# Chemical Reagent for Detecting Tension Wood in Selected Tree Species

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Reaction wood is a wood defect arising during the growth of the tree in the part of the trunk that is under tension (hardwood tree species) or compression (coniferous tree species). Beech (*Fagus sylvatica* L.) tension wood has different anatomical and chemical characteristics than normal (opposite) wood. The difference in density is conditioned by the percentage of the gelatinous layer (G-layer). Fibre cells in reaction beech wood have a different cell wall structure and a different chemical composition. Tension wood cannot be detected by the naked eye. It is only possible to assume its occurrence based on the macroscopic characteristics of the logs, such as a woolly surface, taper or eccentric pith, and so forth. However, these are imprecise and unreliable methods that have minimal effectiveness, especially when shortening the length of the log for cut-outs. This study aimed to create a unique chemical reagent for the detection of tension wood in logs and timber and wood products immediately. The present research can contribute to the mitigation of flaws resulting from the reaction of wood in timber production while addressing noticeable constraints in manufacturing, such as energy resources and the availability of wood raw materials. This can be achieved through the efficient identification of reaction wood in materials. The colour change is only temporary and will fade over time. After the chemical reagent has dried on the surface, the surface can be milled. The colour change extends to a depth of approx. of 3 to 5 mm.

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## INTRODUCTION

Reaction wood can be regarded as a wood defect that arises during the growth of the tree in the part of the trunk that is under tension (for hardwood species) or for compression (in coniferous tree species). This stress is caused by various external factors: One-sided stress on the tree by wind and snow, frost, asymmetric tree crown, tree growth in extreme conditions (steep slopes), *etc*. The formation of reaction wood is also conditioned by the age of the tree, such that the occurrence of reaction wood is more pronounced in young trees (Siau 1984; Vilkovský *et al.* 2023). In the current era of wood technology advancements, it is crucial to take into consideration key constraints in manufacturing, including energy sources and the availability of wood raw materials (Majka

and Sydor 2023). With the noticeable presence of beech wood, its utilization has become a topic of great importance in terms of quality based on the works of Geffertová *et al.* (2019) and Gardiner *et al.* (2014). The quality assessment of beech wood involves evaluating its structure, properties, and the occurrence of defects within the material (Vidholdová and Slabejová 2022). Tension wood is recognized as a significant defect, as it negatively affects the overall quality of solid wood and imposes limitations on its industrial and construction applications. As also shown by Vilkovská *et al.* (2018), the properties of chemical reagents are also of relevance in construction, as tension wood exhibits greater deformation compared to normal wood. Timely identification of tension wood can facilitate the selection of more stable wood for construction purposes. Research findings have confirmed a tension wood ratio ranging from 14% to 21% in beech logs (*Fagus sylvatica* L.) (Vilkovská *et al.* 2018).

Tension wood in hardwood species is very difficult to detect visually. The difference between reaction wood and normal wood in a transverse fresh cut is not distinct. In the case of beech, tension wood can be observed exceptionally when it is strongly developed, as a lighter surface on the transverse sections and as white glossy bands on the longitudinal sections. Beech reaction wood in the longitudinal direction is manifested in the course of sawing as a pronounced woolly sawn surface, which is associated with fiber pluck from the wood surface. This characteristic only appears when sawing fresh beech wood, resulting in poorer cutting quality and potential difficulties during processing. Reaction wood remarkably increases the heterogeneity of the wood (Vilkovská *et al.* 2018; Geffertová *et al.* 2019).

From the point of view of the cell wall composition between reaction and normal wood, the difference is more pronounced. Figure 1 shows the different secondary cell wall compositions between the reaction and normal wood. In normal wood, the secondary cell wall is composed of layers S1, S2, and S3, while in reaction wood, the S3 layer is replaced by a gelatinous layer or G-layer. In some cases, it is thicker than the S2 layer (Kúdela and Čunderlík 2012).
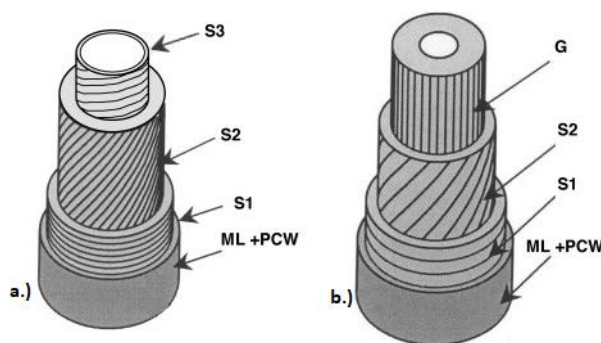


**Fig. 1.** Microscopic structure of the cell wall in a.) normal wood and reaction wood b.) (Déjardin *et al.* 2010, Reused under Creative Commons CC BY 4.0)

The G-layer has been the focus of a lot of research, including the studies of Clair *et al.* (2010, 2003) and Meloche *et al.* (2006), which dealt with the chemical composition of the G-layer. According to the authors, the G – layer is composed exclusively of a high proportion of crystalline cellulose and is non-lignified.

Through chemical analyses, it has been observed that tension wood exhibits an increased cellulose content, ranging from 8% to 33%, while having a lower proportion of lignin (19% to 26%) and pentosans (16% to 22%). Furthermore, tension wood displays a higher degree of cellulose crystallization, as shown by Kačíková (2001). In reaction wood with a well-developed G-layer, the amount of pentosans is reduced, and there is a 10% higher glucose content compared to normal wood. The extent of lignification in the G-layer decreases as the reaction wood becomes more developed (Kúdela and Čunderlík 2012). The present observations are consisted with those of Chang *et al.* (2009), who describe the chemical composition of reaction wood, claiming that tension wood mainly comprises a high proportion of crystalline cellulose. According to the work of Hon and Shiraishi (2000), the composition of the cell wall of tension wood and its micro and sub-microscopic structure is characterized as a reinforced matrix, composed mainly of cellulose, where the inclination of the microfibrils gives the necessary rigidity to and the increased content of crystalline cellulose. Is also shown by research Kačíková (2001) concerned with estimating the cellulose crystallinity between tension wood and opposite wood, which reports an increased proportion of crystalline cellulose.

Variations in the intensity and shape of absorbance bands were discovered when comparing the measured FTIR spectra of tension and normal wood, indicating differences in chemical compounds as well as their structures (Table 1). A characteristic absorbance band of hemicelluloses is located at a wavenumber of 1734 cm$^{-1}$, corresponding to vibrations of carboxyl groups in xylan, while another band at 1236 cm$^{-1}$ is assigned to CO in xylan. In samples with a content of tension wood, the intensity of these absorbance bands is lower, suggesting a reduced content of xylan-type hemicelluloses (Vilkovská *et al.* 2018).

The ratio of lignin to polysaccharides content in wood was evaluated using the absorbance ratio $A_{1504}/A_{1369}$ (Pandey and Pitman 2003). In both cases, was discovered this ratio is lower in tension wood samples.

**Table 1.** Comparison of the Chemical Composition between Tension Wood and Normal Wood Samples with the Use of Absorbance Values Measured at Specific Wavenumbers (Vilkovská *et al.* 2018).

| Sample | $A_{1734}$ | $A_{1236}$ | $A_{1504}/A_{1369}$ |
|---|---|---|---|
| Normal wood$_1$ (NW$_1$) | 0.311 | 0.330 | 1.19 |
| Tension wood$_1$ (TW$_1$) | 0.292 | 0.314 | 1.12 |
| Normal wood$_2$ (NW$_2$) | 0.293 | 0.326 | 1.17 |
| Tension wood$_2$ (TW$_2$) | 0.257 | 0.284 | 1.15 |

The results obtained from the FTIR analysis are consistent with the chemical analysis findings of tension and normal wood, as reported by Kačíková (2001). According to the author, tension wood exhibits a lower proportion of lignin and pentosanes, as well as a higher percentage of α-cellulose compared to normal wood. The FTIR spectral results can be correlated with the levels of amorphous and crystallized I cellulose. A lower absorbance ratio of $A_{1335}/A_{1315}$ indicates a higher degree of crystallinity (Colom *et al.* 2003). Additionally, two other parameters, TCI and LOI, are calculated to estimate the crystallinity of tension and normal wood. TCI represents the overall degree of order in

cellulose, while LOI represents the ordered regions of cellulose perpendicular to the chain direction (Široký *et al.* 2010).

**Table 2.** Comparison of Absorbance Ratios Revealing Cellulose Crystallinity in Tension (TW) and Normal Wood Samples (NW) (Vilkovská *et al.* 2018)

| Absorbance Ratio | NW$_1$ | TW$_1$ | NW$_2$ | TW$_2$ |
|---|---|---|---|---|
| TCI (A$_{1370}$/A$_{2900}$) | 0.726 | 0.765 | 0.772 | 0.777 |
| LOI (A$_{1424}$/A$_{898}$) | 1.417 | 1.816 | 1.655 | 1.698 |
| A$_{1335}$/A$_{1315}$ | 0.985 | 0.614 | 0.492 | 0.388 |

Based on the values obtained for all three parameters (Table 2), it can be concluded that tension wood (TW) exhibits a greater proportion of crystalline cellulose than normal wood (NW) (Vilkovská *et al.* 2018). These findings are consistent with the research presented by Kačíková (2001). The presence of tension wood at the microscopic level can be determined using various methods under laboratory conditions (Hon and Shiraishi 2000). By applying chemical reagents such as safranin and light green, normal wood can be distinguished from reaction wood (Fig. 2). Due to the higher cellulose content, tension wood exhibits a light green colouration. Microscopic analysis of stained sections allows for the determination of the proportion and intensity of tension wood in the samples (Kúdela, Čunderlík 2012; Bozkurt and Erdin 2000).



**Fig. 2.** Colour differentiation of the presence of normal wood red color and reaction wood green color based on the use of safranin and light green Kúdela and Čunderlík 2012).

A second possibility for microscopic detection involves the use of chloride-zinc-iodine solution. Based on the different chemical compositions of normal and reaction wood, iodine binds differently to the individual layers of the cell wall, causing a change in the colour of the tension wood. The detection of reaction wood by this method is rapid but temporary, as iodine sublimes rapidly in the air. Observations of many authors have tried using this method, and the results have been unstable, with in some cases faint to invisible staining or dark colour. Another method is the detection of tension wood at the sub-microscopic level, where it is possible to observe the typical gelatine G-layer, following Clair *et al.* (2011).

Other methods of macroscopic detection include the visual identification of the shiny appearance of tension wood. This is based on research by Onaka (1949) and Badia *et al.* (2005). Observation is made on a cross-section after the surface of the prepared disk has been dried. A visible shiny appearance more accurately detects the presence of tension wood in the log (Fig. 3). The disadvantage of this method is that it is necessary to take a sample from the log, process its surface by milling, and then dry it in a laboratory kiln for 7 to 8 h. It is therefore a time-consuming method and additional equipment is required.
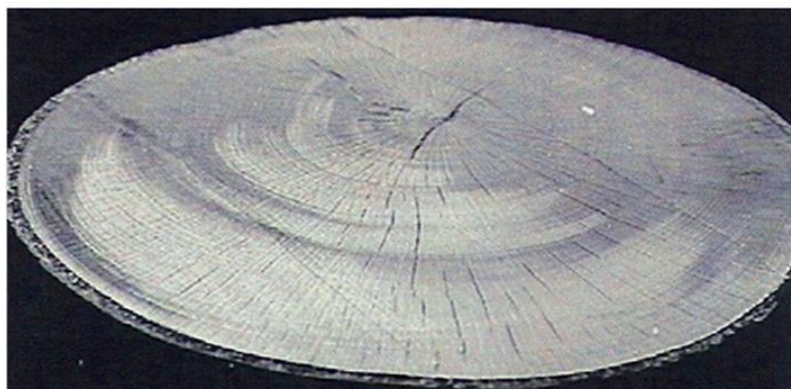


**Fig. 3.** Visibility of reaction (*Tension*) beech wood after drying cross section (Kúdela and Čunderlík 2012).

The main objective of this study was to develop a novel chemical reagent that enables immediate detection of tension wood in logs and timber and other wood products. Until now, there has been no known and yet desired reagent that can be easily used in industry conditions without laboratory equipment and that will provide clear and consistent visualization of reaction wood. The new reagent and its application method are intended to yield distinct and convincing results, enabling the detection of reaction wood to be transferred from the laboratory to processing operations, where it can assist in the processing and evaluation of logs. The present findings have the potential to mitigate defects arising from reaction wood and in wood processing or its application in construction. Furthermore, they address the significant constraints in manufacturing, such as energy sources and the availability of wood raw materials, by facilitating the rapid identification of reaction wood in materials.

## EXPERIMENTAL

Experimental measurements were conducted using beech wood (*Fagus sylvatica* L.) with varying timber dimensions, predominantly $50 \times 60$ mm, and $30 \times 100$ mm. There were approximately 500 pieces of timber. A further goal was to determine the effectiveness of the chemical reagent. This was done with over 100 pieces of logs with a diameter from 30 to 60 cm.

The selection of suitable samples for the verification of the chemical reagent consisted of several analyses and measurements on both the macroscopic and microscopic levels. The selection was targeted for a log with the greatest curvature and eccentric pith

as well (Fig. 4). Later in the laboratory conditions, disks were taken from the selected logs. All disks were dried in a laboratory kiln Memmert HCP 108 (103 °C approx. 48 h), which made the shiny appearance zone more visible, which confirms the presence of tension wood in selected samples. After these steps, a reagent for the detection of tension wood and verify the correctness of the chemical reagent. The analysis consisted of selected samples through FTIR analyses, which confirmed the presence of reaction wood (Vilkovská *et al.* 2018).



**Fig. 4.** Selections beech logs on yield a.) log with greatest curvature, b.) log with eccentric pith, c.) shiny appearance after dying in disks.

## The Chemical Reagent

The reagent was prepared from of two solutions (A and B), which were prepared separately. After the subsequent reaction, they were mixed to create a unique solution for the detection of reaction wood. It is convenient when the solution is mixed about an hour before application.

- **Solution A:** Mix zinc chloride *ZnCl₂* (5 to 20 g) with distilled water *H₂O* (10 mL). After dissolving, let the solution cool to room temperature.
- **Solution B:** Mix the required amount of crystalline potassium iodide of alkaline metal especially *KI* (2 to 6 g) with iodine *I₂* (0.02 to 0.5 g). Let both substances react with each other until the mixture turns a light brown-yellow colour. After the colour of the mentioned mixture, add the necessary amount of distilled water (10 mL). The solution is mixed until the iodine is completely dissolved. Mix solution A with solution B to form a dark brown solution. Such a solution is ready for immediate use, or it is stored in a dark, closed glass bottle away from sunlight.

*The chemistry that differentiates this work from the current state of the art*

If potassium iodide is mixed with elemental iodine in aqueous solution, it forms, like other iodides, the triiodide ion $I_3^-$:

$$KI\ (aq) + I_2\ (s) \rightarrow KI_3\ (aq) \tag{1}$$

It is proposed that the reason this system works is due to the greater solubility of $KI_3$ in comparison to $I_2$.

Based on the above-mentioned characteristics of KI (*Potassium iodide*) and elemental iodine, even when they are mixed in a dry state, the crystalline forms will influence each other, and the state of both substances will change. After the addition of water, this is manifested by the excellent solubility of iodine without the need for

subsequent filtration of the undissolved part, which improves and facilitates the applicability of the colouring reagent.

The present reagent works based on chemistry that influences the structure of the tension wood material. The reagent $ZnCl_2$ swells the macromolecules of cellulose and thus the hydrogen bonds between cellulose chains are destroyed, and the crystallinity of the cellulose is also reduced. Amorphous cellulose is formed, which promotes the accumulation of iodide bonds, which are also caused by the absence of lignin in the G-layer. As the G-layer becomes more developed, a change occurs, whereby the cellulose molecules change their arrangement and the microfibrillar space increases. Thus, there is better penetration of the reagent into the structure of the reaction wood and greater staining.

The wood zone in which the reaction wood is sought is also considered to be a very important aspect for detection. It is impossible to find the reaction wood by chemical reagent in the sapwood zone because of the large number of starchy substances, which immediately stain the wood black. This is also the case for the detection of starch in the wood itself when using chemicals, *I* (*iodine)* and *KI*. The mature wood zone of beech, with its different structural composition, is physiologically less active than the sapwood zone and the number of living cells gradually decreases from the sapwood to the mature wood zone and is replaced by fibrous cells which no longer contain starch substances.

## Terms, Procedures, and Applications

The requirements for the surface treatment of the wood (cross-section) are easily achievable even under operating conditions. The surface must be free of dirt such as sawdust, soil, dirt, and so forth. For accurate detection, the cross-section must be sawn with a sharp saw so that the wood fibres are not pulled out, the individual layers of the surface of the cell walls of the wood fibres are broken, and the surface is not burned. Torn fibers can cause distortion of the results. For this purpose, it is better to use a band saw or chainsaw, circular saw, or crosscut saws (mobile or stationary) to obtain a quality surface.

The chain saw was used under industrial conditions to prepare suitable samples (*disks for detection shiny appearance, prepared surface for application chemical reagent*) from logs. The saw should have the following parameters defined for the suitable griding tools, namely the height of the depth limiter should not be higher than 0.25 mm. For a good quality of cut, the griding angle must be maintained and must be at least 30°. However, everything depends on the quality of the surface and the degree of cleaning of the logs (from dirt, sawdust). And it is necessary that the sawing fibers are not torn out, which would distort the results on the surface of the wood for application a reagent. Then we can say that the quality of the surface is fine for the application of the agent under industrial conditions.

Under laboratory conditions, the surface quality itself was evaluated after using the circular saw and the band saw for timber or lumber based on the surface roughness value using the STN EN ISO 21920 standard. The surface quality was evaluated using a portable Mahr-type pocket surf roughness tester (Mahr Federal Inc. USA). The surface topography after sawing with a chain saw under operating conditions and with a band saw and circular saw was recorded. Surface roughness was evaluated through the mean arithmetic deviation of the profile ($R_a$). Roughness was evaluated at selected locations over a length of 18 mm. The measurement was taken in the radial direction only and compared with the surface after plain milling. After band sawing, the wood surface in terms of roughness was in the range of 3 to 5 µm and after plain milling the wood surface was 3 to 3.5 µm. Therefore,

the surface thus formed was suitable for the application of the reagent. When sawing with a circular saw, the dependence is also influenced by the number of teeth on the blade. With more teeth there was lower roughness and better quality. With 50 teeth, the roughness was about 7.4 to 8.8 µm. This surface was also suitable for the actual application of the reagent, and therefore no further technological operations were necessary to improve the surface quality. The advantage of this detection method is that it can be applied at any level of moisture content of the wood. The application of a chemical reagent to wood can be done by painting or spraying. The most effective way of application is painting, since this achieves the best penetration of the substance into all parts of the wood.

Detection of the reaction wood zone was based on the colour change after reagent application. The colour change was evaluated using the CIELAB colorimetric space colour coordinates $L^*$, $a^*$, $b^*$. Testing was performed using the Color Reader CR-10 colorimeter (Konica Minolta Sensing, INC., Sakura, Japan). All measurements were carried out at four points on cross section, and the measured location was marked. Color measurements were taken at identical positions immediately after reagent application, 24 and 48 h after application. The selection of the measurement positions was made so that the without reaction wood N – normal wood. Zone R, zone with the presence of reaction wood. The color difference parameter $\Delta E$ was calculated as follows,

$$\Delta E^* = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \tag{1}$$

where $L_1^*$, $a_1^*$, and $b_1^*$ are the values of color spectra before the drying process and $L_2^*$, $a_2^*$, $b_2^*$ are the values of color spectra after the drying process or milling process. The overall color change $\Delta E^*$ (Table 3) was classified under the rules distribution of color changes according to Cividini *et al.* (2007).

**Table 3.** Evaluation Criteria of Overall Color Change $\Delta E^*$

| Range of $\Delta E^*$ | Rate of Color Difference |
|---|---|
| $\Delta E^* < 0.2$ | Not visible difference |
| $2 > \Delta E^* > 0.2$ | Small difference |
| $3 > \Delta E^* > 2$ | Color difference visible with high quality screen |
| $6 > \Delta E^* > 3$ | Color difference visible with medium quality screen |
| $12 > \Delta E^* > 6$ | High color difference |
| $\Delta E^* > 12$ | Different colors |

For an even more detailed analysis of the confirmation of our measurements and analyses in reaction wood detection by staining (red to red brown), a MIRA 3 electron microscope (Tescan Orsay Holding, Brno, Czech Republic) was used. According to the microscopic images, the actual occurrence of reaction wood in the stained zone was confirmed.

## RESULTS AND DISCUSSION

The detection method shown in this research is new and unique in that it precisely defines the correct procedure of applying the chemical reagent to the wood and the chemical composition of the reagent itself. This guarantees accurate detection of tension wood based on its different colouration. 1 m$^2$ of surface can be coated by 200 mL of

chemical reagent. The chemical reagent is applied to the cross-section of the wood. Absorption of chemical reagents is higher in the fresh state, and lower absorption is found after the drying process. After the application, the colour of the wood changes immediately. Non-reaction wood, including heartwood or mature wood, gains a yellow-brown shade. Tension wood is intensively coloured in a dark red to purple-brown colour. The sapwood zone changes from dark blue to black when the wood is wet (Figs. 5 and 6). Individual zones of wood are visible to the naked eye even in slightly reduced lighting. For example, different types of colouring timber are shown in Fig. 5.
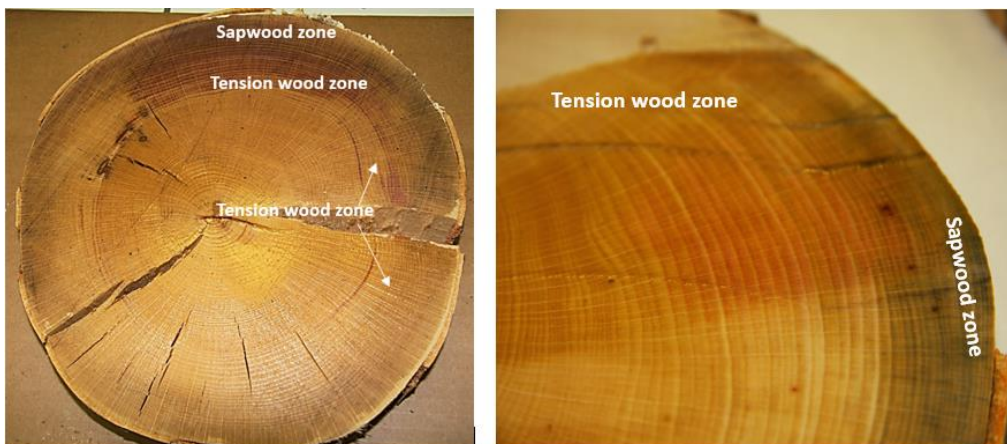


**Fig. 5.** Sawn and milled disc of beech wood with applied chemical reagent after drying



**Fig. 6.** Application of reagent on the log yard on surface of logs (Temperature was below zero)

One of the signs for the selection of samples for analysis of reaction wood using the chemical reagent was a woolly surface on the longitudinal side, which is one of the macroscopic signs of the presence of reaction wood in the blanks or samples (Fig. 7c). Reaction wood was confirmed after application of chemical reagent on samples. Another field of use is scientific and research activity, where this method enables accurate detection of tension wood when selecting sample material and timber, respectively. Verification of the presence of tension wood in the used samples (Fig. 7) under industrial conditions. In Fig. 7 (a,b) the red colour on the samples was clearly apparent. This indicates the reaction wood, and the yellow shows the zones where the reaction wood was not found. All samples had been coated by chemical reagent on all surfaces.
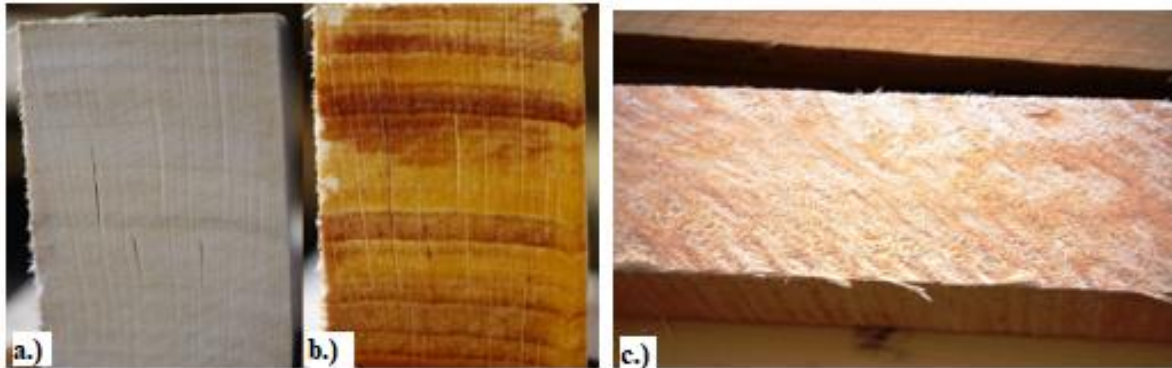
**Fig. 7**. Application of the chemical reagent on timber in industry conditions (Fresh state) a.) samples without chemical reagent, b.) after application chemical reagent, c.) woolly surface first sign of reaction wood in samples

The principle of detection of tension wood relies on the fact that this part of the wood has a different chemical composition. Tension wood has a higher proportion of cellulose. After the application of the reagent, there is a reaction of cellulose with zinc chloride. With the breaking of hydrogen bonds in the G-layer of reaction wood with a larger proportion of cellulose and the subsequent oxidation of the resulting aldehyde groups with iodine, a remarkable dark brown or red colour is formed (Fig. 8). The stabilization of linear iodine chain complexes may be due to some extent to the lack of lignin in the G layer. The connection of the G layer with the other layers of the cell wall is very weak. If lignin were present, it would fill such pores and iodine would have nowhere to bind; therefore the present reagent works only on reaction wood and not on normal wood (Fengel and Wegener 1989).
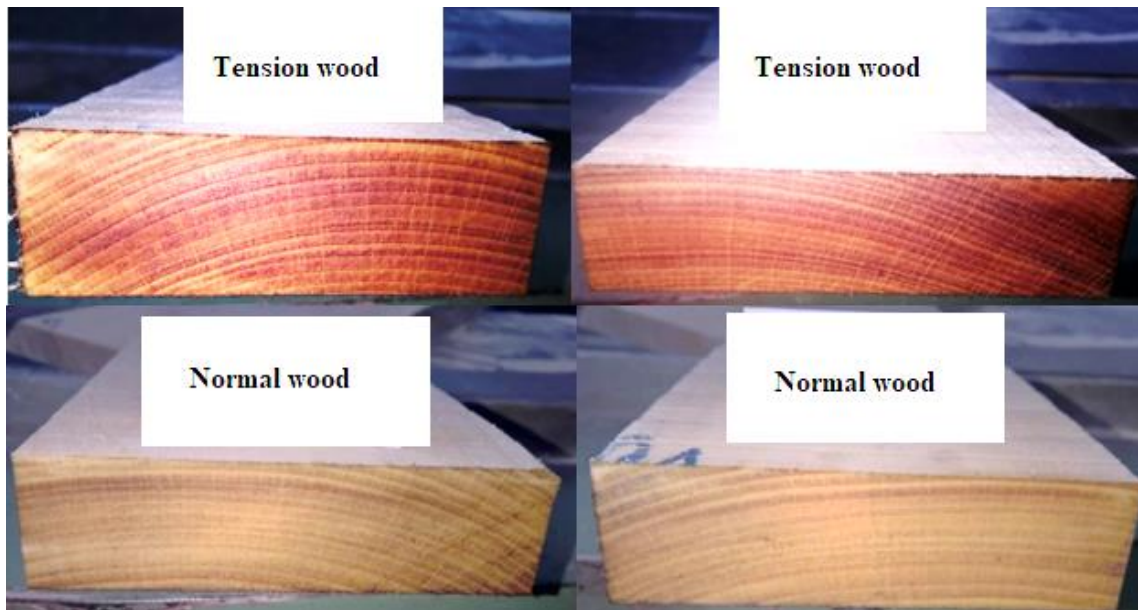


**Fig. 8**. Application of the chemical reagent on samples in laboratory conditions (*Fresh state*)

Verification of the finding that the present reagent and staining procedure represents the reaction wood zone was carried out using a MIRA 3 Electron microscope (Tescan Orsay Holding, Brno, Czech Republic). As a result, it was confirmed that indeed the reagent was effective in differentiating the tension wood tissue. The zone stained red or reddish brown represents the reaction wood zone. Due to the detailed sorting and selection of the reaction wood samples through macroscopic features, the measured results were also confirmed in the case of microscopic analysis (Fig. 9).
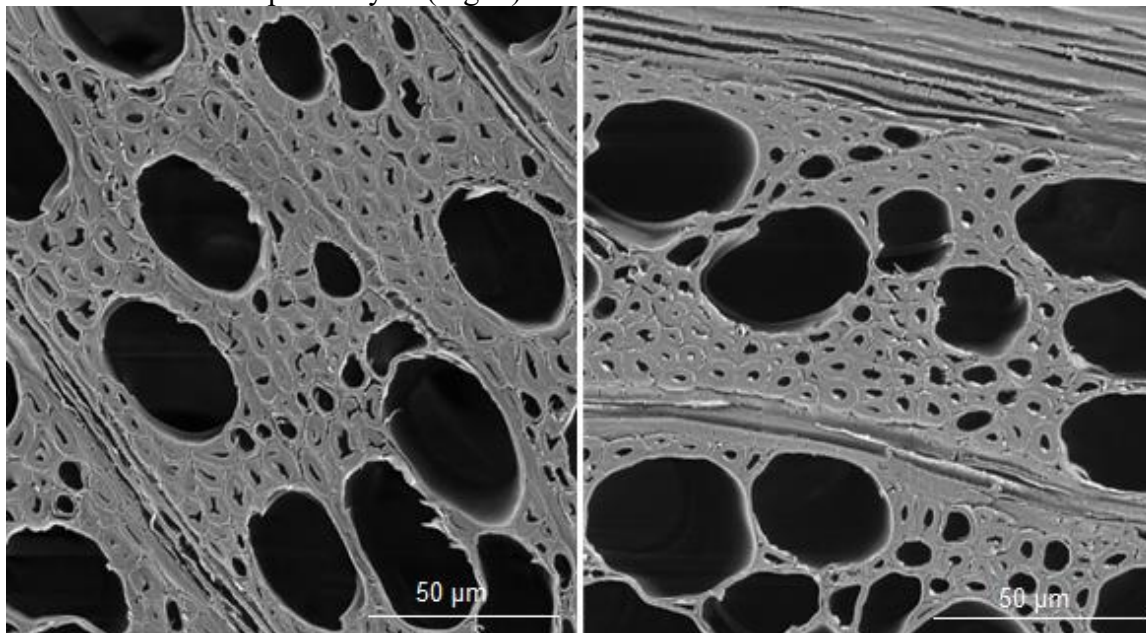


**Fig. 9.** a.) Reaction wood (50 μm) b.) Normal wood (50 μm)

In Fig. 9 b, thick-walled fibrous cells with a loose G-layer are visible. The present findings confirm studies of authors (Clair *et al.* 2003, 2006). These authors claim that due to the almost parallel orientation of the cellulose microfibrils (0 to 5 °) with the fibrous cell axis and the absence of lignin, it is expected to undergo large transversal shrinkages, which are cause of tearing the G-layer from the outer layers $S_1$ and $S_2$ in the drying process. The present measured results, which are in concordance with Čunderlík and Hudec (2002), show that the non-lignified G-layer is likely to have deformable cell walls and thus reduced compressive tensile strength of reaction wood as well as irregular lumen. In microscopic observations, it was found that reaction wood has fewer vascular cells. The smaller lumen diameter leads to reduced permeability.

The colour change is only temporary and will fade over time (Fig. 10). After the chemical reagent has dried on the surface, the surface can be milled. The colour change extends to a depth of approx. 3 to 5 mm.
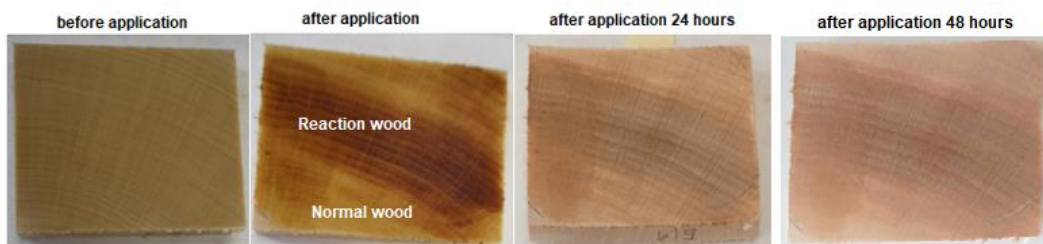
**Fig. 10.** Colour change before application and after application of chemical reagent on the surface

The depth of penetration of the chemical reagent was determined by sawing off the layers from the front of the samples. The depth of penetration is affected by moisture content and the development of reaction wood. Everything depends on the type of wood, dry or fresh, and the method of application by painting or spraying. Chemical reagent does not damage the quality of the wood raw material or the detected wood and wood products. Figure 10 shows further measurements before and after chemical reagent application with the reaction wood and normal wood zones highlighted as well as the colour change at 24 and 48 h after application.

Measurements according to the colour coordinate values were analysed (Fig. 11). The colour coordinate values of $L^*$, $a^*$, and $b^*$ before and immediately after application, after 24 h, and after 48 h on the samples in the non-reaction zone (N) and reaction wood zone (R) are shown in Fig. 11.
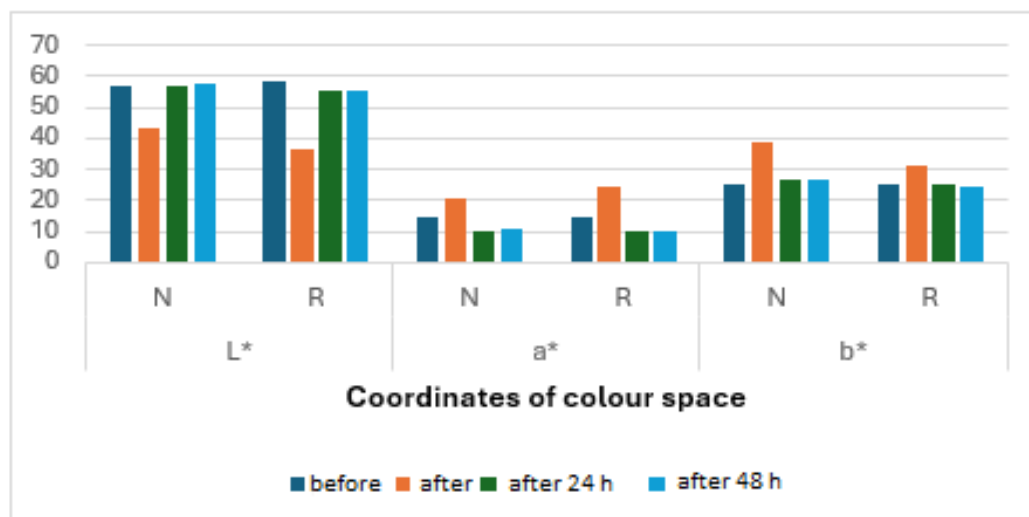


**Fig. 11.** Colour coordinates of $L^*$, $a^*$, and $b^*$ (N) normal wood (*without reaction wood*) and with reaction wood (R)

The largest change in color coordinates was measured shortly after the application of the chemical reagent. In the measurements after 24 and 48 h, the values returned to those measured before the reagent application. Thus, both the reactive and non-reactive samples almost reached the original color. Only the value of the $a^*$ coordinate decreased compared to the original value after 24 and 48 h. After reagent application, the value of the $L^*$ coordinate decreased noticeably. The reduction was greater in the zone of reaction wood,

which was visibly darker. The value of the *a\** coordinate increased after application, with a noticeable increase in the reaction wood zone. Accordingly, the reaction wood stained remarkably reddish brown. The value of the *b\** coordinate changed more in the normal wood, which stained yellow. The present findings are in accordance with Donaldson *et al.* 2007 and Onaka (1949) as well.

The calculated data confirmed a remarkable colour change after the application of the chemical reagent compared to the original wood colour (Table 4).

**Table 4.** Color Difference ΔE Normal Wood (N) and Reaction Wood (R)

| Wood Zone | Before/ after application | Before application/after 24 h | After 24 h / after 48 h | Before application / after 48 h |
|---|---|---|---|---|
| Normal (N) | 19.97 | 4.63 | 1.1 | 4.4 |
| Reaction (R) | 24.72 | 5.47 | 0.85 | 5.9 |

All values were greater than 12. The measurements confirmed that the colour change of the specific zones shortly after the application of the reagent was clearly visible to the naked eye, and the differences in colour change allow the zones to be identified accurately. The colour difference plotted against the measurements after 24 h was in the range of 3 to 6, which are changes visible using a medium quality filter. Differences between zones were minimal. The color differences at 48 h after reagent application compared to the measurements at 24 h can be characterized as invisible changes.

Geffertová *et al.* (2019) likewise scrutinized colour properties of reaction wood. The differences in colour between zones normal and reaction were minimal. The largest color changes of beech wood were recorded between wet reaction and opposite wood ($\Delta E$=18.6). Except for $\Delta E$ when comparing reaction wet and dried wood, all observed values of the total color difference were $\Delta E > 3$. Tarmian *et al.* (2011) believe that the higher $\Delta E$ values for reaction wood can be explained by the shininess of the zone, which is an indicator of tensile reaction wood. They characterized the colour differences after drying as invisible changes. The colour of zones having shiny appearance is lighter, resulting in an increased $L^*$ coordinate value. According to Badia *et al.* (2005) and Keeya *et al*. (2000), to some extent, the higher lightness of tension wood is also influenced by the content of the G - layer, which is rich in cellulose. However, reaction wood is not always light in colour, and in some tropical woods, such as mahogany-type woods according to Donaldson *et al.* (2010), the colour difference values can be significantly different.

Onaka (1949) and Clair *et al.* (2003) attempted to identify reaction wood in oak, locust, poplar, and beech wood. Based on the cited work, Dogu and Grabner (2010) used the chemical reagent zinc-chlorine-iodide, which caused the parts of the beech and poplar samples containing tension wood to turn black. From the present findings, it can be concluded that the ineffectiveness of the present reagent by the authors Dogu and Grabner (2010) may be to some extent due to the application in the sapwood zone, which is physiologically active. It contains many parenchymatous (*living cells*). A high level of vitality of the parenchyma was also shown by Fengel and Wegener (1989). The sapwood zone contains a greater amount of starchy substances. Starch is found in living cells, and it is the parenchyma that extends the capacity to store starchy substances in the wood, where they are found in a total proportion of about 50 to 80% starch in parenchyma cells.

However, detecting tension wood in deciduous tree species such as poplar and beech proved challenging with this reagent. The present observations are consistent with those of Hon and Shiraishi (2000), who reported that tension beech wood appeared purplish or reddish-brown, while normal wood appeared yellow when different chemical reagents were used. Similar studies by Bozkurt and Erdin (2000) described tension wood as grey and normal wood as yellowish. The authors discovered that this method was not as effective for poplar or oak wood due to difficulties in analysing tension wood distribution in the disk.

Already in the past, there were attempts to detect tension wood in many different types of wood, including black locust (*Robinia pseudoacacia L.*), beech (*Fagus sylvatica* L.), and European aspen (*Populus tremula* L.) using chemical substances. However, the results were uncertain, and this method was not used, as also shown by Hon and Shiraishi (2000).

In the present study, the colouration of the sapwood zone in wood with moisture content higher than the fibre saturation point (FSP) is attributed to increased starchy substances that react strongly with iodine, resulting in a dark blue-to-black colour. In wood with moisture content lower than the FSP, noticeable colouration occurs only in tension wood. According to results Gardiner *et al.* (2014), colour changes by chemical reagents are more pronounced in wet tension wood compared to dried wood. This knowledge could also be applied in the early detection of reaction wood in industrial practice.

Clair *et al.* (2003) and Chang *et al.* (2009) showed that iodine binds differently to individual layers of the cell wall due to the distinct chemical compositions of normal and reaction wood, leading to a colour change in tension wood. While some researchers employed zinc-chlorine-iodide at a macroscopic level, as also shown by Hon and Shiraishi (2000), its stability for examination at that level was limited. Referring to the widely used microscopic-level approach mentioned by Onaka (1949), tension wood appeared purplish or reddish-brown, while normal wood appeared yellow. Based on the cited work, Bozkurt and Erdin (2000) reported tension wood as grey or bluish-purple and normal wood as yellowish-brown. In the current study, tension wood exhibited black hues, while normal wood displayed a yellow or yellowish-brown colour after the application of zinc chlorine-iodide. Microscopic analysis easily identified areas with gelatinous fibres.

Other parts of the log, the heartwood and sapwood zone, were coloured light brown or yellow-brown colour. The colour detection of tension wood is visible until the chemical reagent dries out, which remarkably affects the moisture content of the wood. On average, the period favourable for colour evaluation is 3 h or more, depending on the moisture content of the wood. By reapplying the reagent to the same area, it is possible to restore the colour distinction between the reaction and normal wood.

The reagent can be used in this example in an automated wood scanning system, which is part of the optimization of the cutting pattern in the processing of logs. The reagent is sprayed onto the cross-sectional of logs before it is moved toward the optical scanner. The scanner evaluates the contrast of the coloured surface from the cross-section on both ends of the wooden semi-finished product and based on this, determines the cutting pattern, ensuring that the zone of reaction wood does not affect the desired utility value of the final product (lumber)

## CONCLUSIONS

1.  The proposed new method for the detection of tension wood with a chemical reagent is very quick and non-destructive.

2.  The proposed detection method is new and unique in that it precisely defines the correct procedure of applying the chemical reagent to the wood and the chemical composition of the agent itself, which guarantees accurate detection of tension wood based on its different colouration.

3.  Applying a chemical reagent to a cross-section of wood, it is possible to detect the zones of tension wood quickly and reliably. This makes it possible to choose the optimal log sawing pattern so that the deformations of the products can be minimal.

4.  Correct surface treatment of the wood surface is important for accurate detection. The surface does not need to be sanded, but the cutting tool must be sharp to avoid pulling out the fibers. This makes it possible to use this method of detection not only in laboratory conditions but also under operating conditions.

5.  The advantage of this method of detection is that the depth of penetration of the chemical agent into the wood is up to 3 to 5 mm; therefore, the wood does not deteriorate. This method can be applied in both exterior and interior conditions.

6.  The colour differences of the different zones are more pronounced when the reagent is applied to wood with a moisture content higher than 30%. The optimal use of detection using a chemical reagent is also before the process of drying and hydrothermal treatment of wood, where this method of detection will allow optimal placement of timber in timber pile about the direction and magnitude of its load.

7.  The importance of detection is also the fact that this zone of wood or individual pieces of lumber with a large proportion of tension wood may be removed from the other process. Removing this wood from processing at the very start is important because the company then does not spend resources and money on processing it, which would lead to the production of an unusable semi-finished product, or product.

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## REFERENCES

Badia, M., Mothe, F., Constant, T., and Nepveu, G. (2005). "Assessment of tension wood detection based on shiny appearance for three poplar cultivars," *Annals of Forest Science* 62(1), 43-49. DOI: 10.1051/forest:2004093

Bozkurt, A. Y., and Erdin, N. (2000). *Odun Anatomisi* ("Wood anatomy"), Faculty of Forestry Publications, University of Istanbul, ISBN 975-404-592-5, Dilek Press, Istanbul.

Chang, S., Clair, B., Ruelle, J., Beauchene, J., Di Renzo, F., Quignard, F., Zhao, G., Yamamoto, H., and Gril, J. (2009). "Mesoporosity as a new parameter for understanding tension stress generation in trees," *Journal of Experimental Botany* 60, 3023-3030, DOI: 10.1093/jxb/erp133

Clair, B., Alméras, T., Yamamoto, H., Okuyama, T., and Sugiyama, J. (2006). "Mechanical behaviour of cellulose microfibrils, in tension wood in relation with maturation stress generation," *Biophysics Journal* 91(3), 1128-1135. DOI: 10.1529/biophysj.105.078485

Clair, B., Alméras. T., Pilate, G., Jullien, D., Sugiyama, J., and Riekel, C. (2011). "Maturation stress generation in poplar tension wood studied by synchrotron radiation microdiffraction," *Plant Physiol.* 155(1), 562-570. DOI: 10.1104/pp.110.167270

Clair, B., Ruelle, J., and Thibaut, B. (2003). "Relationship between growth stress, mechanical-physical properties, and proportion of fibre with a gelatinous layer in chestnut (*Castanea sativa* Mill.)," *Holzforschung* 57, 189-195. DOI: 10.1515/HF.2003.028

Clair, B., Alméras. T., Pilate, G., Jullien, D., Sugiyama, J., Riekel, C. (2010). Maturation stress generation in Poplar tension wood studied by synchrotron radiation microdiffraction, *Plant Physiology*. 152 (3), 1650 pp.  DOI: 10.1104/pp.110.167270

Colom, X., Carrilo, F., Nogués, F., and Carriga, P. (2003). "Structural analysis of photodegraded wood using FTIR spectroscopy," in: *Polymer Degradation and Stability*, Vol. 80, no.3, pp. 543-549. DOI: 10.1016/S0141-3910(03)00051-X

Déjardin, A., Laurans, F., Arnaud, D., Breton, C. H., Pilate, G., and Leplé, J. C. H. (2010). "Wood formation in angiosperms," *Comptes Rendus Biologies,* 333(4), 325-334. ISSN 1631-0691. DOI: 10.1016/j.crvi.2010.01.010

Dogu, A. D., and Grabner, M. (2010). "A staining method for determining the severity of tension wood," *Turkish Journal of Agriculture and Forestry* 34(5), 381-392. DOI: 10.3906/tar-0906-209

Donaldson, L., Radotic, K., Kalauzi, A., Djikanovic, D., Jeremic, M., 2010. Quantification of compression wood severity in tracheids of (*Pinus radiata* D.) *Journal of Structural Biology*, 169 (1) 106-115pp. DOI: 10.1016/j.jsb.2009.09.006

Fengel, D., and Wegener, G. (1989). *Wood—Chemistry, Ultrastructure, Reactions*, 2nd Ed., Walter de Gruyter, Berlin. ISBN 3-11-00848-3

Gardiner, B., Barnett, J., Saranpää, P., and Gril, J. (2014). *The Biology of Reaction Wood*, *Springer Series in Wood Science*, Berlin, Heidelberg: Springer-Verlag. DOI: 10.1007/978-3-642-10814-3_6

Geffertová, J., Geffert, A., Vilkovská, T., Klement, I., Vacek, O. (2019). "Selected aspects of the reaction beech wood," in: *Acta Facultatis Xylologiae Zvolen*: vedecký časopis Drevárskej fakulty Technickej univerzity vo Zvolene., no. 2, pp. 5-15. ISSN 1336-3824

Hon, D. N. S., and Shiraishi, N. (2000). *Wood and Cellulosic Chemistry*, Marcel Dekker, New York, Vol. 2, 914 pp. ISBN 0-8247-0024-4, DOI: 10.1201/9781482269741

Kačíková, D. (2001). "Makromolekulové vlastnosti hlavných zložiek bukového dreva z hľadiska sulfátových buničín," Zvolen: Technická univerzita vo Zvolene, 84 pp.

Keey, R. B., Langrish, T. A. G., and Walker, J. C. F. (2000). *Kiln-drying of Lumber*, Springer, Berlin, 326 pp., ISBN-10: 9783540661375

Kúdela, J., and Čunderlík, I. (2012). "Bukové drevo štruktúra, vlastnosti, použitie," Technická Univerzita vo Zvolene, 152 pp. ISBN 978-80-228-2318-0.

Majka, J., and Sydor, M. (2023). "Analysis of stress development during kiln drying of beech timber," *European Journal of Wood and Wood Products* 81, 1189-1200. DOI: 10.1007/s00107-023-01967-y

Meloche, C. G., Knox, J. P., and Vaughn, K. C. (2006). "A cortical band of gelatinous fibres causes the coiling of redvine tendrils: A model based upon cytochemical and immunocytochemical studies," *Planta* 225(2), 485-498. DOI:10.1007/s00425-006-0363-4

Onaka, F. (1949). "Studies on compression and tension wood," *Wood Research*., Bulletin of the Wood Research Institute, Kyoto University, Japan, 24, pp. 1-88.

Pandey, K. K., and Pitman, A. J. (2003). "FTIR studies of the changes in wood chemistry following decay by brown-rot and white-rot fungi," *International Biodeterioration & Biodegradation* 52(3), 151-160. DOI: 10.1016/S0964-8305(03)00052-0

Siau, J. F. (1984). *Transport Processes in Wood*, *Springer – Verlag*, Berlin, Heidelberg, New York, Tokyo, 245 pp. ISBN: 978-3-642-69215-4

Široký, J., Blackburn, R. S., Bechtold, T., Taylor, J., and White, P. (2010). "Attenuated total reflectance Fourier-transform infrared spectroscopy analysis of crystallinity changes in lyocell following continuous treatment with sodium hydroxide," *Cellulose* 17(1), 103-115. DOI: 10.1007/s10570-009-9378-x

Tarmian, A., Foroozan, Z., Gholamiyan, H., and Gérard, J. (2011). "The quantitative effect of drying on the surface color change of reaction woods: Spruce compression wood (*Picea abies* L.) and poplar tension wood (*Populus nigra* L.)," *Drying Technol. Roč.* 29(15), 1814-1819.

Vidholdová, Z., and Slabejová, G. (2022). "The decay resistance of four hydrothermally treated hardwood species," *Acta Facultatis Xylologiae Zvolen*, ISSN 1336-3824. - Vol. 64, no. 2, pp. 17-27. DOI: 10.17423/afx.2022.64.2.02

Vilkovská, T., Klement, I., Výbohová, E. (2018). "The effect of tension wood on the selected physical properties and chemical composition of beech wood (*Fagus sylvatica* L.)," *Acta Facultatis Xylologiae Zvolen* 60(1), 31-40, ISSN 1336-3824.

Vilkovský, P., Klement, I., and Vilkovská, T. (2023). "The impact of the log-sawing patterns on the quantitative and qualitative yield of beech timber (*Fagus sylvatica* L.)," *Applied Sciences* 13(14), article 8262. DOI: 10.3390/app13148262