Discrimination between Softwood and Hardwood based on Hemicellulose Content obtained with Portable Nuclear Magnetic Resonance

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Abstract

Wood is a hygroscopic material that can reach an equilibrium moisture content when ambient temperature and relative humidity are constant. Moisture affects all properties of wood, as well as its preservative treatment. The hygroscopic behavior of wood can be attributed to the hydroxyl groups of its constituents. Since hemicellulose shows the greatest water affinity, it can be considered the main responsible for water entering into the wood mass. Below the fiber saturation point (FSP), wood moisture is only stored in the cell walls. Proton Nuclear Magnetic Resonance (NMR) is a relative method used for the evaluation of moisture content distribution in wood and NMR relaxation is an excellent tool to study the hygroscopic behavior of different woods below the fiber saturation point. This work aimed to test the hypothesis of discriminating among softwoods and hardwoods of different botanical species and identifying further sub-clusters of woods on the basis of the NMR proton spin-spin (T_2) and spin-lattice (T_1) relaxation times of their cell wall water in the hygroscopic moisture range. Towards this goal, a portable low-field NMR instrument was used to develop a specific non-invasive NMR protocol for in situ investigation useful in the wood industry and/or cultural heritage applications.

1. Introduction

Wood is a biological heterogeneous and anisotropic porous material (Capuani et al. 2020). It is characterized by fibers with a cell wall composed of natural polymers, such as cellulose, hemicellulose, and lignin. Among them, cellulose can be considered the most abundant component of wood (Alesiani et al. 2005). Wood can be also described as a porous system with strongly variable and multi-scale porosity. In particular, each wooden species has pores, such as pits, perforations, and the lumen of vessels, tracheids, and fibers, with peculiar dimensions and spatial organization (Capuani et al. 2020; Stagno et al. 2021a).

Wood is classified as softwood and hardwood. Softwood has a quite homogeneous microstructure mostly dominated by one kind of structure, called tracheid (Capuani et al. 2020; Stagno et al. 2021a). Different from softwood, hardwood has more complex anatomical features and greater structural variation (Stagno et al. 2021a). Indeed, its microstructure is made up of conducting elements, i.e. vessels, and strength-giving elements, i.e. fibers.

Furthermore, due to its hygroscopicity, wood can absorb moisture from the surrounding environment in the form of vapor or liquid water. Moisture affects all properties of wood. While moisture in the cell lumens only produces an increment of weight (Tsoumis 1991), moisture contained in cell walls influences the mechanical and thermal properties of wood (Bartolucci et al. 2021). Moisture content (MC) of wood also affects its resistance to decay and insects as well as its preservative treatment (Tsoumis 1991). At constant temperature (T) and relative humidity (RH), wood reaches an equilibrium state characterized by a certain equilibrium moisture content (EMC) (Glass Samuel V; Zelinka 2010). A sorption isotherm is a discrete representation of equilibrium moisture states of wood with its surrounding environment and each state is attained after either adsorption or desorption of water molecules (Engelund et al. 2013).

A central role in the hygroscopic behavior of wood can be ascribable to the hydroxyls of its constituents. Cellulose and hemicellulose have a higher content of hydroxyl groups than lignin. However, because cellulose is mostly in crystalline form that is not accessible to water, hemicellulose is considered to have a greater affinity to water (Schirarend 1986; Berry and Roderick 2005; Kulasinski et al. 2015). So, hydroxyl groups of hemicellulose catch water molecules by forming hydrogen bonds and are responsible for moisture entering the wood mass. Since softwoods and hardwoods show a different hemicellulose content, i.e. hardwoods have more hemicellulose than softwoods (Holtzapple 2003; García Esteban et al. 2005), distinct hygroscopic behavior of their cell walls is expected (Elder and Houtman 2013). When dried wood is taken at room temperature, at least a monomolecular layer of water is bonded to its constituents (Chami Khazraji and Robert 2013) and, its cell walls start swelling. Then, other water molecules align above those are associated with the hydroxyl groups and form H-bonds (Berry and Roderick 2005). The result is a water poly-molecular layer. An additional part may enter by capillarity condensation in the cell wall voids and pits but, it is considered insignificant below 99.5% RH (Thygesen et al. 2010). The fiber saturation point (FSP) is the moisture content that occurs when cell walls are saturated with water and cell lumens are empty. At this point, cell walls stop swelling and, the strength of the timber no longer changes with the moisture content (Berry and Roderick 2005). Below the FSP, only bound water is present in wood, and water in the smaller pores of cell walls shows a switching behavior between liquid and vapor phases (Beckstein and Sansom 2003). Above the FSP, water starts filling cells lumens as free water. Conventionally, the FSP is set around 30% of wood moisture content. However, it can also be considered as the wood EMC when RH is close to 100% (Berry and Roderick 2005).

The EMC is also affected by the wood sample history and, this phenomenon is known as sorption hysteresis. As an example, when a greenwood sample is dried, its EMC reached for adsorption will be lower than its EMC attained for desorption (Glass Samuel V; Zelinka 2010). Furthermore, it has been noticed that around 60–70% RH, the sorption isotherm of wood exhibits an upward bend. This behavior can be explainable by the softening of amorphous polymers (Olsson and Salmén 2004; Engelund et al. 2013). During softening, the viscosity and rigidity of the wood polymeric network are reduced because of the transition of its amorphous parts from a glassy state to a rubbery state (Engelund et al. 2013). Due to this process, the cell wall capacity of accommodating water molecules might increase. At room temperature, softening of hemicelluloses occurs around 75% RH (Olsson and Salmén 2004; Engelund et al. 2013).

Nuclear Magnetic Resonance (NMR) is a relative method used for the evaluation of moisture content distribution in wood and masonry (Camuffo 2018). Compared to traditional relative methods for moisture content evaluation, the main advantages of NMR are the accuracy in moisture content determination and the greater penetration depth (European Committee for Standardization 2017). Portable Low-field Nuclear Magnetic Resonance (LFNMR) has been used to study different water compartments within the wood structure with particular interest for the over-hygroscopic range where water can be found not only in the cell wall but also in cell lumina and other voids with different sizes (Fredriksson and Thygesen 2017; Stagno et al. 2021c). These studies (Menon et al. 1987; Araujo et al. 1992; Labbé et al. 2002; Labbé et al. 2006; Almeida et al. 2007; Thygesen and Elder 2009; Elder and Houtman 2013; Fredriksson and Thygesen

2017; Stagno et al. 2020; Stagno et al. 2021c) highlighted the LFNMR potential in characterizing water compartments of wood for probing its different anatomical elements. On the other hand, water in wood in the hygroscopic range (i.e. below the FSP) is only located in the cell wall compartment. However, cell wall water has also been separated into tightly bound to macromolecules and less bound to cell walls (Casieri et al. 2004; Fantazzini et al. 2006; Thygesen and Elder 2009; Bonnet et al. 2017; Rostom et al. 2020). All the aforementioned works pointed out that water is an excellent probe of wood characteristics because it is sensitive to wood ultrastructure. Moreover, water features in wood can be used to assess the wood morphology and hygroscopic behavior.

This work aimed to exploit the possibility to discriminate among different wood samples belonging to softwood and hardwood groups and identify possible sub-clusters of woods on the base of NMR relaxation of their cell wall water in the hygroscopic range. Towards this goal, a portable LFNMR instrument was used to develop a specific non-invasive NMR protocol for in situ investigation useful in the wood industry and/or cultural heritage applications.

2. Experimental

2.1 Materials

Fifteen cylinder-like wood samples (Table 1) of 2.5 cm in height and 3 cm in diameter were studied. The samples were previously dried inside the Universal Memmert Oven stove at a temperature (T) of 103.5 ± 0.5°C for 24 hours. Their botanical species and their common name are reported in Table 1.

Table 1
Botanical species and common name of the samples, their densities, and wood group softwood (S) or hardwood (H).

Botanical species	Common name	Density (kg/m^3)	Wood group
Mitragyna ciliata	bahia walnut	530 ± 40	H
Populus alba	white poplar	480 ± 40	H
Picea abies	red spruce	540 ± 40	S
Abies alba	Russian silver fir	530 ± 40	S
Aningeria altissima	akatio walnut	560 ± 40	H
Abies alba	European silver fir	350 ± 30	S
Quercus petraea	sessile oak	630 ± 50	H
Juglans nigra	English walnut	680 ± 50	H
Aningeria altissima	tanganyika walnut	520 ± 40	H
Entandrophragma cylindricum	sapele mahogany	550 ± 40	H
Toona ciliata	Australian red cedar	520 ± 40	S
Pinus ponderosa	European Virginia pine	510 ± 40	S
Lovoa trichilioides	African walnut	550 ± 40	H
Picea rubens	American red spruce	520 ± 40	S
Pinus ponderosa	American Virginia pine	530 ± 40	S

Since in this study NMR acquisitions were performed at different RH levels and NMR signal acquired by portable NMR Bruker instrument is particularly sensitive to little RH variations, a climate chamber was realized by using a Styrofoam box with inner volume 43 x 36 x 30 (h x l x w) cm^3 (see Fig. 1). Styrofoam was chosen because of its insulating properties to prevent vapor exchanges with the external environment. Indeed, according to Nilsson et al. (Nilsson 2018), a climate chamber is recommended to maintain temperature stability because temperature fluctuation of ± 0.1°C may produce an RH change of ± 0.5%. To keep the box temperature constant, the air conditioning system set at T = 20°C was turned on during all the experiments time. In this way all measurements were performed by inserting the wood samples inside the box at a selected value of relative humidity and constant temperature of T = 20 ± 1°C, which were monitored by using the TROTEC BC06 thermo-hygrometer (uncertainty of ± 1°C within the measurement range 0° to 40°C for T and ± 3.5% within the measurement range 20° to 80°C for RH).

In a first phase, named A, four samples corresponding to Russian silver fir, European Virginia pine, akatio walnut, and white poplar (see Table 1) were equilibrated at three levels of relative humidity equal to RH_{A1} = 46.0 ± 3.5%, RH_{A2} = 78.0 ± 3.5% and RH_{A3} = 94.0 ± 3.5% while in a second phase, named B, all the

samples were equilibrated at RH_B = 94.0 ± 3.5% (see Fig. 1). RH_{A1} was the environmental relative humidity of the laboratory. $RH_{A2}$was obtained by adding in the box a container with 130 ml of liquid water. $RH_{A3}$was reached by using a saturated saline solution of potassium sulfate (K_2SO_4) (Nilsson 2018). It is important to notice that the EMC of wood at the three RH levels is expected to be approximately 9%, 15%, and 24%, respectively, according to the EMC calculation table (Noack 1989; W.T. Simpson 1998; Glass Samuel V; Zelinka 2010).

2.2 Methods

2.2.1 Wood density

Average dried weight values by gravimetric method (Noack 1989) were obtained for each wood species. Masses of all dried wood samples were measured with an analytical balance BP211D Sartorius and their volume was calculated. Then, the density of each sample was expressed in kg/m^3.

2.2.2 NMR relaxometry

The NMR relaxometry measurements were performed using a BRUKER minispec mq-ProFiler with a single-sided magnet that generates a static magnetic field of 0.35 T. Therefore, ^{1}H resonance frequency was equal to 17 MHz. The single-sided NMR was equipped with an RF probe for performing experiments by collecting NMR signal from a sample volume defined from the sample surface to 2 mm inside the sample itself (Stagno et al. 2021b). Hard radiofrequency pulses of duration equal to 6 μs and a dead time acquisition of 2 μs were used. In both phases A and B the longitudinal relaxation time (T_1) was acquired by using a Saturation Recovery (SR) sequence with minimum/maximum variable delay time (t) = 1/800 ms, with a repetition time(TR) = 0.02 s, number of averaged scans, NSA = 1024, increment factor 1.2. For each sample, the SR experiment was repeated five times to test the reproducibility of the T_1 measurement and calculate the standard error (STE) associated with the T_1 mean values. On the base of the measured T_1, the TR was set for the transversal relaxation time (T_2) measurement, performed using a Carr-Purcell-Meiboom-Gill (CPMG) sequence. The CPMG was carried out by selecting a delays list from 0.042 ms to 21 ms, with TR = 500 ms, 500 echoes, NSA = 1024, and echo time, TE = 42 μs. This TE allowed eliminating the contribution of solid wood (i.e. the contribution from immobile protons of the wood polymers) (Casieri et al. 2004), which was estimated to be less than 30 μs (Araujo et al. 1992; Hartley et al. 1996), in the T_2 measurements. Also in this case the experiment was repeated five times for each wood sample to extrapolate STE of the T2 mean values.

2.3 Data processing

To obtain the T_1 values, a bi-exponential function:

$$S(t) = M_1 \times \left[1 - \exp\left(-\frac{t}{T_{1,1}}\right)\right] + M_2 \times \left[1 - exp\left(\frac{t}{T_{1,2}}\right)\right]$$

1

was fitted to experimental data. In Eq. 1, $T_{1,1}$ and $T_{1,2}$ are the spin-lattice relaxation times belonging to two different water compartments associated with the magnetizations M_1 and M_2, respectively, S(t) is the NMR signal.

Similarly, to quantify T_2 values, a bi-exponential function

$$S(TE) = M_1 \times \exp\left(-\frac{TE}{T_{2,1}}\right) + M_2 \times \exp\left(-\frac{TE}{T_{2,2}}\right) + c$$

2

was fitted to the CPMG signal (S(TE)). $T_{2,1}$ and $T_{2,2}$ are the spin-spin relaxation time components with M_1 and M_2 the associated magnetizations and c a constant to consider the noise floor.

All data were elaborated by using OriginPro 8.5 software. The goodness of each fit was evaluated by using the $\bar{R}^2$ (i.e. the R^2 corrected for the number of the regressors).

Each T_1 and T_2 component measured at 46, 78, and 94% RH was plotted as a function of the relative humidity. Then, the k-means clustering algorithm of Matlab2021a (Statistics and Machine Learning Toolbox), which computes the sum of absolute differences i.e. each centroid is the component-wise median of the points in that cluster, was performed to verify the existence of at least two clusters of T_1 and T_2 at RH_B = 94% among the fifteen samples. Furthermore, correlation plots among wood samples density and all measured relaxation components were obtained.

3. Results

In Table 1 dry density of woods is reported. For the four chosen wood samples (Russian silver fir, European Virginia pine, akatio walnut, and white poplar), T_1 and T_2 components obtained by Eq. (1) and Eq. (2), respectively, are shown in Table 2. Each relaxation component was then plotted as a function of the relative humidity as displayed in Fig. 2 and Fig. 3.

Table 2
T_1 and T_2 components and their standard errors (STE) calculated at RH_{A1} = 46, RH_{A2} = 78, RH_{A3} = 94% by using Eq. (1) and Eq. (2).

	$T_{1,1}$	$T_{1,2}$	$T_{2,1}$	$T_{2,2}$
		46% RH_{A1}		
Russian silver fir	0.89 ± 0.19	61.51 ± 4.78	0.16 ± 0.01	0.57 ± 0.01
European Virginia pine	1.13 ± 0.09	54.32 ± 4.10	0.152 ± 0.002	0.53 ± 0.01
Akatio walnut	1.19 ± 0.05	59.02 ± 2.23	0.152 ± 0.004	0.57 ± 0.02
White poplar	1.34 ± 0.08	66.99 ± 2.09	0.152 ± 0.004	0.550 ± 0.004
		78% RH_{A2}		
Russian silver fir	0.84 ± 0.05	46.91 ± 2.50	0.17 ± 0.01	0.60 ± 0.01
European Virginia pine	1.01 ± 0.09	36.65 ± 1.80	0.180 ± 0.004	0.60 ± 0.01
Akatio walnut	1.62 ± 0.06	44.34 ± 1.95	0.178 ± 0.004	0.87 ± 0.01
White poplar	1.89 ± 0.04	52.00 ± 1.83	0.178 ± 0.004	0.98 ± 0.01
		94% RH_{A3}		
Russian silver fir	1.44 ± 0.05	36.51 ± 1.48	0.178 ± 0.004	0.69 ± 0.01
European Virginia pine	1.39 ± 0.12	28.24 ± 1.97	0.20 ± 0.01	0.70 ± 0.01
Akatio walnut	1.67 ± 0.04	30.33 ± 0.64	0.248 ± 0.004	1.33 ± 0.01
White poplar	2.05 ± 0.11	39.49 ± 1.71	0.192 ± 0.004	1.38 ± 0.02

Table 3 shows the longitudinal relaxation times of all the fifteen samples obtained by the bi-exponential function of Eq. (1). In Table 4 the transversal relaxation times obtained by Eq. (2) are displayed. Figure 4 shows the correlation plots among density and relaxation times. The cluster plots that were obtained by correlating the $T_{1,1}$ vs. $T_{2,2}$ (Fig. 5a) and $T_{1,2}$ vs. $T_{2,2}$ (Fig. 5b) and by supposing the existence of two clusters in the k-means algorithm is shown in Fig. 5. Moreover, in Fig. 6a similar cluster plot but with three hypothesized clusters is shown.

Table 3
T_1 components calculated by Eq. (1) and their standard errors (STE) at RH_B = 94% for the fifteen samples.

Common name	$T_{1,1}$ ± STE (ms)	$T_{1,2}$ ± STE (ms)
bahia walnut	1.39 ± 0.08	26.76 ± 1.37
white poplar	2.05 ± 0.11	39.49 ± 1.71
red spruce	1.26 ± 0.12	33.09 ± 0.61
Russian silver fir	1.44 ± 0.05	36.51 ± 1.48
akatio walnut	1.67 ± 0.04	30.33 ± 0.64
European silver fir	1.19 ± 0.03	23.64 ± 0.76
sessile oak	1.69 ± 0.19	67.66 ± 0.59
English walnut	2.55 ± 0.06	84.58 ± 1.70
tanganyika walnut	1.66 ± 0.06	39.44 ± 1.13
sapele mahogany	1.50 ± 0.4	81.13 ± 2.33
Australian red cedar	1.67 ± 0.23	59.85 ± 1.48
European Virginia pine	1.39 ± 0.12	28.24 ± 1.97
African walnut	1.92 ± 0.08	28.38 ± 0.87
American red spruce	1.15 ± 0.17	33.76 ± 0.58
American Virginia pine	1.04 ± 0.03	22.80 ± 0.59

Table 4
T_2 components calculated by Eq. (2) and their standard errors (STE) at RH_B = 94% for the fifteen samples.

Common name	$T_{2,1}$ ± STE (ms)	$T_{2,2}$ ± STE (ms)
bahia walnut	0.214 ± 0.004	1.098 ± 0.004
white poplar	0.192 ± 0.004	1.38 ± 0.02
red spruce	0.19 ± 0.01	0.64 ± 0.01
Russian silver fir	0.178 ± 0.004	0.69 ± 0.01
akatio walnut	0.24 ± 0.01	1.33 ± 0.01
European silver fir	0.196 ± 0.004	0.806 ± 0.004
sessile oak	0.280 ± 0.004	0.952 ± 0.004
English walnut	0.216 ± 0.004	1.25 ± 0.01
tanganyika walnut	0.190 ± 0.004	1.096 ± 0.004
sapele mahogany	0.238 ± 0.002	1.546 ± 0.004
Australian red cedar	0.22 ± 0.01	0.90 ± 0.02
European Virginia pine	0.20 ± 0.01	0.70 ± 0.01
African walnut	0.25 ± 0.01	1.606 ± 0.004
American red spruce	0.214 ± 0.004	0.72 ± 0.01
American Virginia pine	0.192 ± 0.004	0.636 ± 0.004

4. Discussion

This work aimed to discriminate among different wood samples on the base of the NMR relaxation of their cell wall water in the hygroscopic range. To develop a non-invasive NMR protocol for in situ investigation useful in the wood industry and/or cultural heritage applications, a portable NMR instrument was used. In the following, to better deal with and discuss the various observations and results obtained, the discussion section was divided into several paragraphs.

4.1 NMR relaxation times components assignment and their dependence on RH

Different behavior of the two components of T_1 relaxation and the two components of T_2 relaxation is highlighted in Figs. 2 and 3. Considering the longitudinal relaxation time, some authors (Fantazzini et al. 2006; Bonnet et al. 2017; Rostom et al. 2020) pointed out the existence of two different components

below the FSP. A fast T_1 component of a few ms or hundreds of μs, which is due to water bound to the cell walls, and a slow T_1 of tens of ms, which is associated with the protons of wood polymers. In this regard, the component $T_{1,1}$ displayed in Fig. 2a, which is of the order of few ms, can be attributed to bound water in the cell walls while the second component $T_{1,2}$ (Fig. 2b), much greater and around tens of ms, can be associated with relatively immobile water within the wood polymers.

Regarding the transversal relaxation time, previous works (Araujo et al. 1992; Hartley et al. 1992; Labbé et al. 2002; Thygesen and Elder 2009) identified a T_2 component around 0.2-3 ms increasing with RH as bound water. Therefore, we can associate the fast component $T_{2,1}$ (Fig. 3a) with water protons tightly bound to macromolecules and the slow component $T_{2,2}$ (Fig. 3b) with protons of cell wall-bound water (Casieri et al. 2004; Thygesen and Elder 2009). On the other hand, as the investigated wood samples were below the fiber saturation point, we did not detect the lumen water that is characterized by T_2 around tens of milliseconds (Labbé et al. 2002). Moreover, because we used a TE = 0.04 ms in the CPMG experiments, we did not measure the faster T_2 component belonging to solid wood (Casieri et al. 2004), estimated to be around 0.01 ms by Labbè et al. (Labbé et al. 2002).

4.1.2 Cell walls reservoir. In Fig. 2, an exponential dependence on the relative humidity of the T_1 associated with the cell walls ($T_{1,1}$) is visible for all four wood samples. Particularly, this component (Fig. 2a), ranging from a minimum of 0.8 ms to a maximum of 2 ms, shows a quite different behavior among softwoods and hardwoods. For the two hardwoods, white poplar and akatio walnut, the $T_{1,1}$ appears to increase with the RH increment. This is due to the growing hydration of the wood cell walls which determines a slower longitudinal relaxation time. In particular, the $T_{1,1}$ increment is higher when RH increases from RH_{A1} = 46% to RH_{A2} = 78% while it is lower from RH_{A2} = 78% to RH_{A3} = 94%. In the two softwoods, Russian silver fir and European Virginia pine, the $T_{1,1}$ seems to be constant when RH changes from RH_{A1} = 46% to RH_{A2} = 78% and it starts to increase rapidly when RH grows from RH_{A2} = 78% to RH_{A3} = 94% reaching a lower maximum value compared to that of the hardwoods. This result can be explained by the fact that the hardwood samples catch more water molecules thanks to their higher hemicellulose content compared to the softwood samples. Also in the softwoods, the $T_{1,1}$ increment is associated with the growing hydration of the cell walls, but this seems to be gained drastically for RH > 78%. This behavior may be a consequence of the hemicellulose softening that at room temperature (T = 20°C) occurs around RH = 75% (Olsson and Salmén 2004; Engelund et al. 2013).

The $T_{2,2}$ component of wood cell walls (Fig. 3b), grows from 0.53 to 1.38 ms describing progressive hydration of the wood cell walls mainly ascribable to hemicelluloses softening. Its growth is faster above RH_{A2} = 78% due to the glass transition of hemicelluloses as described by Engelund et al. (Engelund et al. 2013). This T_2 component also shows a distinct behavior among softwoods and hardwoods reflecting their different hygroscopicity. On this subject,, hardwoods have cell walls made by a higher amount of hemicellulose (Holtzapple 2003) that is characterized by a lot of polar groups (OH groups) able to retain water increasing wood hygroscopicity (García Esteban et al. 2005).

4.1.3 Polymers water reservoir. The $T_{1,2}$ component in Fig. 2b shows an opposite behavior as a function of RH compared to that of the $T_{1,1}$ (Fig. 2a). Starting from a value of 50–60 ms at RH_{A1} = 46%, the $T_{1,2}$ decreases for both softwoods and hardwoods with the increase of RH, reaching a minimum value around 30–40 ms. This is explainable considering that water tightly bound to polymers gains mobility with the RH increment. In the solid-like range, this increase of mobility is associated with a speeding up of the spin-lattice relaxation time due to the faster exchange of energy between spins and lattice (Brown and Koenig 1992).

In this regard, the $T_{2,1}$ component (Fig. 3a) spanning from 0.15 to 0.24 ms, appears to slightly grow during the RH increment except for akatio walnut that shows a rapid increase (from 0.18 to 0.25 ms) when RH changes from 78 to 94%. This observation can indicate greater mobility of water protons in akatio walnut macromolecules and that it is approaching the FSP. In fact, as described in the literature (Jankowska and Kozakiewicz 2016), the FSP is negatively correlated with the wood density so denser woods have a lower FSP. The akatio walnut sample investigated in this paper has the highest density (around 560 kg/m^3, see Table 1) among the other three samples and for this reason, a low FSP is expected. In general, the $T_{2,1}$ component is quite similar for softwoods and hardwoods and describes the slow variation of mobility of the water protons tightly bound to the macromolecules.

4.2 Relaxation times vs. density correlation

As expected, the plot in Fig. 4 suggests that T_1 moderately correlates with the wood dry density (kg/m^3), as previously shown by Stagno et al. [3]. The dependence of $T_{1,1}$ and $T_{1,2}$ on the dry density of woods indicates that T_1 is also affected by intrinsic features of the wood. Particularly, English walnut is characterized by the longest T_1 and the highest dry density associated with its compact structure due to a diffuse-porous ring with infrequent pores and frequent tyloses [37]. Conversely, European silver fir has the lowest density and the shortest T_1 because of its homogeneous structure constituted by more than 95% of open elements, i.e. tracheids [3, 38].

4.3 Clustering

4.3.1 Two clusters hypothesis. The main purpose of clustering by hypothesizing two clusters was to detect a possible different behavior among softwoods and hardwoods based on the measured relaxation times. The plot in Fig. 5a shows how the different species of wood are distributed according to their $T_{1,1}$ and $T_{2,2}$ relaxation times. A clear differentiation of cell wall reservoir between softwoods and hardwoods is visible. Softwoods cluster centroid is [1.22, 0.69], which indicates that softwood samples are distributed around the median value of $T_{1,1}$ = 1.22 ms and of $T_{2,2}$ = 0.69 ms. Indeed, while hardwoods seem to be spread among different values of T_1, softwoods occupy a quite narrow region of the plot that roughly ranges from 1 to 1.5 ms. Moreover, the hardwoods cluster centroid is [1.67, 1.25]. Indeed, hardwoods show higher values of $T_{2,2}$ if compared to softwoods. Softwoods, indeed, have $T_{2,2}$ always shorter than 0.806 ± 0.004 ms, and hardwoods always longer than 0.90 ± 0.02 ms. Basically, at RH_B =

94% the cell wall reservoir of softwoods is characterized by lower values of T_1 and T_2 than the cell wall reservoir of hardwoods.

In Fig. 5b, a similar result is shown but considering the $T_{1,2}$ and $T_{2,1}$ components. Two different clusters can be observed: cluster 1 with a centroid of [74.39, 0.23] and cluster 2 with a centroid of [30.33, 0.20]. As for the plot in Fig. 5a, the $T_{1,2}$ component of hardwoods is spread to different values. On contrary, softwoods show shorter $T_{1,2}$. The $T_{2,1}$ component is quite similar for all the woods. This result suggests that on the base of the polymers water reservoir it is not possible to distinguish among softwood and hardwood samples because of their quite similar T_1 and T_2 relaxation times. Anyway, two clusters were detected with cluster 1 which contains four hardwoods (sessile oak, sapele mahogany, English walnut, and Australian red cedar) characterized by long $T_{1,2}$ and $T_{2,1}$ likely indicating greater hydration of their polymers.

4.3.2 Three clusters hypothesis. To evaluate the existence of other possible clusters by using the $T_{1,1}$ and $T_{2,2}$ components, which are the relaxation times that provided a good differentiation among softwoods and hardwoods, a three clusters analysis was performed and shown in Fig. 6. This plot suggests two sub-clusters of the hardwoods cluster. The cluster called hardwoods 2, with centroid [2.05, 1.38], contains the samples with longer $T_{1,1}$ (English walnut, white poplar, and African walnut), whereas the cluster called hardwoods 1, with centroid [1.66, 1.10], the samples with shorter $T_{1,1}$ (sapele mahogany, akatio walnut, bahia walnut, sessile oak, tanganyika walnut, and Australian red cedar).

4.4 Final discussion

In Fig. 7a schematic representation of the hygroscopic behavior of the wood cell wall polymers exploited in this work to discriminate between softwood and hardwood is displayed. Specifically, in parallel with the increase of RH, the hemicellulose hydrates more. The hydroxyl groups of the hemicellulose capture water molecules through hydrogen bonds that affect the NMR relaxation times of the cell wall reservoir ($T_{1,1}$ and $T_{2,2}$), which allow discriminating between softwood and hardwood. Hardwoods have a higher hemicellulose content compared to softwoods, therefore their cell walls can reach greater hydration with more water molecules that are bound to the hemicellulose hydroxyls.

5. Conclusions

In this work, we tested the hypothesis of discriminating among softwoods and hardwoods of different botanical species based on their NMR relaxation times. To this end, a non-invasive protocol was tested on fifteen softwood and hardwood samples below the fiber saturation point by using a portable low-field NMR instrument. The results obtained in this paper suggest that, to discriminate between different softwoods and hardwoods by NMR relaxation times, it is necessary to perform the NMR measurements below the FSP but at relative humidity higher than 75% that corresponds to the humidity at which the hemicellulose softening occurs. Moreover, both the transversal and longitudinal relaxation times of the cell walls bound water ($T_{1,1}$ and $T_{2,2}$) and polymers water reservoirs ($T_{1,2}$ and $T_{2,1}$) have to be quantified.

Specifically, the NMR relaxation times associated with the cell walls water reservoir allow to discriminate among hardwoods and softwoods and between two sub-clusters of hardwoods. Furthermore, according to results obtained below the FSP, small RH variations might affect the relaxation times. A controlled environment with constant relative humidity and temperature is therefore highly recommended to perform non-biased NMR relaxation time measurement. The NMR protocol presented in this study can be enhanced by studying a greater number of wood species and including further NMR parameters, such as the water diffusion coefficient (Stagno et al. 2021a; Stagno et al. 2021c), which may reflect the different hygroscopic behavior of softwood and hardwood connected to the different ultrastructural composition of their cell walls.

In conclusion, although limited to only 15 botanical species, the non-invasive NMR protocol performed by a portable instrument, allowed preliminary discrimination among species of softwood and hardwood, which could be useful for the wood industry and/or cultural heritage applications.

Declarations

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Valeria Stagno, Sara Ricci, and Silvia Capuani. The first draft of the manuscript was written by Valeria Stagno and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures

Figure 1

Schematic representation of the climatic chamber composed by A) a sealed Styrofoam box with B) the TROTEC BC06 thermo-hygrometer used to monitor RH and T. In case 1) where RH_{A1} was 46% only the NMR mouse and the wood samples were placed inside the chamber, whereas in case 2) a container with 130 ml of water was added to reach an RH_{A2} = 78% and in case 3) a saturated saline solution of K_2SO_4 was used to reach $RH_{A3/B}$ = 94%

Figure 2

(a) Plot of $T_{1,1}$ as a function of RH and (b) plot of $T_{1,2}$ as a function of RH for two softwoods (Russian silver fir and European Virginia pine) and for two hardwoods (white poplar and akatio walnut). Lines are for illustration purposes only

Figure 3

(a) Plot of $T_{2,1}$ as a function of RH and (b) plot of $T_{2,2}$ as a function of RH for two softwoods (Russian silver fir and European Virginia pine) and for two hardwoods (white poplar and akatio walnut). Lines are for illustration purposes only

Figure 4

Correlation plots among wood density and relaxation times components of the cell wall reservoir, (a) and (d), and of the polymers water reservoir, (b) and (c), at RH_B = 94%. The displayed parameters r and p indicate the correlation coefficient and the p-value, respectively. The dashed red line indicates the significant linear correlation.

Figure 5

Cluster plots obtained by k-means algorithm between $T_{1,1}$ and $T_{2,2}$ (a) and $T_{1,2}$ and $T_{2,1}$ (b) of the fifteen samples at RH_B = 94%. In (a) the centroid of cluster 1 is [74.39, 0.23] and of cluster 2 is [30.33, 0.20]. In (b) softwoods cluster has centroid of [1.22, 0.69] and hardwoods cluster of [1.67, 1.25]

Figure 6

Cluster plot obtained by hypothesizing three clusters in k-means algorithm between $T_{1,1}$ and $T_{2,2}$ of the fifteen samples at RH_B = 94%. For the cluster of hardwoods 1 the centroid is [1.66, 1.10], for hardwoods 2 is [2.05, 1.38], whereas for softwoods is [1.22, 0.69]

Figure 7

Schematic representation of cell wall polymers hydration in parallel with the RH increase. Hydroxyl groups of hemicellulose catch water molecules through hydrogen bonds. The $T_{1,1}$ and $T_{2,2}$ relaxation components measured in this work and associated with the cell wall-bound water can be considered as markers allowing to discriminate between softwood and hardwood on the base of their different hygroscopic behavior mainly due to their different hemicellulose amount. Hardwoods are characterized by a greater number of hemicellulose macromolecules that capture more water molecules during hydration. Therefore, on average, they show higher $T_{1,1}$ and $T_{2,2}$ than softwoods