

Wood Species and Treatment Selection for Transparent Wood Fabrication – A Scoping Review

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Abstract

Background

Research on the topic of transparent wood (TW) has gained a lot of traction in recent years, with the largest uses as an energy-efficient building material, particularly as a replacement for glass and optical materials involving UV shielding and light management. However, there is no coherent or standardised framework in literature with regards to the best choice of wood species and optimised treatment parameters for different wood species to obtain optical performance.

Methods

This paper uses a scoping review methodology developed by Arksey and O'Malley. Scopus, Web of Science and Google Scholar databases were used to source relevant literature from 2016–2026, as well as references found in these articles.

Results

The effectiveness of different treatments on different wood types and species was compared to identify, which treatment / species combination yield the best optical properties in TW and it was found that hard- and softwoods require different treatments and that wood density affects treatment parameters greatly. Furthermore, the feasibility to upscale production with regards to wood availability is discussed, as the commercially available wood species are not often used to produce TW.

Conclusions

The results indicate a significance lack in standardisation for treatment protocols optimised for a certain wood species and a lack of research into commercially available wood species like pine and eucalyptus.

Introduction

Transparent Wood (TW) has gained significant attention in recent years due to its versatile applications^[1-6]. Combining the optical qualities of transparent polymers with the mechanical strength of wood, TW holds the potential to replace many optical materials. As a more sustainable, less hazardous and environmentally friendly alternative, TW offers superior thermal insulation and good optical and mechanical properties^[5,7]. In recognition of this, numerous original studies have explored potential applications of TW and its performance and functionality in various fields ^[1,6,8-26]. Examples are the development of light-diffusing materials that glow in the dark, energy-efficient windows, solar cells, smart windows, biodegradable electronics and optical devices^[18,27-34]. However, limitations in optical and mechanical performance, together with scalability, remain an obstacle for the industrial commercialisation of TW. These challenges highlight the need for further exploitation of the fabrication parameters and mechanisms pertaining to the advancement of TW. A critical challenge moving forward is to achieve a balance between the incorporation of functional components and the preservation of the desirable wood properties.

The discovery of TW was based upon an abandoned anatomical study by Fink ^[35] and pursued in 2016 by two independent research groups^[36,37]. They and subsequent researchers demonstrated that by exposing veneer to various delignification methods followed by polymer impregnation with a transparent polymer (e.g., epoxy, PMMA, PVP etc.), wood obtains the potential to transmit and scatter 95 % of light it is subjected to^[4,38]. The aim was to improve optical clarity by means of bleaching chromophores and diminishing most of the lignin, which contributes to light scattering and absorption, without deteriorating the structural performance of the wood skeleton. This is achieved through various delignification treatments, such as oxidative (NaClO_2 , $\text{CH}_3\text{COOH} + \text{H}_2\text{O}_2$, H_2O_2), alkaline (NaOH , Na_2SO_3) and organosolv (ethanol, methanol, acetone etc.) treatment. These are adopted from the pulp and paper industry and are typically performed at temperature ranges 60 – 100 °C, 90 – 150 °C and 100 – 160 °C^[39,40], respectively. These treatments are reproducible on several wood species, however, some

wood species turn completely whiteness, while others just yellow and some suffered complete structural failure of the wood structure^[27,41]. From the various considered treatments, steam modification (e.g., $\text{CH}_3\text{COOH} + \text{H}_2\text{O}_2$) of the wood was the most effective approach with shorter treatment times (e.g. 4 h for balsa wood and 8 h for pine) compared conventional delignification methods where the wood is fully submerged in the chemical solution. The steaming approach was also found to preserve the wood skeleton well for samples thicker than 20 mm^[42].

The high degree of light transmittance and high mechanical strength are the main advantages of TW compared to e.g., glass. The high optical clarity is possible, because cellulose, lignin and hemicellulose share a similar refractive index to that of polymer (~ 1.5) impregnated into the wood^[35]. The size and distribution of cell / vessel lumina and the presence of additional voids created by the delignification treatment determines the degree of light transmission and refraction of the TW. Light transmittance is higher (i.e., $\sim 95\%$) if light rays travel parallel to the grain (Figure 1B) compared to perpendicular to the grain (Figure 1A), which results in a higher haze ($\sim 90\%$)^[37].

The fracture toughness (MJ/m^3) and resistance to stress of TW is much higher than glass^[5,43], however, the mechanical performance of TW is determined by the degree of delignification, which changes the mechanical properties of the wood, as well as the polymer filler the type of impregnation technique.

Taking this into account, the appropriate choice of wood species to produce TW is essential to ensure the best performance. Wood is a highly anisotropic and heterogeneous material, which optical, mechanical and physical properties vary across the three anatomical directions: longitudinal, radial and tangential. The performance of TW depends strongly on the type of wood (hard-/softwood, heart-/sapwood, early-/ latewood) and its properties, such as density, anatomical structure, chemical composition, extractive content, hygroscopicity and the presence of defects. These wood properties vary between trees of the same species and between species and are caused by environmental and site factors, which are region dependent.

One aim of this review is to determine the feasibility to expand TW production more towards commercially relevant wood species, which differ for specific regions. Globally 40 % and 31 % of the forest plantations are broadleaved and coniferous trees, respectively. with the genera *Pinus* (20 %) and *Eucalyptus* (10 %) as the principal resources for the timber and pulp production across the world. Other commercially planted genera are *Acacia*, *Hevea*, *Tectona*, *Picea*, *Betula*, *Larix*, *Populus*, *Abies*, *Quercus*, *Pseudotsuga*, *Fagus* and *Nothofagus* ^[44-47].

The present literature dealing with TW investigates a broad range of wood species, however the majority deals with balsa and basswood^[19,39], which are not commercially important species. Although some attempts have been made, the literature dealing with TW made from *Pinus* and *Eucalyptus* is limited.

Various new novel treatment techniques are reported across the literature, but the majority of publications concentrates on the end result, namely the performance of TW in a specific application, rather than refining and optimising existing techniques according to the wood species used^[39]. While most chemical treatments are reproducible on both soft- and hardwoods to a degree, treatment conditions, such as times and temperatures might differ. The challenges of 1) reducing fabrication times and complexity of procedures, 2) improving environmental impact and 3) scalability are discussed in several reviews^[26,42,48]. The review approach has been adopted over the last decade from narrative, over systematic, to a more integrative and critical framework. For example, A review by Li, et al. ^[1] discussed different preparation methods, the optical and mechanical performance and highlighted potential functionalisation and applicational routes TW may possibly take. His work built upon numerous publications, which dealt with the application of TW^[3,5,7,29,31,36,37,49,50]. Follow-up review articles summarised recent developments in fabrication techniques, material properties and/ or the application of TW in various fields^[1,6,8-26,39,48,51]. Chutturi, et al. ^[8] provides a meta-analytic review, which covers synthesis processes, characterisation techniques, functionality and application of TW. Terzopoulou, et al. ^[19] and Moher, et al. ^[52] both reviewed the polymer matrices used, applications, delignification/ impregnation parameters, optical, thermal and mechanical properties, and identified gaps in literature. Wu, et al. ^[53] and Rai, et al. ^[54] conducted life cycle assessments of TW and found that sodium hydroxide/ sodium sulfite/ hydrogen peroxide-based delignification followed by epoxy infiltration resulted in the lowest environmental impact. In summary, literature reporting on TW treatment is widely distributed different scientific areas, and not all papers report the same properties to

determine the effectiveness of their treatment. Most papers do also not give much information about the wood properties before treatment, which makes it very difficult to find the best possible treatment for a certain wood species.

This review attempts to fill this gap, by comparing the effectiveness of various treatments for industrially relevant wood species and trying to determine the best possible treatment and treatment parameters for different wood species.

To address this knowledge gap, a scoping review was selected to systematically map the available evidence. The review synthesises present evidence on industrially relevant wood species and their properties, the treatment methods and the properties of the resulting TW. To our knowledge no review of this kind exists. This review evaluates the existing body of literature with regards to the fabrication of TW made from different wood species to allow the optimisation of species-specific treatment parameters. While polymer infiltration is a key aspect in TW fabrication, it will not be discussed in this work, as we are trying to highlight the effect of the wood properties on the process as highlighted in Figure 2.

Research design and Methodology

This review was conducted using the methodological framework proposed by Arksey and O'Malley^[55], and the reporting of the review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR)^[52,56]. The research questions guiding the study were as follows:

1. Which wood species have been investigated in TW literature and what are their inherent wood properties?
2. To what extent do the wood species investigated reflect the commercially significant plantation species?
3. What are the common treatment protocols for those species and how effective was the treatment?

Search strategy and study selection

The following electronic databases were used for literature search: Web of Science, Scopus and Google Scholar, as well as the reference lists within those publications and searching in individual, relevant journals. The search terms were transparent wood or translucent wood within the title, abstract and keywords (Figure 4) and literature was limited to peer-reviewed articles written in the English between 2016 and 2026. From each manuscript, information regarding wood species name, treatment parameters (e.g., exposure time, concentration, temperature) and wood properties (e.g., type, dimensions, chemical composition, cellular structure, colour attributes) was extracted. All articles were screened and grouped according to the genus name of the utilised wood species.

Results and Discussion

Literature search

In this scoping review, 132 articles were included and it was observed that the amount of published literature dealing with TW increased significantly over the last decade with a maximum around 2024, after which it decreased somewhat, while expanding into various subject areas as seen in Fig. 5. The identified wood species from all the publications are listed in Table 1 and wood species are grouped according to hard- and softwoods.

A total of 32 review articles were identified within the study. An initial review by Li, et al. ^[1] discussed different preparation methods, the optical and mechanical performance, and highlighted potential functionalisation and applications. This work built on various publications investigating the applications of TW ^[1,6,8-26,39,40,48,51,53,54,57-61]. Follow-up review articles employed a similar methodological structure and are mostly comprehensive reviews summarising recent developments, fabrication techniques, material properties and the application of TW in various fields ^[1,6,8-25]. Review articles that took a semi-systematic or meta-analytic approach were published by Chuttur, et al. ^[8] and Terzopoulou, et al. ^[19]. Chuttur, et al. ^[8] provides a complete review, which systematically covers the synthesis processes,

characterisation techniques, functional/ structural features and application in a clear, ordered manner. However, this review did not focus on different wood species and types.

A wide group of wood species was used to produce TW across the studied literature. 100 Articles were identified tabulated in Table 1. The most popular wood species were balsa ($n = 30$) and basswood ($n = 17$), followed by poplar ($n = 10$), pine ($n = 9$) and birch ($n = 7$), which represent majority of the articles. In addition, beech ($n = 3$), ash ($n = 1$), aspen ($n = 1$), rubberwood ($n = 3$), eucalyptus ($n = 2$), chinese and douglas fir ($n = 3$), spruce ($n = 3$), ailanthus ($n = 1$), oguman ($n = 1$), melia ($n = 1$), walnut ($n = 1$), maple ($n = 1$), oak ($n = 1$), larch ($n = 1$), paulownia ($n = 1$), alder ($n = 1$) and rosewood ($n = 1$) were mentioned as resource to produce transparent wood.

Table 1
Summary of the amount of publications for each wood species.

Wood type	Wood species (common name)	Total articles	Ref.
Hardwoods	Balsa (<i>Ochroma</i>)	30	[4,7,27,28,32–34,36,38,62–82]
	Birch (<i>Betula</i>)	7	[64,69,75,81,83–85]
	Oguman / Okoumé (<i>Aucoumea klaineana</i>)	1	[83]
	Ash (<i>Fraxinus</i>)	1	[64]
	Basswood (<i>Tilia</i>)	17	[5,27,29,30,37,42,73,83,86–93]
	Poplar (<i>Populus</i>)	10	[2,43,49,94–100]
	Beechwood (<i>Fagus</i>)	3	[3,101]
	Eucalyptus (<i>Eucalyptus</i>)	2	[41,102]
	Alder (<i>Alnus</i>)	1	[81]
	Rubberwood (<i>Hevea</i>)	3	[103–105]
	Ailanthus (<i>Ailanthus</i>)	1	[104]
	Oak (<i>Quercus</i>)	1	[99]
	Maple (<i>Acer</i>)	1	[106]
	Melia (<i>Melia</i>)	2	[99,100]
	Walnut (<i>Juglans</i>)	1	[83]
	Aspen (<i>Populus</i>)	1	[107]
	Paulownia (<i>Paulownia</i>)	2	[108,109]
Softwoods	Pine (<i>Pinus</i>)	9	[27,41,42,64,83,84,92,110,111]
	Douglas fir (<i>Pseudotsuya</i>)	2	[27,59]
	Chinese fir	1	[83]

Wood type	Wood species (common name)	Total articles	Ref.
	(<i>Cunninghamia</i>)		
	Spruce	3	[107,112,113]
	(<i>Picea</i>)		
	Larch	1	[107]
	(<i>Larix</i>)		

The result tabulated in Table 1 suggest a large proportion of present literature is dedicated towards hardwoods (~ 80%) rather than softwoods (~ 20%). From those studies, the majority used balsa and basswood as a wood scaffold, due to their excellent optical properties and ease of processing.

A large portion of the wood species listed in Table 1 are commercially used species, such as eucalyptus, paulownia, birch, okoume, poplar, ash, pine, spruce, larch and fir, which displayed suitable characteristics for TW production. On the other hand, the species most frequently used to produce TW i.e., balsa and basswood, have a relatively small economic footprint when commercial forestry^[114].

Wood properties

The attributes of TW are highly dependent on the inherent wood properties of the wood scaffold. These properties influence the effectiveness of the chemical treatment and the overall performance of the TW. It is therefore critical to understand the wood before proceeding with any treatment procedures. This section provides an overview of the wood properties of the wood species reported in literature and their effect on the performance of the TW materials.

The general the chemical composition of wood is 18–35% lignin and 65–75% carbohydrates, which includes cellulose and hemicelluloses. The lignin content in hardwoods ranges from 17–25% and is somewhat lower than in softwoods (25–35%)^[115,116]. In general, the cellulose content of softwoods is 40–45%, while that of hardwoods is about 38–49% and the hemicellulose content of softwoods is with 7–14% lower than that of hardwoods (19–26%)^[117]. Cellulose and hemicellulose provide structural stability and strength^[118], while lignin acts as a binding agent for the cellulose microfibrils and provides structural support^[119]. In the fabrication of TW, the chemical composition affects the treatment parameters, which aim to optimise lignin removal while retaining the structural integrity of cellulose.

Cellulose forms crystalline micro-fibrils that are surrounded by amorphous hemicelluloses. Hemicellulose dissolves rapidly in strong acids, such as hydrochloric acid, sulfuric acid and phosphoric acid, whereas the crystalline cellulose fibrils are insoluble in strong alkali solvents. However, fiber separation may occur even in mild treatment conditions typically a result of lignin and hemicellulose degradation, which act as binders between cellulose fibrils.

Lignin is primarily distributed in the middle lamellae between individual fibers and acts as glue to hold the cellulose fibrils together. The primary building blocks of lignin are p-hydroxycinnamyl alcohols, which include p-coumaryl alcohol (I), coniferyl alcohol (II), and sinapyl alcohol (III). Lignin accounts for more than 80 %of the light absorption on the wood surface and gives wood its dark colour. In the pulp and paper industry, lignin is removed from fibres to isolate the white cellulose fibers. In the fabrication of TW, lignin removal is a crucial preparation step to minimize light scattering and absorption caused by the chromophores. Optimal lignin reduction is achieved when the wood turns completely white after treatment (Figure 6a); however, in most cases, a high transparency is possible even if the wood maintains some colour (Figure 6b)^[64]. Softwoods generally have a higher lignin (25 – 35 % content than hardwoods (18 – 25 %; however, the variation in the lignin composition is much greater in hardwoods, which leads to structural differences (Table 2). For example, the lignin structure in hardwoods mainly consist of of guaiacyl and syringyl units, whereas softwoods consist predominately of guaiacyl units. Due to the complex molecular structure of lignin and the integration with the cellulose fibres, selective lignin removal is a challenging task, as this process can compromise the structural integrity of the cell wall and the degradation of other components during the treatment process which is often unavoidable.

Anatomical differences between hard- and softwoods are due to variation in the cell morphology. Hardwoods contain large vessel elements between smaller fibers, while softwoods have a more uniform cell structure of long, narrow tracheids. These anatomical differences affect the density and mechanical performance of the wood and the resulting TW properties. The most relevant wood properties for TW performance, such as density, lignin- and extractive content are listed in Table 2. The variability within species can be attributed to environmental growth factors, which lead to variations in the wood structure. Both density and extractive content play a major role in the degree of delignification or “whiteness” that can be achieved when producing TW.

Table 2
Approximate average wood properties of the most frequently used species for TW fabrication.

Wood Type	Species	Av. Density (g/ cm ³)	Av. Lignin content (%)	Av. Extractive content (%)	Ref.
Hardwoods	Balsa	0.16	24.00	2.00	[27,73,120,121]
	Birch	0.64	22.00	3.00	[85,122–124]
	Ash	0.60	27.00	3.00	[64,121,125,126]
	Alder	0.45	12.00	4.00	[121,127]
	Aspen	0.36	18.00	4.00	[121,128]
	Basswood	0.38	20.00	3.00	[129]
	Poplar	0.42	21.00	4.00	[127,130,131]
	Ailanthus	0.55	28.00	3.00	[104,132]
	Rubberwood	0.54	25.00	4.00	[104,133]
	Walnut	0.60	29.00	5.00	[121,134]
	Maple	0.65	23.00	4.00	[121]
	Melia	0.55	24.00	4.00	[135]
	Rosewood	0.80	34.00	5.00	[121,136]
	Oak	0.70	29.00	12.00	[121]
	Beechwood	0.64	23.00	3.00	[121,137]
	Eucalypt	0.70	28.00	3.00	[138–140]
	Paulownia	0.46	23.00	4.00	[141]
	Okoumé	0.45	28.00	4.00	[142,143]
Softwoods	Pine	0.55	29.00	4.00	[144,145]
	Douglas Fir	0.48	28.00	3.00	[121,146]
	Chinese fir	0.39	31.00	3.00	[83,147,148]
	Spruce	0.35	27.00	4.00	[149]
	Larch	0.56	28.00	13.00	[121,150]

The variation in wood density depends on the wood structure and chemical composition, as well as extractive content. Generally, wood density values range from $< 0.5 \text{ g/cm}^3$ (low-density) over $0.5\text{--}0.8 \text{ g/cm}^3$ (medium-density) to $> 0.8 \text{ g/cm}^3$ (high-density). Balsa, the wood most commonly used to make TW, has the lowest density with a range from $0.08\text{--}0.4 \text{ g/cm}^3$. Typical low to medium density species are bass and poplar wood, while eucalyptus, birch, beech, oak, walnut, maple and ash fall in medium to high density range. Wood density varies within a tree both vertically and horizontally, because of different proportions of mature and juvenile wood, as well as heart- and sapwood within the log. Generally, juvenile wood has a lower average density than mature wood and this is more pronounced in softwoods. In some wood species, shorter rotation ages result in a higher proportion of juvenile wood, which is typically more notable in plantation grown hardwoods, such as eucalypts, poplar and balsa, which have shorter rotation ages than softwoods. Depending on the tree age, up to 70% of the log diameter can consist of heartwood, resulting in regions high in extractives^[151], as shown in Fig. 7 for eucalyptus.

Density variations are further affected by the extractive content, which cause the visual difference between the darker heartwood and lighter sapwood (Fig. 7). Some eucalyptus species and aspen, for example, can show hardly any colour differences between heart- and sapwood and/ or growth rings resulting a homogenous wood structure. Some softwoods like larch generally contain more extractives than hardwoods. Normally, the extractive amount is strongly species dependent and some tropical species (e.g., rubberwood, ailanthus) tend to have a high extractive content^[121]. Other wood species, such as balsa and paulownia generally have a low extractive content due to their fast-growing nature. Extractives include waxes, fats, terpenes, and sugars and affect the taste, odour, colour and decay resistance of the wood and can potentially extend the delignification process, if not carefully considered. Extractives can make up 3–10% of the wood composition and vary in type and amount between tree species^[152,153]. Fatty acids (esters with alcoholic functional groups) are more prominent in softwoods, while in heartwood resinous acids are more dominant (carboxylic acid functional groups). Table 2 shows that balsa wood has a very low extractive content, which is a typical feature for low-density tropical hardwoods.

Density is also affected by growth characteristics in the form of early- and latewood rings (Fig. 8d), as well as differences between heart- and sapwood where vessel arrangement and cell diameter differ. Growth rings are more distinct in softwoods than in hardwoods where the vessel size and amount changes rather than cell wall thickness of fibers (Fig. 8)^[154]. Typically, earlywood tracheids have a thinner cell wall with a larger lumen diameter compared to latewood tracheids, which as dark bands in the year rings and are very prominent in some species. Softwood can further be classified as thin walled (e.g., yellow pine) or thick-walled (e.g., Douglas fir)^[155,156] depending on the lumen diameter. Hardwoods on the other hand can be either ring-porous (e.g. ash), where year rings are clearly visible or diffuse-porous (e.g. balsa, basswood, birch, beech and poplar), where the cell dimensions change gradually. In ring-porous wood, the vessels are much larger in the earlywood than in the latewood, whereas in diffuse-porous trees vessel diameter changes gradually throughout a growth cycle. The amount and size of vessels affect light transmission greatly, especially along the grain, while the light transmission across the grain is governed by grain direction and growth ring features. Vessel diameters typically range from 50 to 200 μm , but can be as large as 300 μm . For example, vessel and tracheids diameters of basswood, maple and pine have typical values of 14–41, 18–68 and 12–28 μm ^[157], respectively. Balsa has larger vessels than most hardwoods with values between 220 and 320 μm reported^[158]. Abbas, et al.^[159] reported the average pore diameter of basswood ($\sim 21 \mu\text{m}$) to be greater than pine ($\sim 18 \mu\text{m}$), poplar ($\sim 12 \mu\text{m}$) and oak ($\sim 9 \mu\text{m}$).

The large pore diameter translates to a greater porosity and the respective average porosity for some the hard- and softwoods listed in Table 2 are: oak: $\sim 63\%$, poplar: $\sim 68\%$, basswood: $\sim 76\%$, birch: $\sim 55\%$, pine: $\sim 71\%$, okoumé: $\sim 71\%$, beech $\sim 47\%$, maple; $\sim 68\%$, larch; $\sim 60\%$, spruce; $\sim 70\%$. As seen most wood species have a lower porosity than balsa^[160–162]. However, the vessel fraction in balsawood tends to increase with density for balsawood unlike in most other hardwoods^[158,160]. Generally, the cumulative pore volume of hardwoods is about 60% lower than softwoods. A high cumulative pore volume can be found in diffuse-porous hardwoods, like spruce, pine, alder, birch and maple. The pore volume affects the process of polymer impregnation into the cell lumina greatly.

To produce TW the wood needs to be delignified and whitened. Effective modification procedures are dictated by processing parameters, such as exposure time, temperature and concentration^[60]. Without prior knowledge of the wood properties, efficient

and effective lignin removal is unattainable. Delignification of denser areas like those found in latewood, heartwood, or reaction wood can be unobtainable, time consuming or result in fiber separation of the cell walls.

Treatment protocols and their effectiveness

Common TW treatment protocols

The most common approach to treat TW is through lignin degradation, which is typically achieved by submerging the wood in an alkaline, acidic or oxidative solutions (chlorite and oxygen-based) for extended periods until the wood is white. Chlorite and oxygen-based methods are both oxidative in nature. However, the latter is usually conducted in an alkaline medium, while chlorite treatment is normally executed in acidic media. In addition, organosolv solutions that are often used are acetone, methanol, ethanol and glycerol in combination with a water and/or an acid catalyst. These solvents are often blended with acids (e.g., hydrochloric acid, sulfuric acid).

The delignification and bleaching techniques are adapted from the pulp and paper industry and make use of the following chemicals^[39,163]:

- **Alkaline delignification:** Kraft (sulfate) pulping ($\text{NaOH} + \text{Na}_2\text{S}$), soda pulping (NaOH) and alkaline sulfite pulping ($\text{NaOH} + \text{Na}_2\text{SO}_3$). In these processes, sodium hydroxide (NaOH) is the primary active chemical responsible for breaking down lignin by cleaving ether linkages dissolving lignin fragments.
- **Acidic delignification:** sulfite pulping (H_2SO_3) in combination with bisulfite salts (e.g., Ca , Mg , Na , or NH_4HSO_3). These treatments make lignin water-soluble and easier to remove.
- **Oxidative (Chlorite and oxygen-based) delignification:** this is a post-pulping process that uses O_2 in an alkaline medium (NaOH) to further reduce the residual lignin content. Under elevated temperature and pressure, oxygen reacts with lignin, breaking ether bonds and forming oxidised products such as carbonyl and carboxyl groups, which increase lignin solubility. Other oxidising agents, such as H_2O_2 , or O_3 or peracids may also be used to enhance lignin removal and improve wood brightness. Other treatments make use of CH_3COOOH or H_2SO_4 to oxidize and breakdown lignin. NaClO_2 activated by an acid, such as acetic acid (CH_3COOH) or hydrochloric acid (HCl). The acid oxidises lignin into smaller, soluble fragments. These processes are strongly pH-dependent, typically operating under acidic conditions (around pH 1.5–2.5), although milder conditions (pH 3–5) are sometimes reported depending on the system and desired selectivity.

After delignification with alkaline solutions like $\text{NaOH}/\text{Na}_2\text{SO}_3$, the wood may be subjected to an additional bleaching step to remove residual colour and / or remaining lignin and improve optical transparency. A common bleaching agent is hydrogen peroxide (H_2O_2). Sodium hypochlorite (NaClO) and sodium chlorite (NaClO_2) acts as both a bleaching and delignification agent. Mild acids, such as acetic acid (CH_3COOH) may be used in intermediate steps with NaClO - like agents to adjust the pH or stabilise the bleaching reaction. It should be noted that NaClO and H_2O_2 have strong oxidising properties that can potentially damage the wood fibers. However, NaClO is a salt that needs to be acidified with an acid (e.g., CH_3COOH) to degrade lignin. NaClO -based treatments showed good potential in TW fabrication at longer treatment times^[49] and the majority of reported studies use NaOH and NaClO as a delignification reagent, followed by additional bleaching steps. Additional whitening of the wood after delignification is mostly necessary alkaline delignification (NaOH) and additional bleaching is done with oxidative agents to decolourise chromophores. NaClO_2 -based treatments do not require additional treatment, as the ClO_2^- - ions act as a bleaching reagent.

After delignification and bleaching the lignin content of wood is typically decreased to less than 3% and the wood appears white. Failure to completely turn the wood white results in a translucent TW material, with high light scattering and absorption^[64].

The degree of delignification depends on the wood species and type of lignin and the effectiveness of the chemical treatment. As mentioned above, the lignin of hardwoods consists mainly of syringal and guaiacyl units, while softwoods consist mainly of guaiacyl units. In all delignification methods, lignin is selectively removed without affecting the cellulose and hemicellulose

components. However, longer exposure times may compromise the structural integrity of the cell structure, as prolonged submersion in an alkaline or acidic solutions can lead to the partial degradation of holocellulose, resulting in mass and strength loss, reduced thickness and collapse of the cell wall structure. In the TW production, however, the aim is to preserve the wood structure while removing majority of the lignin content as possible. Literature shows that softwoods typically require harsher treatment conditions than hardwoods due to their higher lignin content. Alkaline treatments can be used for both hard- and softwoods, while soda pulping is better suited for hardwoods.

If the lignin removal is not complete, the wood preserves its natural colour and the ring structure remains clearly visible in both hard- and softwoods. Mi, et al. [27] and Anish, et al. [104] noted that latewood rings remained prominent in pine wood after alkaline treatment, indicating the need for extended exposure times, which could in turn diminish the structural integrity of the cell walls. Ibañez, et al. [41] reported that *Eucalyptus bosistoana* did not achieve complete whiteness after 6 h of delignification with 2% and 3.5% NaClO₂. Consequently, light rays are absorbed by the intact chromophores in darker regions, thus leading to uneven light scattering and transmittance through the wood structure.

It should be noted that not all of the reported articles aim to whiten the wood. Some studies intend to retain and preserve the natural colour and texture of the wood without removing too much of the chromophoric substances and lignin [83]. In those scenarios, bleaching agents are excluded from the fabrication procedure and/or performed at shorter exposure times.

Generally, the delignification rate increases with higher temperature and longer reaction times. However, the acid concentration tends to have an optimal range below or above which the efficiency will be reduced [133]. In contrast, alkaline and oxidative-based solutions require higher concentrations for more effective lignin removal. The optimal temperature ranges for alkaline and oxidative-based delignification are 60–150°C and 120–210°C for acidic delignification [20,40]. The temperature range for each treatment type depends on the end application of the TW and can reach temperatures > 150°C [40,119,164]. For TW fabrication lower temperatures are desirable since structural integrity of the wood should be maintained as well as possible. The most common temperature ranges for TW treatment are below 100°C [39].

The removal of lignin can also lead to the degradation of hemicellulose, which will weaken the cell wall structure. In severe cases the cells separate at the middle lamellae, or honeycombing occurs in the wood structure [64,165]. Some hardwoods, such as *Eucalyptus*, appear to be more vulnerable to fiber separation at prolonged exposure time and high temperatures. Barbosa, et al. [102] reported that by treating *E. grandis* with NaOH and Na₂S for longer than 1 h at 90°C resulted in fiber separation of the wood cell walls at a wood thickness of 0.6 mm. This occurs because at temperatures exceeding 70°C, lignin degradation i.e., structural changes of the constituent, becomes more prominent [166]. In contrast, Ibañez, et al. [41] investigated *E. bosistoana* and reported no damage to the cell structure in eucalyptus. These findings imply that fiber separation is determined by the intensity of the delignification process and the anatomical wood characteristics. Wu, et al. [83] observed honeycombing after delignification in Himalayan Birch, Chinese Fir, Basswood, Pine, Oguman and Black Walnut.

Another physical property that can influence the degree of delignification and the performance of TW is the extractive content. In hardwoods many of the extractives are found in the heartwood region, while in softwoods, the dark latewood rings have a higher extractive content than earlywood rings. This leads to a variation in density along the vertical and horizontal axis of the tree and affects the degree of bleaching after chemical treatment [83].

More environmentally friendly delignification methods use steaming with NaClO₂ or H₂O₂ with or without acetic acid to turn the wood white [42]. In these treatments, the wood is placed above the solution and steamed. NaOH delignification may be performed prior to steaming with peroxide [87]. Li, et al. [42] showed that steaming the wood with 30% H₂O₂ resulted in less fiber separation compared to steaming with NaClO₂ and that the combination of H₂O₂ with acetic acid shortened treatment times.

The different delignification treatments investigated in literature are listed in Tables 3. Initially sulfite and sulfate delignification processes were employed, which were later largely replaced by sodium chlorite treatments. The large variation in the temperature and exposure time ranges compiled in Table 2 may be due to various factors considered across the different studies. Therefore, these ranges do not necessarily represent the success of obtaining a white wood template but depends on

the end user's expectations. To avoid confusion, "same" indicates that the primary delignification agent was used as both delignification and bleaching agent.

Table 3
Summary of delignification treatments for hard- and softwood species

	Wood species	Primary delignification	Additional Bleaching	Temperature range (°C)	Exposure time (h)	Ref.
Hardwoods	Basswood	NaClO + acetic acid	Same	RT	2–72	[129]
	Balsa	C ₂ H ₄ O ₃ [*]	None	80	3–12	[82]
	Balsa, Basswood, Eucalyptus, Ash, Birch, Poplar, Beech, Maple, Rubberwood,	NaClO ₂ + acetic acid	Same H ₂ O ₂	RT, 70–95	6–24	[41,49,64,84,94,95,105,129]
	Basswood, balsa	NaOH	H ₂ O ₂	Steaming, 100	4–24	[42]
	Eucalyptus	NaOH + Na ₂ S	H ₂ O ₂	90	0.25–2	[102]
	Basswood, beech, poplar	NaOH + Na ₂ SO ₃	H ₂ O ₂	boiling	2–60	[5,29,37,43]
	Birch, Basswood, Oguman, Black Walnut	Ethanol	None	NR	NR	[83]
	Basswood	H ₂ O ₂ + acetic acid	Same	Steaming	2–12	[42]
	Basswood	H ₂ O ₂	Same	Steaming	4–20	[42]
	Rubberwood, Ailanthus	NaOH + EDTA [*]	MgSO ₄ [*] + H ₂ O ₂	70	3–4	[104]
	Poplar	NaOH + Na ₂ EDTA	MgSO ₄ + H ₂ O ₂	70	Until white	[96]
	Alder, Balsa, Beech, Birch	PAA	Same	80	Until white	[81]
	Balsa, Birch, Ash, Basswood, Poplar	NaOH + MgSO ₄ + DTPA + H ₂ O ₂	Same	70	2–4	[64]
	Aspen	H ₂ O ₂ + C ₆ H ₉ N ₃ O ₉ [*] + NaOH + distilled water	Same	60	12	[107]
	Melia, Poplar, Oak	NaOH + EDTA + MgSO ₄	H ₂ O ₂	70	3	[99]
	Rosewood	H ₂ O ₂	Same	60 (Microwave)	3–9	[167]
	Paulownia, Balsa	KOH	NaClO ₂ + glacial acetic acid	75 & 90	16	[34,108]
Softwoods	Pine	NaClO	Same	boiling	3–5	[92]
	Doughlas Fir, Pine	NaClO ₂ + acetic acid/ glacial acid	H ₂ O ₂	70–90, Boiling	2–18	[27,41,64,84,111]

Pine	NaOH + MgSO ₄ + DTPA + H ₂ O ₂	Same	70	8	[64]
Pine	H ₂ O ₂	Same	Steaming	8	[42]
Pine	Ethanol	None	Room temperature	NR	[83]
Pine	NaOH + Na ₂ SO ₃	H ₂ O ₂	Boiling	14	[110]
Chinese Fir,	Ethanol	None	RT	NR	[83]
Spruce	H ₂ O ₂ + acetic acid	Same	Steaming, 40–80	0.5–12	[112,113]
Spruce	NaOH + glacial acetic acid	None	80, RT	6	[113]
Spruce, Larch	H ₂ O ₂ + C ₆ H ₉ N ₃ O ₉ + NaOH + distilled water	Same	60	12	[107]

A comparison of the reported treatments suggests that softwoods require longer exposure times at similar treatment conditions, probably due to their higher lignin content^[42,64,84]. Consequently, at extended exposure times softwoods can lose structural integrity faster than hardwoods, due to fiber separation, resulting in larger weight loss compared to hardwood. Li, et al.^[64] reported that ash wood and pine became weaker after prolonged delignification and could not maintain their shape during mechanical testing, unlike balsa and birch. This is due to the gradual removal of lignin from the middle lamella which weakened intercellular bonds. Unfortunately, direct comparison between hardwood and softwood under identical treatment conditions are scarce in literature.

Generally, the treatment time can be linked to the extractive content and wood with a lower extractive content requires shorter treatment times. In addition, the delignification rate seems to be more severe in the first hour^[90] and slows down with increasing exposure time. For example, basswood boiled for 12 h and bleached until it became white lost approximately 25% more lignin in the first hour and a significance change in colour^[92].

With respect to the orientation of wood, radially cut wood was found to delignify faster than longitudinally cut wood^[37,91] and it was observed that treatment times for thin soft- and hardwoods (< 2 mm) were approximately the same^[42,99] independent of the treatment type. For example, both balsa and birch wood treated with NaOH + MgSO₄ + DTPA + H₂O₂ required 2 h of exposure to obtain similar performance outcomes. This may be explained by the fact that both species have a comparable extractive content of approximately 2.5%^[121]. In contrast, Maple with a higher extractive content of around 4.3%, required treatment times greater than 2 h with a similar treatment type^[73,106].

Wood density was identified to be an important parameter to influence the delignification efficiency and treatment conditions. Wood with a lower wood density seems to require shorter treatment times for similar wood types, regardless of the treatment used^[41,64,102]. However, data found in literature is scarce and density is not consistently reported in literature, which limits direct comparison between wood species and the delignification procedures. Balsa takes up to 5 h to turn white, whereas birch can take up to 12 h when using NaClO_x - like treatments. Some hardwoods with lower density can have shorter treatment times than softwoods with a higher density. For example, 5 mm thick pine required a treatment time of 8 h to obtain the same delignification as 5 mm thick Basswood, which only required 4 h^[42]. Even at 10 mm thickness, basswood only required a treatment time of 5 h, which is significantly lower than the 8 h required for 5 mm thick pine.

The treatment time seems to have a greater influence on the delignification efficiency for hardwoods than softwoods^[84], although some studies, such as Ibañez, et al.^[41] claim that wood density has no effect on processing parameters. Wood density

appears to govern the choice of bleaching treatments. Lower density wood species respond well to milder systems like NaOH/Na₂S followed by H₂O₂, while higher density wood species are more difficult to treat, even with stronger agents like NaClO₂.

Both soft- and hardwoods are treated in similar temperature ranges independent of the treatment type. However, temperature seems to affect the delignification efficiency more in hardwoods than softwoods. According to Wu, et al. [84], increasing the temperature (particularly above 70°C) increases the percentage of lignin removal and the effect was more noticeable in birch than in pine, with residual lignin contents of 8–12% and 15–20%, respectively. Other studies report that oak and beech undergo substantial delignification to about 2–3% at temperatures close to 175°C, whereas a softwoods like Spruce require temperatures exceeding 200°C to achieve comparable lignin removal. These results suggest that hardwoods respond more to increased temperature during delignification treatment than softwoods, resulting in more efficient lignin removal.

With respect to bleaching, peroxide-steaming seems to be more effective than submerging the wood into a bleaching solution, which suggests that direct contact between the wood and the solution should be avoided (Table 2). This can be done by bleaching with H₂O₂ and / or acetic acid after NaOH treatment, which seems to be more efficient on hardwoods than softwoods. For example, basswood with a thickness of 5 mm required 4 h to turn completely white, whereas pine wood of a similar thickness required 8 h of bleaching. This can be explained by the lower wood density of Basswood and the different cell structure of hardwoods, which contain large vessel elements^[42,113].

Bleaching by submersion in a liquid is typically performed in a temperature range of 40–80°C, while bleaching with NaClO/NaClO₂ and/ or H₂O₂ can also occur at room temperature for extended time. In most TW delignification regimes delignification is carried out prior to bleaching, because bleaching at earlier stages can lead to fiber separation and compromise the structural integrity of the wood template. Softwoods are less prone to fiber separation during bleaching, because of their lower density and lignin-rich middle lamella, although performing delignification before bleaching is still recommended for optimal optical performance and structural integrity.

Treatment effectiveness and performance

As described previously, several treatment methods have been developed to fabricate TW, yet it is difficult to decide, which delignification treatment is the most effective for a certain wood species and more importantly, how the treatment success can be quantified. Generally, the effectiveness of treatment methods is assessed by the lignin removal, transmittance, haze and the whiteness of the wood template post treatment. However, not all studies quantify the same properties for the different wood species, which makes it very difficult to compare the success of different treatments for each of those wood species.

The effectiveness of chemical treatment and the delignification rate depend on the wood species and its dimensions, as describes in Table 5. Wood with a high extractive content generally tend to treat more difficult. Also, with increasing wood thickness the rate of delignification decreases, due to longer diffusion pathways and limited penetration of the chemicals^[42,87]. Variations in lignin removal between samples with comparable dimensions can be attributed to the location and distribution of lignin in the cell walls, the composition of the lignin structure, the wood density and anatomical structure.

Optical properties, such as transmittance and haze describe the amount of transmitted and scattered light through the wood and are determined by the void percentage of the wood structure, wood thickness and fiber alignment. They are typically determined with a photo spectrometer in a wavelength range of 400–800 nm with different sensor placements. The transmittance measures the light that passes directly through the sample, while haze determines the scattered light intensity.

Colour can be measured with a CIE colour meter, which determines a colour value in a 3D space along the L (black/white), a (red/green) and b (blue/yellow) axes. Delignification typically results in an increase in L as the wood turns white^[64].

An attempt to compare the effectiveness regarding colour, light optics and lignin removal of different chemical TW treatments for different wood species is shown in Table 4. A direct comparison is very difficult as the experimental values between the reviewed publications and their respective wood species differ greatly with regards to sample dimensions, sample orientation (|| and ⊥ grain) and treatment parameters. Treatment time is typically dependent on wood thickness, with thicker wood samples

requiring longer treatment times. Light transmittance is indirectly proportional to the residual lignin content, and the sample thickness and haze will increase with sample thickness. The cutting direction also plays a major role in the optical performance, as displayed in Fig. 1. Light rays can pass the wood structure more easily parallel to the grain than perpendicular, where the light must pass through multiple cell wall layers, resulting in a reduction in light transmittance.

The values in Table 4 display the ranges of results reported across literature.

Table 4

Resulting TW properties depending on wood species, thickness, exposure time and orientation (||: parallel to the grain and ⊥: perpendicular to the grain) investigated in TW literature.

Wood type	Wood species	Thickness and grain direction (mm)	Exposure time (h)	Residual Lignin (%)	Transmittance (%)	Haze (%)	Lightness (%)	Ref.
Hardwoods	Balsa	1–5 ()	8–12	5.5–19.9	~ 90	80	white	[33,34,66,82]
		0.7–10 (⊥)	6–12	2–2.5	40–92	30–83	white / 80	[32,34,36,64,69,81]
	Birch	0.7–10 (⊥)	12	1.2–3.3	90–94	31–63	white / 80	[64,69,81]
	Ash	1.5 (⊥)	4 & 18	5.3 & 22.3	~ 60	~ 83	white / 80	[64]
	Basswood	0.05–40 ()	4–20	0.84–3	61–90	80–95	white	[5,29,37,42]
		0.42–3 (⊥)	4–72	1.1–2	61–91	10–90	white	[37,42,88,90,129]
	Poplar	0.1–5 (⊥)	2–8	0.06–8.3	40–95	61–94	white / 89	[43,49,95,96]
	Beechwood	0.3–5 ()	12	NA	15–86	15–65	white	[3,101]
		0.7 (⊥)	NR	0.9	89	63	white	[81]
	Eucalyptus	0.6–3.5 (⊥)	0.25–5	15–24	65–75	NR	50–75	[41,102]
	Alder	0.7	NR	1.2	89	50	white	[81]
	Rubberwood	2 (⊥)	4	12	59	94	not completely white*	[104]
	Ailanthus	2 (⊥)	3	20	55	89	white	[104]
	Oak	2 (⊥)	3	NR	~ 72	NR	white	[99]
	Maple	0.5 (⊥)	2	8.4	~ 90	~ 70	yellow	[106]
	Melia	2 (⊥)	3	NR	~ 77	NR	white	[99]
	Walnut	0.44 (⊥)	NR	NR	< 2.5%	NR	natural colour* ~35	[83]
	Aspen	2.5 ()	12	NR	~ 90	NR	not completely white*	[107]
	Paulownia	20 ()	16	6	89	95.4	white	[108]
	Okoumé	0.15 (⊥)	NR	NR	< 20%	NR	natural colour* ~60	[83]

Wood type	Wood species	Thickness and grain direction (mm)	Exposure time (h)	Residual Lignin (%)	Transmittance (%)	Haze (%)	Lightness (%)	Ref.
Softwoods	Pine	5 ()	8	0.8	~ 87	~ 90	white	[42]
		1.5 (⊥)	18	5.2*	~ 70	~ 77	white / 80	[64]
	Douglas Fir	2 ()	0.5–9	NR	~ 80	~ 93	not completely white*	[27]
		0.6 (⊥)	1–9	3	~ 87	~ 65	white	[27]
	Chinese fir	0.4 (⊥)	NR	NR	< 7%	NR	natural colour* ~30	[83]
	Spruce	2.5 ()	12	NR	~ 71	NR	not completely white*	[107]
	Larch	2.5 ()	12	NR	~ 80	NR	not completely white*	[107]

* For aesthetic purpose, to maintain wood character, or retain lignin.

The reported values of residual lignin content vary among species between < 1% to about 24%. As discussed previously, softwoods tend to require longer treatment times to reach the same degree of delignification as hardwoods. Of the hardwoods balsa, basswood, poplar and beech reached the lowest residual lignin contents after treatment of around 1%, which can be directly linked to the wood density, as the lighter wood structure with a larger void volume (lumen size) makes it easier for chemicals to penetrate into the wood. The residual lignin content in softwoods was generally somewhat higher, around 12–18%, although complete lignin removal was achieved in pine and basswood.

As observed in Table 5, vast differences exist in balsa and basswood also yield the best optical properties, with the highest transmittance and haze values of around 90%. This can be linked to the lower lignin, extractive content and high porosity of these species compared to others. Basswood tends to scatter the light more than balsa and has a higher haze and lower transmittance due to its heterogeneous grain structure and higher void volume, which in hardwoods is directly linked to the size and number of vessels [5,37,73,90]. The transmittance in softwoods, was generally lower than in hardwoods, with around 70–85%. This can be explained by the cellular structure of softwoods, which contain uniformly sized, narrow tracheids and no large vessel elements.

Wood species with a high initial lignin content, such as rubberwood, ailanthus or most softwoods (Table 1) also tend to have higher residual lignin contents of > 20%. *Eucalyptus* has a relatively low lignin and extractive content and a smooth grain structure, which makes it a suitable candidate for TW, however, due to the higher wood density, the residual lignin content is significantly higher than that of Balsa and Basswood and the transmittance is with 60–75% significantly lower.

The wood type, i.e., hard- or softwood, as well as the wood density affect the optical properties of TW significantly. Generally, hardwoods show a better transmittance than softwoods and low-density wood species tend to exhibit better optical performance. The anatomical structure, such as the size and number of vessels determines if light is directly transmitted or scattered and if transmittance or haze dominates. The void volume correlates positively with an increase in haze. Therefore, to obtain a high degree of light transmittance, wood with a higher void volume is desirable. Diffuse porous hardwood has a higher transmittance than ring porous hardwood, as the early- and latewood rings have distinctly different densities and delignification degrees.

Most studies do not report values for the lightness (whiteness) of the samples but only that the samples were treated until white. The few that report values support that wood density and initial lignin content affect the whiteness of the treated sample

with lower density poplar reaching an L value of 89 and *Eucalyptus* only 50–75. Most species reached L values of around 80% when they were reported to be white.

Although the degree of delignification and the treatment times vary between hard- and softwoods, softwoods tend to reach comparable optical properties with a high transmittance of > 80% for pine and Douglas Fir and high haze values. These values are comparable to the transmittance values obtained in Balsa and Basswood, despite the larger wood density, lignin and extractive content. This can be explained by the more uniform cell structure in softwoods, which supports direct light transmittance.

Table 5 attempts at summarising and compare the effect of different treatment protocols on the optical properties of TW. This table provides a broad overview of the reported optical performance of different treatment methods used for TW fabrication.

Table 5
Effectiveness of TW treatment with regards to optical properties

Treatment methods	Wood species	Transmittance (%)	Haze (%)	Ref.
NaClO/ NaClO ₂ and/ or acetic acid, and/ or glacial acid, and/ or H ₂ O ₂	balsa, basswood, birch, poplar, fir, pine, ash, maple, beech	15–95	18–95	[41,49,64,67,84,92,94,95,101,105,106,129]
NaOH + Na ₂ SO ₃	basswood, poplar, pine, beech, balsa	40–90	61–98	[3,5,29,37,43]
NaOH + MgSO ₄ + EDTA/ DTPA + H ₂ O ₂	balsa, birch, ash, basswood, poplar, spruce, larch, rubberwood, ailanthus	55–80	80–95	[64,96,99,104,113]
H ₂ O ₂ and/ or steam, and/ or acetic acid, and/or NaOH	basswood, pine, rosewood	40–90	80–97	[42,167]
Organosolv	birch, basswood, pine, fir, walnut	2.5–20	NR	[83]

Although alkaline suflite and kraft-type delignification treatments are the most established protocols in industry, a comparison of published literature suggests that chlorite-type treatments results in the highest transmittance, while the alkaline treatments result in a high haze (Table 5). Solvent-type treatments are the most promising with regards to environmental impact and yield promising optical properties.

Conclusions

This scoping review highlights the wood species most used to produce TW, which are not necessarily commercially used species. Given the increasing attention the topic of TW is currently attracting, more emphasis should be placed on existing resources and the optimisation of treatment methods to allow upscaling and industrial applications.

This article also highlights the importance of considering the wood type and species and select the correct treatment method when producing TW to optimise the optical properties. The wood species and treatment protocols from the currently available literature were compiled and compared. The main findings suggest that a higher light transmittance can be achieved

- parallel to the wood grain, which allows light rays to travel through the cell lumina. In contrast, a higher haze is achieved perpendicular to the fiber direction. However, a high haze can also be achieved by using more porous wood species with a high void content.
- for low density wood species, as the density is typically correlated with a higher lignin content and a denser cell structure, which makes it difficult for chemicals to penetrate the wood.

- for wood species with a low initial lignin and extractive content, as these are the chemical components that impart colour to the wood.

- for hardwoods rather than softwoods, as they tend to have a lower lignin content and vessels to support light transmittance.

Alkaline treatments administered as steam treatment were found to be the most effective with regards to optical properties, even in thicker wood samples. The treatment time is highly dependent on the wood thickness, and the initial lignin content of the wood species and hardwoods were found to require less treatment time than softwoods, due to their lower lignin content.

The review indicates that globally dominant wood species like *Pinus* and *Eucalyptus* are rarely used for TW production and only two articles were dedicated to investigating the performance of *Eucalyptus* as a delignified wood scaffold for TW, while nine articles reported on the use of *Pinus*. However, if TW is to be produced on an industrial scale, it is important to study the best processing methods for relevant species.

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Author Contribution

K Nefdt: Literature search and compilation of review article
M Meincken: writing and editing

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Figures

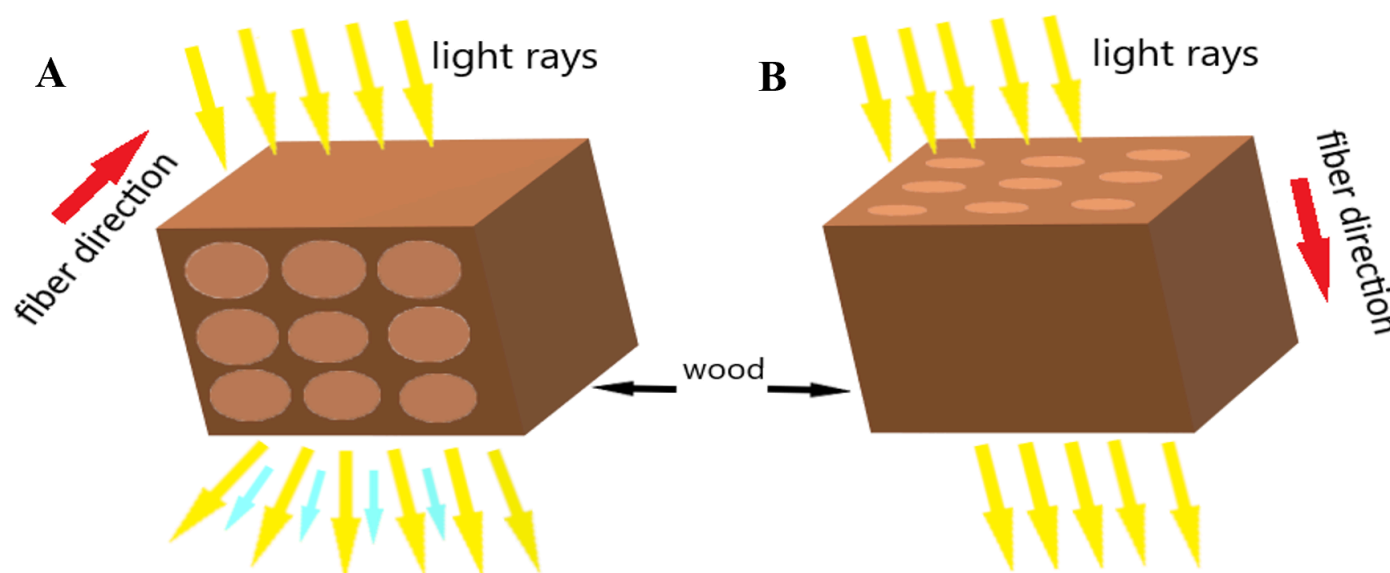


Figure 1

Light transmission and scattering in wood a) perpendicular to the fiber direction and b) parallel to the fiber direction^[36].

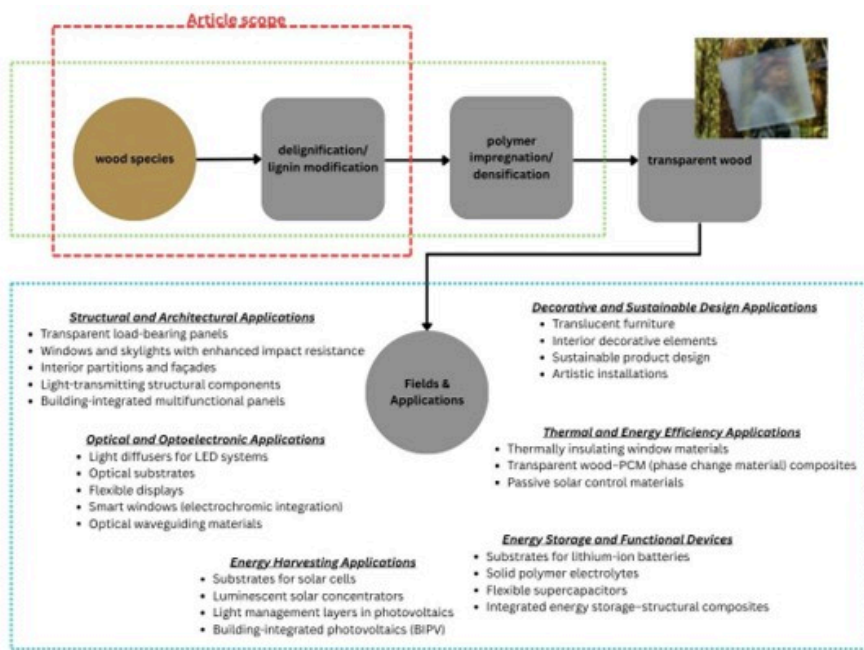


Figure 2

A schematic diagram of the TW fabrication process. The steps highlighted in red represent the primary focus of this review.

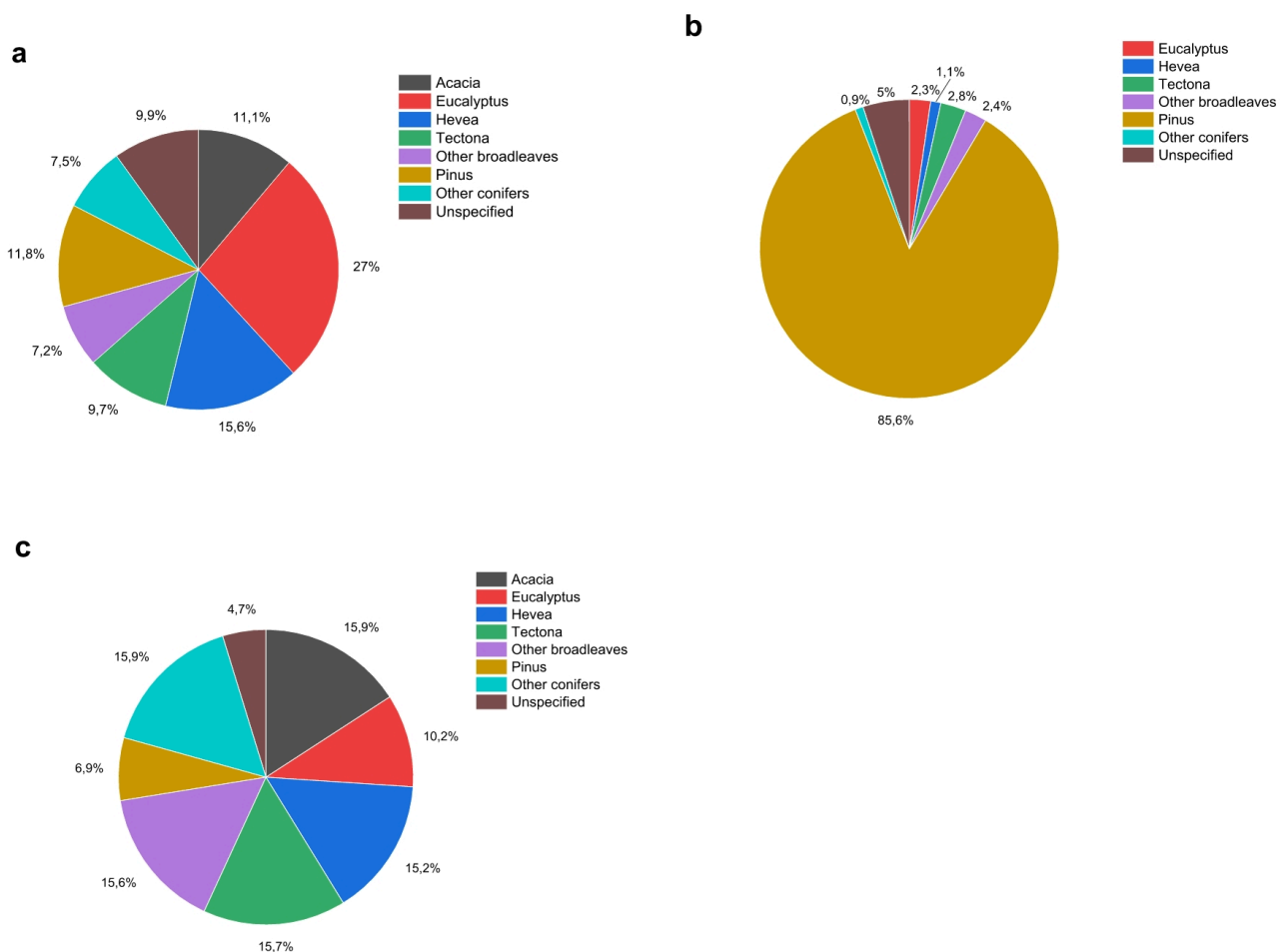


Figure 3

Contribution of major genera planted in (a) Africa, (b) North-Central America and (c) Asia. Data are derived from the FAO *Global Forest Resources Assessment 2000* [46].

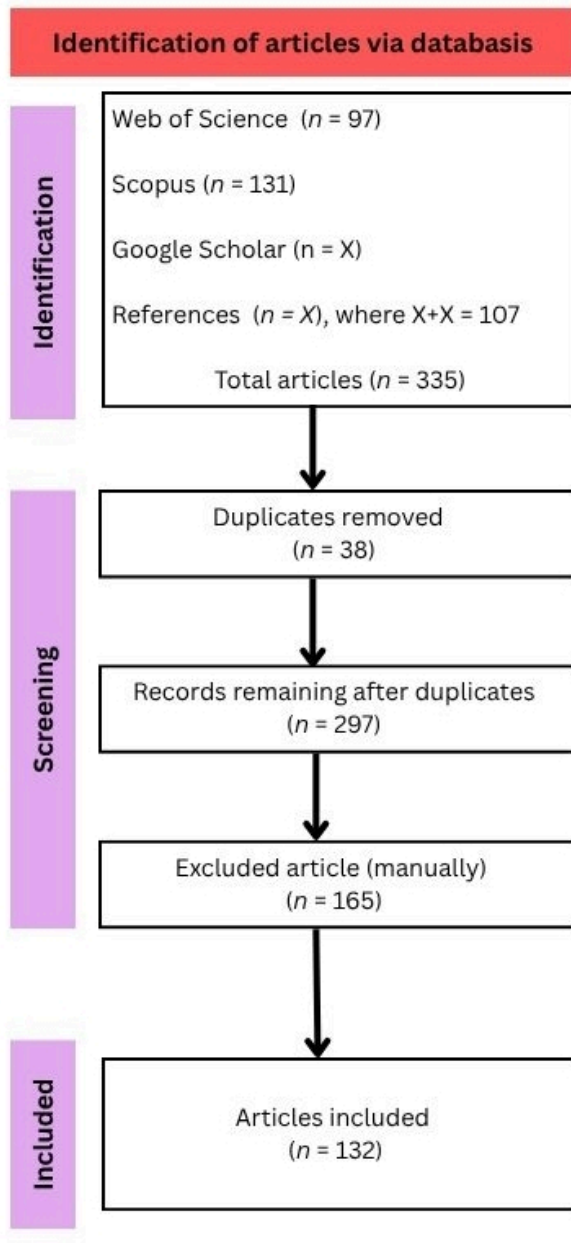


Figure 4

PRISMA-ScR flow diagram of the literature search and study selection process conducted.

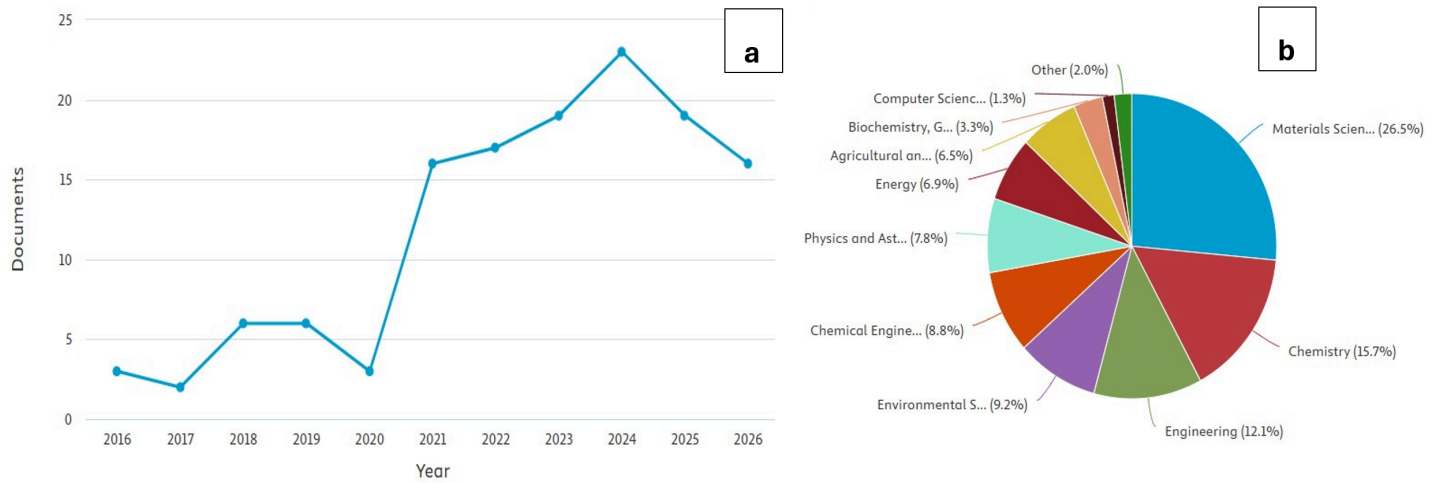


Figure 5

An example of the distributed publications dealing with TW based on year of publications (a) and subject area according to Scopus (b).



Figure 6

Photos of a) a high degree of delignification and b) a low degree of delignification in *Pinus patula* veneer strips of 0.5 mm thickness.



Figure 7

Eucalyptus cladocalyx logs showing pronounced sap- and heartwood sections

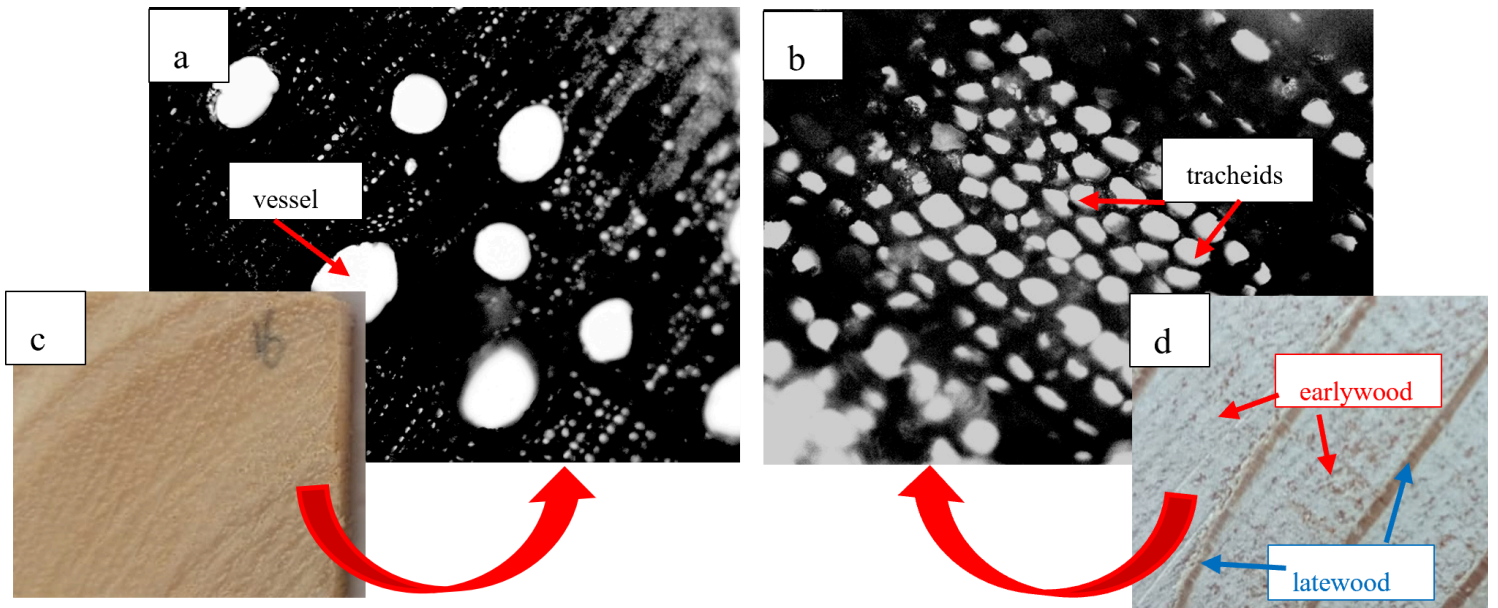


Figure 8

Microscope images of a) diffuse porous vessels of *Eucalyptus grandis* and b) earlywood and latewood tracheids of *Pinus patula*. Wood surface of c) *Eucalyptus grandis* and d) *Pinus patula*.