties of ETW can help dissipate heat generated by WLEDs and maintain optimal operating temperatures. This can therefore contribute to the longevity and reliability of the lighting system. Similar studies (Wang et al., 2022; Zhu et al., 2016c) have also reported on the successful development of ETW for optoelectric devices.

ETW can also be used to create photovoltaic devices like transparent solar cells or luminescent solar concentrators (LSCs). By embedding light-absorbing or light-emitting materials within the wood matrix, transparent wood can convert sunlight into electricity or concentrate light onto photovoltaic cells, enabling energy harvesting. Researchers have reported on the successful application of ETW in photovoltaic panels (Wu et al., 2023; Li et al., 2019c; Yang et al., 2021). This is due to the unique properties of ETW, such as its optical transparency, mechanical strength, and thermal insulation, which make it an ideal candidate for various applications in electronic and photovoltaic devices. Whether it is serving as a substrate for flexible electronics, a protective enclosure for photovoltaic cells, or a light-scattering medium in luminescent solar concentrators, ETW offers a versatile and sustainable solution to pressing challenges in these industries.

Although ETW offers unique properties, it still has some few drawbacks which need to be addressed for it to become a widely adopted material in various industries. Table 3 summarizes the advantages and drawbacks of ETW in comparison to glass.

Table 3
Advantages and drawbacks of ETW in comparison to glass.

Advantages	Drawbacks
Can have a higher transparency although not as high as glass.	Achieving sufficient transparency often requires thin layers of transparent wood, which may limit its use in applications requiring thicker materials.
Good thermal insulation properties which can contribute to energy efficiency in buildings.	Less durable than glass, therefore, may be susceptible to degradation over time due to exposure to weather, UV radiation, and other environmental factors.
Lighter than glass, making it easier to handle and transport.	The manufacturing process involves multiple steps and may require specialized equipment. This can contribute to higher production costs and limit the scalability of the technology.
Made from a renewable resource, therefore it is more sustainable than glass.	The manufacturing process can be more expensive.
Retains some of the natural wood's mechanical strength.	Has limited applications. For instance, it may not be the best choice for applications where extreme clarity, such as in high-end optics, is required.

7. Future considerations

While ETW presents an innovative and sustainable alternative to traditional glass, it is important to acknowledge some of the current gaps and limitations associated with this material as this will help guide the future directions. Below are some novel insights and approaches that could be explored in future to enhance the production of transparent wood:

- **Use of alternative polymers:** Investigating and developing new transparent polymers that can replace the traditional ones used in the impregnation process. Experimenting with polymers that offer improved transparency, durability, and environmental sustainability could enhance the overall performance of transparent wood.
- **Development of scalable manufacturing techniques:** For future applications, thick and large-scale transparent wood structures are highly desirable. Currently, scaling up the production process to create large, ETW panels or structures remains a challenge. Techniques that work for small samples may not easily translate to larger pieces, and maintaining uniformity becomes more challenging as the size increases (Jia et al., 2019; Li et al., 2019; Wang et al., 2018; Zhang et al., 2022a). Developing scalable and cost-effective manufacturing techniques is crucial for the widespread adoption of transparent wood.
- **Integration of nanomaterials:** Incorporating nanomaterials into the transparent wood matrix to enhance its properties. Nanoparticles with specific optical, thermal, or mechanical characteristics could be introduced to improve transparency, strength, or other desirable attributes of the material.
- **Improvement of the lignin removal techniques:** Finding more efficient and environmentally friendly methods for lignin removal. The current process involves chemical treatments that can be resource intensive. Developing alternative methods, such as enzymatic or biological approaches, could reduce the environmental impact of transparent wood production.
- **Waste utilization:** Investigating ways to utilize byproducts from the transparent wood manufacturing process, such as lignin, in other applications. Finding valuable uses for these byproducts can contribute to the overall sustainability of the production process.
- **Energy-efficient fabrication processes:** Developing energy-efficient processing methods to reduce the environmental footprint of transparent wood production. This includes exploring alternative energy sources, optimizing heating, and curing processes, and minimizing waste generation.
- **Improvement of fabrication techniques to increase the life span of ETW:** As a biomaterial, ETW is susceptible to degradation over time. This may be due to factors such as moisture and humidity, microbial activity, UV exposure, temperature fluctuations as well as chemical exposure. Addressing these issues related to the biodegradability and life span is necessary and it involves a combination of material improvements, design considerations, and industry-wide practices. Some studies suggested the use of coatings or treatments to extend the material's life span (Janesch et al., 2020; Jiang et al., 2018; Liu et al., 2023). While coatings or treatments can be effective in extending the lifespan of ETW, it is important to note that they also come with certain limitations and challenges such as high costs and environmental and health risks. It is therefore important to consider these issues when using coatings.

8. Conclusion

Since its discovery in 1992, ETW has undergone significant research and development, leading to its exploration for various applications. Engineered transparent wood is energy efficient material with a lower thermal conductivity than glass. It is also made from a renewable and sustainable resource, thereby making it an environmentally friendly glass alternative. While challenges such as scalability and cost-effectiveness still need to be addressed, ongoing research suggests a promising future for transparent wood in various industries, driven by its unique combination of optical transparency, mechanical strength, and sustainability. As technology advances and more practical solutions are developed, transparent wood is poised to play a growing role in sustainable and innovative material applications.

CRediT authorship contribution statement

Nontobeko P. Simelane: Writing – review & editing, Writing – original draft. **Olatunde Stephen Olatunji:** Supervision. **Maya Jacob John:** Writing – review & editing, Supervision. **Jerome Andrew:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors also declare that there are no conflicts of interest regarding the publication of this paper.

Data availability

Data will be made available on request.

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