Wood Science and Technology (2024) 58:1153–1180
https://doi.org/10.1007/s00226-024-01561-2

ORIGINAL

How thermal treatment affects the chemical composition and the physical, mechanical and swelling properties of Scots pine juvenile and mature wood

Magdalena Broda[1] · Carmen-Mihaela Popescu[2,3] · Kamil Poszwa[1] · Edward Roszyk[1]

Received: 6 February 2024 / Accepted: 10 May 2024 / Published online: 26 May 2024

Abstract

High variations in juvenile wood properties in the radial direction and its worse performance than mature wood make it less suitable for some applications and often treated as waste material. This study aimed to assess how thermal modification affects the chemical composition and the physical, mechanical and swelling properties of Scots pine juvenile and mature wood. An additional goal was to evaluate if the modification can equalise the differences in selected properties of juvenile wood to those of mature wood so that from waste material, juvenile wood can become a fully-fledged raw material for various industrial applications. Thermal treatment at 220 °C influenced wood chemical composition, degrading mainly hemicelluloses but also affecting cellulose and lignin, which resulted in a reduction of hydroxyls and carbonyl/carboxyl groups. These changes were more pronounced for mature than juvenile wood. It reduced mass loss and swelling rate, and increased swelling pressure in the tangential and radial directions to a higher degree for juvenile than mature wood. Changes in mechanical properties in compression were statistically significant only for mature wood, while wood hardness remained unaffected. Although the applied heat treatment improved the performance of juvenile wood by reducing its swelling rate, it did not equalise the examined properties between juvenile and mature wood. Since higher juvenile wood proportion is expected in the wood supply from the future intensively managed forests, there is still a need to find suitable modification methods or better processing techniques so that instead of being thrown away as waste, it could be used broadly in various industrial applications.

Extended author information available on the last page of the article

Introduction

Juvenile wood refers to wood formed usually in the first 10–20 annual rings adjoining the pith. The term comes from the cambial age when this part of the wood was produced. The wood located further from the pith towards the bark is called mature wood (Zobel and Sprague 2012; Moore and Cown 2017). Juvenile and mature wood distribution in a tree trunk is presented in Fig. 1.

Juvenile wood is characterised by high variations in wood properties in the radial direction (in the following annual rings). These include anatomical features like cell dimensions, cell wall thickness, microfibril angle in the S2 cell wall layer (MFA), and spiral grain angle, as well as other properties such as chemical composition, density, mechanical properties, susceptibility to internal checking, shrinkage and distortions during drying, latewood percentage content, resin content, and higher incidence of reaction wood. Some properties like MFA, longitudinal shrinkage, resin content and spiral grain angle typically decrease exponentially within the first 20 annual rings, while others, including cell wall thickness, density, latewood percentage content, modulus of elasticity and modulus of rupture, cell length, mechanical strength, moisture content, and transverse shrinkage increase. Then, in the wood of older cambial age (mature wood), most of these radial alterations between annual rings are more subtle and mainly result from changeable growing conditions (Kretschmann and Cramer 2007; Moore and Cown 2017).

Several researchers have investigated the variability of wood properties in the radial direction across a broad range of wood species (Bao et al. 2001; Alteyrac

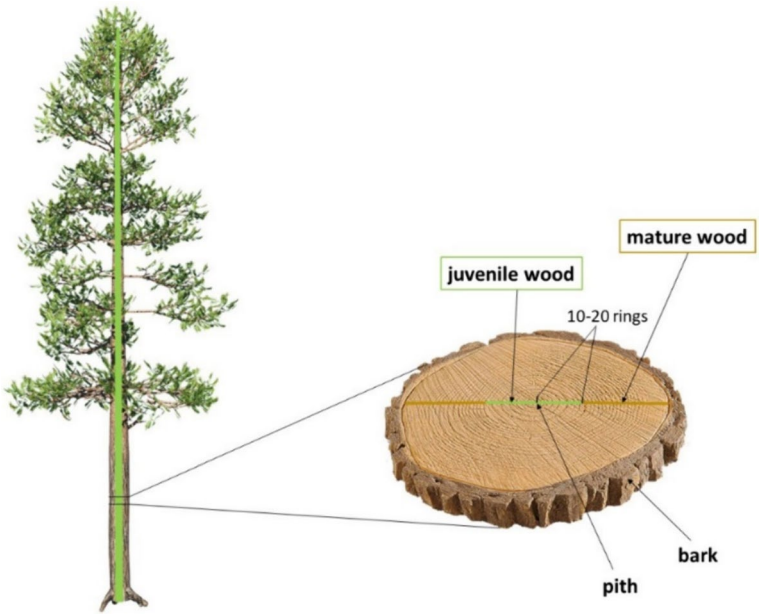

Fig. 1 Schematic distribution of juvenile and mature wood in a tree trunk and its cross-section (from pith to bark)

et al. 2006; Jordan et al. 2007; Mansfield et al. 2009; Bal and Bektaş 2013; Auty et al. 2014; Moore et al. 2015a; Kimberley et al. 2015; Sedlar et al. 2019; Mania and Nowicki 2020; Roszyk et al. 2020; Arslan et al. 2021; Sarkhad et al. 2021; Tumenjargal et al. 2022). Based on that research, the main differences between juvenile and mature wood properties have been recognised (Table 1).

In general, the properties of juvenile wood differ from those of mature wood, and they are less desirable from a processing and practical application perspective. They strongly impact the performance of end products since it depends on the anatomical, chemical, physical and mechanical properties of wood (Moore and Cown 2017; Huang et al. 2021; Zanuttini and Negro 2021). As a result of the radial variability of the wood properties, the end product of juvenile wood is expected to have different characteristics from that of mature wood.

Juvenile wood is considered a lower-quality raw material, particularly for solid-wood products that require good dimensional stability, high strength and stiffness (structural applications), and absence of defects, including resin features, knots and checks (appearance uses) (Moore and Cown 2015; Ruano et al. 2022). Due to low density and high microfibril angle, juvenile wood has higher longitudinal shrinkage and lower bending strength and modulus of elasticity compared to mature wood (Bhat et al. 2001; Adamopoulos et al. 2007; Ivković et al. 2009; Moore et al. 2012; Roszyk et al. 2020). The resulting poor dimensional stability manifests in inequivalent swelling or shrinkage in different anatomical directions under unstable humidity conditions. Moreover, due to the strong gradient in microfibril angle within juvenile wood, the timber is prone to twisting and warping during drying (Danborg 1994;

Table 1 Selected properties of juvenile versus mature wood (Moore and Cown 2017)

Wood qualities	The characteristics of juvenile wood in relation to mature wood
Anatomical features	Shorter cells (tracheids) with smaller diameters and thinner cell walls (where a lower contribution of the S2 layer in relation to the double cell wall thickness characterises softwoods)
Microfibril angle	Higher MFA, with values typically higher for softwoods (40–50°) than hardwoods (25–35°)
Spiral grain angle	Higher spiral grain angle typically reaches a maximum in the first few annual rings from the pith and then drops to lower values in mature wood
Annual rings	Wider growth rings with lower latewood percentage
Reaction wood	Increased incidence of reaction wood—compression wood in softwoods and tension wood in hardwoods
Density	Density is typically lower by 10–20%. In some pine species, mature wood can be more than twice as dense as juvenile wood
Mechanical properties	Lower mechanical strength and modulus of elasticity resulted from lower density and higher microfibril angle
Shrinkage, distortions	Higher longitudinal shrinkage, which, together with high microfibril angle, spiral grain angle and incidence of reaction wood, increases the tendency for distortion
Chemical properties	Higher lignin content in the cell wall at lower cellulose content. Higher resin content in wood
Other features	Increased susceptibility to internal checking

Wagner et al. 2002; Soares et al. 2019). All these can cause severe problems for wooden structures, even if they impact only a certain number of timber elements (Barnett and Bonham 2004; Moore et al. 2009; Lachenbruch et al. 2011). The only areas for juvenile solid-wood utilisation are interior finishing and decorative elements, as well as some furniture designs where unique grain patterns are of higher importance than the mechanical strength of wood. Larger cells and lower density can be advantageous by making this part of wood easier to work with and providing an end product with unique aesthetic properties (Paes et al. 2015; Blackburn et al. 2021).

The influence of juvenile wood on the characteristics of reconstituted panel products (i.e., flakeboards, particleboards and fibreboards) is much smaller than that of solid-wood products. Although the dimensional stability of panels made of juvenile wood was lower compared to those made of mature wood, the mechanical properties were usually similar (Pugel et al. 1990; Shi et al. 2005; Pecho et al. 2005; Cloutier et al. 2007; Moore and Cown 2017). Nevertheless, the proportions of juvenile to mature wood should be limited to ensure the satisfactory performance of end products.

In the case of laminated wood products, such as glulam, cross-laminated timber (CLT), laminated veneer lumber (LVL), and plywood, utilisation of juvenile wood can be possible only as inner layers, while outer zones should be made of a material of higher strength and stiffness to mitigate the adverse impact of juvenile wood on the mechanical properties of an end product (Lee et al. 2005; Nazerian et al. 2011; Hughes 2015; Brandner et al. 2016; Moore and Cown 2017).

On the contrary, the pulp and paper industry is an application where juvenile wood can be preferentially used, particularly in the production of fine writing and magazine papers. Lower density and a higher proportion of larger, thin-walled cells make the pulping process easier and thus more economically viable, and the paper has sufficient tensile strength and optical behaviour (Corson and Richardson 2007; Severo et al. 2013; Moore and Cown 2017). However, due to generally lower mechanical strength and stability, juvenile wood is unsuitable for manufacturing Kraft pulps that require high tear strength, boards for packaging grades or other paper products such as high-quality printing paper (Corson 1984, 1991; Myers 2002; Moore and Cown 2017).

Juvenile wood formation is a natural process that occurs in all tree species. The size of the juvenile wood zone and its properties are affected by environmental, genetic and silvicultural factors (Zobel and Sprague 2012).

The presence of juvenile wood typically did not affect wood processing because the primary raw material resource was old-growth trees from natural forests where the early growth of trees was suppressed by surrounding plants so that the proportion of juvenile wood was small (Larson 2001; Zobel and Sprague 2012). Over the past few decades, however, genetic manipulations focused mainly on improving tree growth and stem form (Hannrup et al. 2004; Gapare et al. 2007; Wu et al. 2008), the intensification of forestry and the pursuit of more cost-efficient production of raw materials inevitably lead to a substantial reduction in rotation length thus an increase in the proportion of juvenile wood in managed planted forest stands. As a result, although the general productivity gains increase, the general quality of raw material available for the wood

industry declines significantly (Zobel 1984; Zobel and Sprague 2012; Antony et al. 2012; Moore et al. 2015b; Zhang et al. 2021).

Understanding the impact of juvenile wood on the performance of end products is necessary to devise effective processing strategies to fully utilise forest resources with increasing content of this material for industrial purposes. In order to address the issues caused by juvenile wood, wood processors may need to modify their systems to account for the growing amount of juvenile wood in future resources or modify the performance requirements for their products. These may be achieved by developing new types of wood products that are less adversely affected by juvenile wood drawbacks or using specific modification methods to improve juvenile wood performance (Moore and Cown 2017).

One of the common methods for improving wood performance is a thermal modification developed to enhance its durability and dimensional stability. Several production plants worldwide utilise this well-established commercial technology in open or closed systems that mainly differ in the medium used to exclude oxygen and the treatment temperature (Sandberg and Kutnar 2016; Gérardin 2016; Hill et al. 2021). The thermal modification affects wood chemical composition, resulting in the degradation of hemicelluloses, an increase in cellulose crystallinity and changes in amorphous cellulose structure. It also leads to lignin depolymerisation in the first stage and further auto-condensation by forming new methylene bridges between aromatic rings. The rearrangement of cell wall polymers caused by thermal treatment reduces wood hygroscopicity, which translates into enhanced dimensional stability and biological durability. It increases wood surface hardness but usually reduces its other mechanical properties, such as stiffness, bending, shear and compression strength (Tjeerdsma et al. 1998; Yildiz and Gümüşkaya 2007; Hill 2007; Hannouz et al. 2015; Candelier et al. 2016).

In this research, Scots pine wood, one of the most common species grown in managed forests and used for industrial purposes in central Europe, was thermally modified to assess how thermal treatment affects the selected physical and mechanical properties of juvenile wood compared to mature wood. To better comprehend these changes, the effect of thermal modification on the chemical wood composition was investigated using the Fourier Transform Infrared Spectroscopy (FTIR) technique. The results will enable a better understanding of the relations between anatomical features and chemical composition of juvenile wood and its susceptibility to thermal treatment compared to mature wood. It will also help to evaluate if the modification can equalise or at least significantly limit the differences in selected properties of juvenile wood compared to those of unmodified or modified mature wood so that from waste material, in the past usually discarded in the production process, juvenile wood can become a fully-fledged raw material for various industrial applications.

Materials and methods

Materials

The research material was Scots pine (*Pinus sylvestris* L.) from a typical forest purchased from commercial timber merchants in the Wielkopolska Region, Poland.

Methods

Sample preparation

Wood samples for individual experiments were cut from pine plank according to the scheme presented in Fig. 2.

Determining the transition from juvenile to mature wood

Selection of juvenile and mature wood zones for the study was based on the length of tracheids, the width of annual rings and the percentage content of latewood (Clark et al. 2006; Mansfield et al. 2016; Chen et al. 2016).

The tracheid length was measured in wood macerates of individual annual rings using a digital microscope 4 K Keyence VHX-7000N (KEYENCE, Osaka, Japan) with an accuracy of 0.01 mm. To prepare wood macerates, early- and latewood zones from selected annual rings were collected in separate weighing bottles and poured with a maceration mixture consisting of equal parts of glacial acetic acid and 30% hydrogen peroxide. Maceration was conducted at 60 °C for 48 h. Then, the

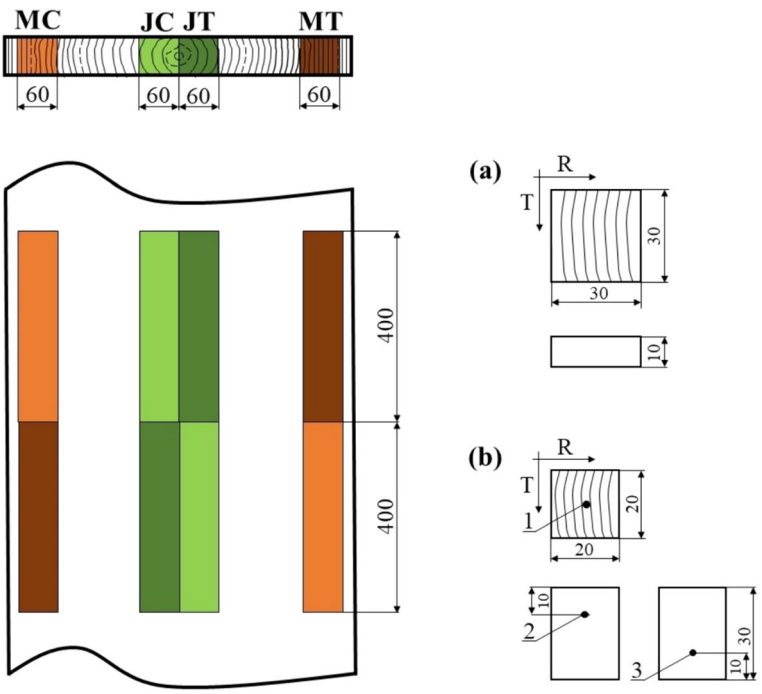

Fig. 2 A scheme for the preparation of juvenile (J) and mature (M) wood samples used for the measurements of wood swelling pressure and kinetics and FTIR analysis (**a**), and mechanical properties (1, 2, 3 –points for wood hardness measurements in the longitudinal, tangential and radial direction, respectively) (**b**); C–control wood (control), T–thermally-treated wood; all dimensions given in mm

macerated wood anatomical elements were washed with water and measured (Fabisiak and Fabisiak 2021). The measurements were taken for every three annual rings from the 3rd to the 51st and every five rings from the 51st to the 86th. Thirty tracheids were measured in both early- and latewood from each annual ring, and then average tracheid length values were calculated for each.

The width of individual annual rings and latewood zones were measured using a BIOtronik® BEPD-19 (BIOtronik, Warsaw, Poland).

Thermal modification

Juvenile and mature wood samples were subjected to thermal treatment according to the industrial method described in the ThermoWood® Handbook (Lahtela 2021). The process consisted of an initial phase in moist air followed by heating in superheated steam after the temperature reached 130 °C, a maximum heating phase (temperature of 220 °C and duration time of 3 h), and a cooling phase with superheated steam followed by cooling in moist air only. Before modification, wood samples were dried to an oven-dry state to avoid hydrolysis of the material during the thermal treatment (Fengel and Wegener 2011; Rautkari and Hill 2014). The mass loss of thermally modified wood was determined in relation to the oven-dry mass of wood before the modification process.

Infrared spectroscopy

Fourier Transform Infrared Spectroscopy was used to analyse the wood chemical composition and investigate the changes caused by thermal treatment in both juvenile and mature wood. The samples were powdered and sieved, and the powder fraction particles with a diameter of <0.2 mm were retained for the analysis. Infrared spectra were recorded in the 4000–400 cm^{-1} region with a resolution of 4 cm^{-1}, using a Bruker ALPHA FT-IR spectrometer (Bruker, Billerica, MA, USA) in KBr pellets. Both sample powder and KBr were carefully weighted, using 3 mg wood powder and 200 mg KBr for each pellet. For each sample, five spectra were recorded, averaged and processed using OPUS 7.5 software. The second derivatives were calculated using Savitsky-Golay method with 21 points. For principal component analysis (PCA) and hierarchical cluster analysis (HCA), the 1550–840 cm^{-1} region from the FTIR spectra was used. The processing was done in the Origin 2023b program (OriginLab Corporation, Northampton, MA, USA).

Physical properties

Wood density and moisture content Wood samples were conditioned for two weeks at a temperature of 23 ± 2 °C and air relative humidity of 35 ± 3% before all measurements. The density of seasoned samples before and after treatment was determined by employing a stereometric method according to ISO 13061-2 (ISO 13061-2 2014). Wood mass and dimensions were measured using an analytical balance with an accuracy of 0.001 g (Sartorius GmbH, Göttingen, Germany) and a digital calliper with an accuracy of 0.01 mm, respectively.

Wood moisture content after conditioning was determined using a standard oven-drying method at 103 ± 2 °C and calculated as a ratio of the mass of water (a difference between the mass of wood after conditioning and at a completely dry state) to the mass of a dry sample.

Additionally, part of the samples intended for swelling measurements were oven-dried at a temperature of 103 ± 2 °C to a constant weight, and their density at a completely dry state was calculated based on dry masses and dimensions.

Kinetics of radial and tangential swelling and wood swelling pressure Wood swelling is an increase in dimensions caused by increased bound water content. The maximum degree of linear swelling is an increase in wood dimensions caused by an increase in moisture from a completely dry state to the fibre saturation point and is expressed as a percentage of wood dimensions in a completely dry state. Since wood is an anisotropic material, it swells differentially in different anatomical directions. Generally, from dry to wet state (fibre saturation point), wood swells about 10% in the tangential direction, 5% in the radial directions, and only 0.1% in the longitudinal direction (Mantanis et al. 1994; Arzola-Villegas et al. 2019).

Wood swelling in the tangential and radial direction was measured for control and treated juvenile and mature wood samples with dimensions of 30 × 30 × 10 mm in the radial (R), tangential (T) and longitudinal (L) directions, respectively. Six replicates with similar density and the pattern of annual rings per variant were used for the measurement. Before the experiment, wood samples were oven-dried at a temperature of 104 °C to a completely dry state. Each specimen was placed in a support stand equipped with a flatbed micrometre so that the measurement direction was tangential or radial in relation to the wood anatomical directions. Then, the stands with samples were placed in water, and the measurements started. The micrometres indications were recorded at specified intervals. For each interval, the degree of swelling was calculated using the following equation:

$$\alpha = \frac{\Delta l}{l_0} \times 100$$

where α is the degree of swelling, Δl is the dimension increase in the measured direction, and l_0 is the dimension of a completely dry sample in the direction of measured swelling.

Swelling pressure is the maximum stress in wood during restrained swelling, or, in other words, the stress required to prevent the wood from swelling completely (Perkitny and Kingston 1972; Mazzanti et al. 2014).

The experiment was performed on the prototype device specially designed for this purpose (Molinski and Raczkowski 1980), allowing for the measurement of the total force needed to retract the permitted linear swelling. Swelling pressure of completely dry control and treated juvenile and mature wood was measured in the radial and tangential directions following the procedure described before (Roszyk et al. 2024), using three replicates of each variant per direction (sample dimensions were 30 × 30 × 10 (R × T × L, like in the experiment described above). Directly before the measurement, each sample was preloaded to eliminate contact deformations.

Swelling pressure was calculated as the quotient of the swelling force and the cross-sectional area of a completely dry specimen according to the following equation:

$$\sigma cp = \frac{P}{A}$$

where σcp is the swelling pressure (in MPa), P is the value of swelling force (N), and A is the cross-sectional area of the sample in a completely dry state.

Mechanical properties

Compression tests and the Brinell hardness method were used to determine the selected mechanical properties of unmodified and modified juvenile and mature pine wood. Methods selection was based on the fact that thermally modified wood is often used as a flooring material; therefore, its hardness (on which the abrasion resistance depends) and compression strength are the most crucial mechanical parameters. Moreover, since juvenile and mature wood differing in density are the research materials, the compression tests were chosen because of the highest relation between wood density and strength from all strength testing methods. Also, due to material restrictions related to the use of juvenile wood and a thermal modification performed at a laboratory scale, the mechanical tests that require as small samples as possible were selected to ensure enough replicates of similar wood specimens to obtain reliable results.

The data obtained were statistically analysed using STATISTICA 13.3 software (TIBCO Software Inc., Palo Alto, CA, USA). One-way analysis of variance (ANOVA) followed by a post-hoc Tukey's honest significance test was applied to find means that are significantly different from each other (significance was established at $p < 0.05$).

Compression tests Compression tests in the longitudinal direction (along the grain) were performed using a numerically controlled test machine, Zwick Z050TH (Zwick/Roell, Ulm/Germany). Wood specimens with dimensions 20 × 20 × 30 mm (R × T × L) were used in the study, with eight replicates of each variant. The modulus of elasticity (MOE), stress at proportionality limit (σ_{pl}), and stress to failure (so-called compressive strength—Rc_L) were determined. Additionally, specific modulus of elasticity (sMOE), specific stress at proportionality limit ($s\sigma_{pl}$) and specific stress to failure (sRc_L) were calculated as the MOE, σ_{pl}, and Rc_L to wood density ratios, respectively.

Brinell hardness The hardness of unmodified and modified juvenile and mature wood in all three anatomical directions was determined using the Brinell method (EN 1534 2000). Eight replicates were used per variant. The measurements were performed on an Amsler universal testing machine (Amsler UTM). A spherical steel indenter with a diameter of 10 mm was pressed against the sample surfaces (Fig. 2b) with an increasing force to 500 N for 15 s, then the maximum load of 500 N was kept for the next 30 s, and finally, the indenter load was reduced to its initial value during the next 15 s.

The minimum and maximum indentation diameters were measured with a Brinell magnifier with an accuracy of 0.1 mm. Then, the averaged values were used to calculate hardness (HB) following the equation:

$$HB = \frac{2F}{D\pi(D - \sqrt{D^2 - d^2}}$$

where F is the loaded force (N), D is the diameter of the pressed indenter (mm), and d is the average measured indentation (mm).

Results

Anatomical characteristics of juvenile and mature pine wood

Figure 3 presents a set of anatomical parameters measured for studied pine wood. An apparent decrease in the width of annual rings (Fig. 3C) and an increase in the length of tracheids (Fig. 3A and B) and percentage content of latewood (Fig. 3D) in successive annual rings can be seen to about fifteenth increment, and then the values stabilise. Based on the graphs in Fig. 3 and the fact that juvenile wood differs from mature wood by the values of the presented parameters and their gradient concerning the ring number and distance from the pith (Moore and Cown 2017), the transition zone between juvenile and mature wood was defined as 15th annual ring.

FTIR

Thermal modification resulted in wood mass loss of 6.6% for juvenile (J) and 5.1% for mature (M) wood. Alterations in the wood chemical composition were characterised using the FTIR technique. Infrared spectra and their corresponding second derivatives for the control and thermally modified juvenile and mature wood are presented in Figs. 4 and 5. Figure 4 shows the 3750–2730 cm^{-1} region, assigned to different stretching vibrations of hydroxyl groups and hydrogen (H) bonds, as well as to methyl and methylene groups from the wood structure (Popescu et al. 2011; Torniainen et al. 2021). Due to the thermal treatment of mature wood, the large band from 3430 cm^{-1} shifted to 3416 cm^{-1}. It was caused by modifications appearing in the component bands, namely: the band from 3576 cm^{-1} (in MC spectrum), assigned to absorbed water weakly bound and intramolecular H bond in a phenolic group (in lignin), is shifted to 3569 cm^{-1} in MT spectrum and decreased in intensity; the band from 3443 cm^{-1}, assigned to O2–H2···O6 intramolecular H bonds stretching modes, presents a slight decrease in intensity; the bands from 3336 and 3263 cm^{-1} (in MC spectrum), assigned to O5–H5···O3 intramolecular H bonds in cellulose and to O6–H6···O3 intermolecular H bonds in cellulose I_β, are shifted to 3342 and 3274 cm^{-1} in MT spectrum and increased in intensity; while the band from 3211 cm^{-1} (in MC spectrum) assigned to O6–H6···O3 intermolecular in cellulose I_α is shifted to 3219 cm^{-1} in

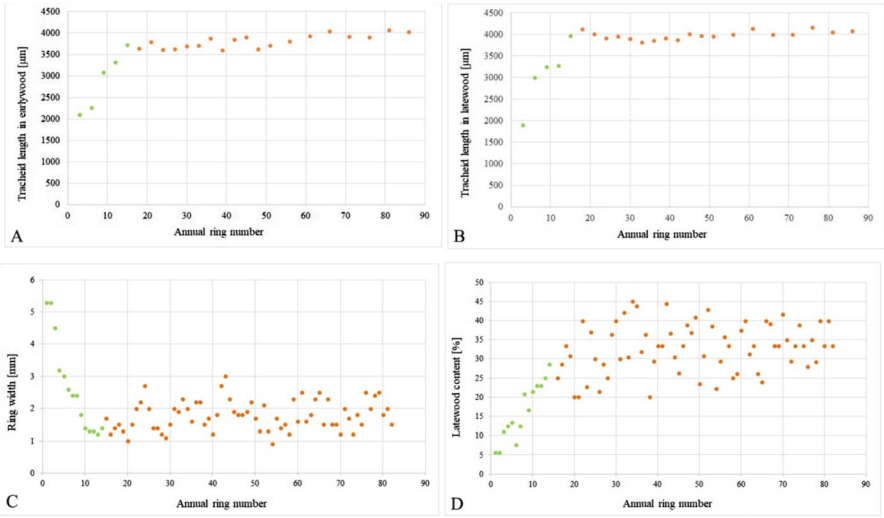

Fig. 3 Average values of tracheid length in earlywood (**A**) and latewood (**B**), ring width (**C**), and latewood content (**D**) in the following annual rings counted from pith to bark; green dots represent juvenile wood, brown dots—mature wood (color figure online)

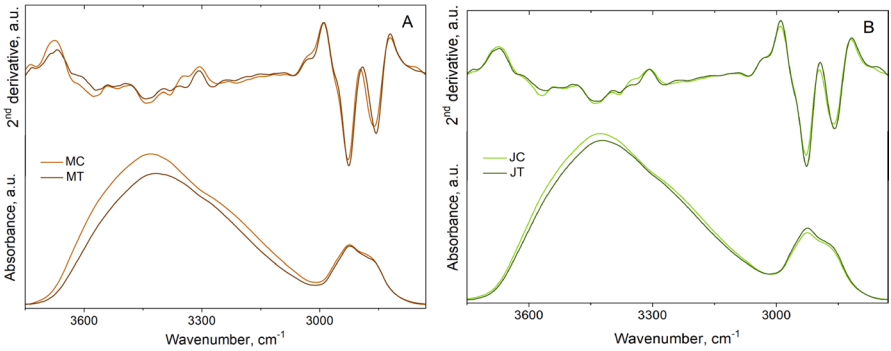

Fig. 4 Infrared spectra and their second derivatives for the control (C) and thermally treated (T) mature (M) and juvenile (J) pine wood in the 3750–2700 cm^{-1} region

MT spectrum (Kondo 2005; Popescu et al. 2011). These modifications are well-visible from the second derivative of the infrared spectra (see Fig. 4A).

Figure 4B shows that the modifications appearing in the juvenile wood spectra following thermal treatment are less pronounced than for mature wood. In this case, the large band from 3426 cm^{-1} in the JC spectrum is shifted to 3421 cm^{-1} in the JT spectrum. From the second derivative spectra of juvenile wood, the following modifications were identified: the band from 3567 cm^{-1} (in JC spectrum) is shifted to 3558 cm^{-1} (in JT spectrum) and shows a slight increase in intensity after thermal treatment; the band from 3342 cm^{-1} (in JC spectrum) is shifted

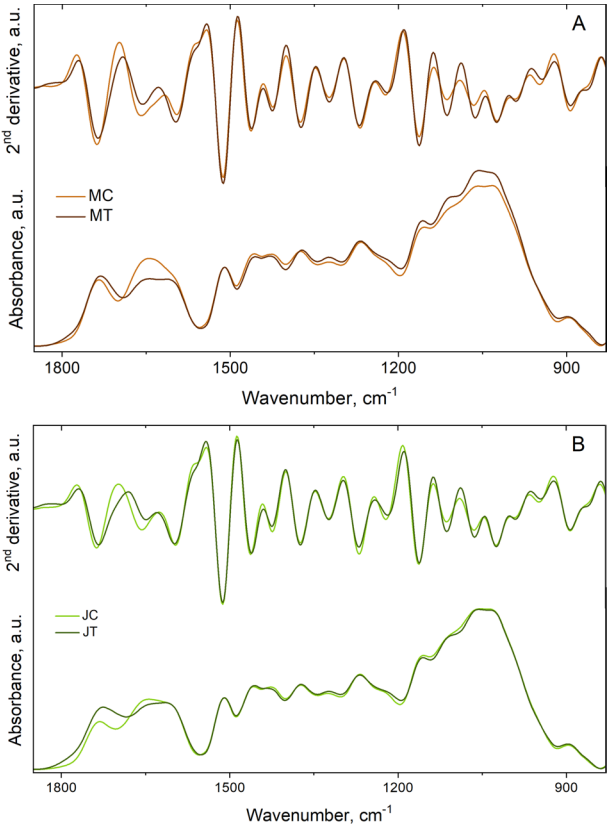

Fig. 5 Infrared spectra and their second derivatives for the control (C) and thermally treated (T) mature (M) and juvenile (J) pine wood in the 1850–800 cm^{-1} region

to 3345 cm^{-1} and increases in intensity (in JT spectrum); while the band from 3262 cm^{-1} (in JC spectrum) is shifted to 3273 cm^{-1} (in JT spectrum).

Table 2 shows hydrogen bond energies for each O–H stretching band calculated using Struszczyk's formula (Struszczyk 1986) and hydrogen bonding distances calculated based on the equation given by Pimentel and Sederholm (1956).

The calculated energies vary between the control mature and juvenile wood, as well as between control and thermally treated wood. The hydrogen bonding energy for the band assigned to absorbed weakly bound water and an intramolecular hydrogen bond in a phenolic group (in lignin) is higher in JC compared to MC and increases after thermal treatment for both types of wood compared to control wood. A similar trend is observed for the energies of the O2–H2···O6 intramolecular and O6–H6···O3 intermolecular hydrogen bonds in cellulose I_β hydrogen bonds (which give bands at about 3440 and 3270 cm^{-1}). All other types of hydrogen bonds present higher energies for the mature wood than the juvenile one. Analysing the thermally treated mature (MT) and juvenile (JT) wood, the energies are increasing for the

Table 2 The energy of the hydrogen bonds and the hydrogen bonding distance calculated for the studied samples

Samples	Hydrogen bonding energy (E_H) (kJ/mol)					
	3570 cm^{-1}	3440 cm^{-1}	3380 cm^{-1}	3340 cm^{-1}	3270 cm^{-1}	3215 cm^{-1}
MC	5.32	14.89	19.34	22.58	27.83	31.57
MT	5.82	14.89	19.42	22.15	27.04	30.99
JC	5.97	15.03	19.20	22.15	27.90	31.35
JT	6.62	15.32	19.49	21.93	27.11	31.14
Samples	Hydrogen bonding distance (R) (Å)					
	3570 cm^{-1}	3440 cm^{-1}	3380 cm^{-1}	3340 cm^{-1}	3270 cm^{-1}	3215 cm^{-1}
MC	2.8346	2.8045	2.7905	2.7804	2.7639	2.7522
MT	2.8330	2.8045	2.7903	2.7817	2.7664	2.7540
JC	2.8325	2.8041	2.7910	2.7817	2.7637	2.7528
JT	2.8305	2.8032	2.7901	2.7824	2.7662	2.7535

hydrogen bonds, which give bands at about 3570, 3440, and 3380 cm^{-1} and decrease for the other three. Variations in the energy values indicate different positions of the specified bands in juvenile wood compared to mature one, both before and after the thermal treatment. A decrease or increase of the hydrogen bonding energy is due to a shifting of the corresponding vibration bands to higher or lower wavenumber. The values of the hydrogen bonding distance vary similarly to the energies, although the variation is very low. An increase in the hydrogen bonding energy may mean a more compact structure, higher bonding energy induces higher activation energy for those bonds to break.

Further modifications were also observed in the fingerprint region between 1850 and 830 cm^{-1} (see Fig. 5). Figure 5A presents the spectra and their second derivatives of the control (MC) and thermally treated (MT) mature wood. In this region, the modifications observed are mainly assigned to C=O, C–O and C–O–C groups. The band from 1738 cm^{-1} (in MC spectrum), assigned to C=O stretching vibration of carboxyl and acetyl groups in hemicelluloses (Popescu et al. 2011; Torniainen et al. 2021), decreases in intensity and is shifted to 1734 cm^{-1} (in MT spectrum). The band from 1659 cm^{-1}, assigned mainly to absorbed O–H from water molecules (Popescu et al. 2011; Torniainen et al. 2021), decreases in intensity in the MT spectrum. Further, the bands from 1424, 1373, 1323, 1163, 1113, and 1066 cm^{-1} assigned to C–H deformation and stretching vibration in lignin and carbohydrates, C_l–O stretching vibration in syringyl derivatives, and C–O–C stretching vibration in cellulose and hemicelluloses show slight increase in intensity, while the bands from 1267, 1226 and 949 cm^{-1} assigned to C–O stretching vibration in lignin, C–O–C stretching vibration mode of the pyranose ring and C–O and C–C stretching vibration of the ring in cellulose and hemicelluloses decreases in intensity in thermally treated sample spectrum (Faix and Böttcher 1992; Pandey and Pitman 2003; Popescu et al. 2011). At the same time, the bands from 1226, 1066, 992 and 949 cm^{-1} (in

MC spectrum) assigned to C–O–C stretching vibration mode of the pyranose ring, C–O stretching vibration mainly from C(3)–O(3)H in cellulose I and C–O and C–C stretching vibration of the ring in cellulose and hemicelluloses are shifted to 1221, 1060, 989 and 943 cm^{-1} (in MT spectrum) (Popescu et al. 2011; Torniainen et al. 2021).

Figure 5B presents the spectra and their second derivatives of the control and modified juvenile wood in the 1850–830 cm^{-1} region. In this case, a decrease in intensity of the band from 1736 cm^{-1} with slight shifting to 1734 cm^{-1} was observed for the JT sample. As in the previous case, the band from 1656 cm^{-1} (in JC spectrum) decreases in intensity and is shifted to 1649 cm^{-1} (in JT spectrum), as well as the bands from 1270, 1221 and 949 cm^{-1} (in JC spectrum) decrease in intensity following the thermal treatment. At the same time, the bands from 1373, 1114 and 1065 cm^{-1} increase in intensity in the JT spectrum compared to the JC one. No real shift towards a lower or higher wavenumber of the bands' maxima was identified in this case.

In order to evidence the variations between the lignin and carbohydrates in the studied samples, the ratios of the integral area of the band from 1510 cm^{-1}, characteristic to lignin (as belongs purely from C=C aromatic skeletal stretching vibration), against different carbohydrate characteristic bands from 1730, 1373, 1155 and 895 cm^{-1} (assigned to C=O stretching vibration of carbonyl, carboxyl and acetyl groups, C–H deformation in carbohydrates and C–O–C stretching vibration in carbohydrates) were calculated—see Fig. 6.

The intensity ratio of the lignin characteristic band from 1510 cm^{-1} against different carbohydrate characteristic bands indicates variations between the mature and juvenile wood as well as between control and thermally modified wood. An increase in the intensity ratio means increased lignin values compared to carbohydrate-specific groups. For example, the value of the I_{1510}/I_{1730} from mature wood, both control and thermally treated, is smaller when compared to the juvenile wood ratio value, but at the same time, it decreases for JT compared to JC. A similar trend is also observed for the I_{1510}/I_{1373} ratio, while the I_{1510}/I_{895} ratio presents different trends—the value for MT is much higher than for the MC, the value for JC is higher than that for MC, but the values of JT is lower than that for MT. This shows that the variation of the C–O–C bond in juvenile wood due to the treatment is lower than in mature wood.

Principal component analysis (PCA) gives detailed information about the differences which may appear between series of similar wood samples (Chen et al. 2010; Popescu et al. 2013, 2020); thus, the chemical changes or chemical differences in the wood structure of mature and juvenile wood and their physical properties as a result of structural differences and thermal treatment are reflected in both PC scores and loadings. In Fig. 7A, the plot of PC1 (principal component factor (1) versus PC2 (principal component factor (2) is presented. PC1 describes 98.4%, and PC2 describes 1.1% of data variance; therefore, the variances existing in the wood spectra can be captured using these two dimensions instead of the initial spectra.

The JC samples presented positive values on PC1 and PC2, while MC presented negative values for PC1 and close to zero for PC2. Thermally treated mature wood (TM) presents negative values for both PC1 and PC2, while JT presents PC2 values

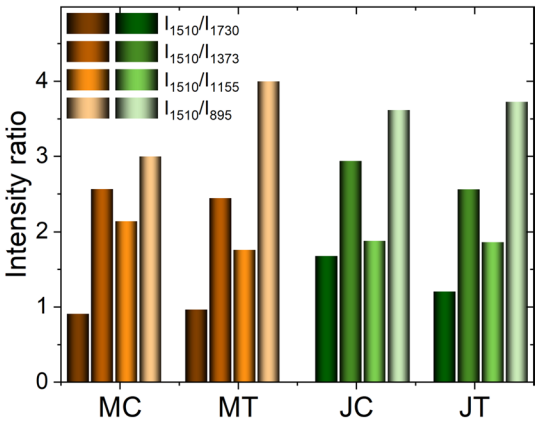

Fig. 6 Variation of the intensity ratio of lignin characteristic band from 1510 cm^{-1} against different carbohydrate characteristic bands from 1730, 1373, 1155 and 895 cm^{-1} for control (C) and treated (T) juvenile (J) and mature (M) pine wood

close to 0 and slightly positive values of the PC1 score. From here, we can conclude that PC1 is the most informative latent variable for the description of chemical differences between mature and juvenile wood, while the PC2 score separates mainly the modified samples from the control ones. The loading plots (Fig. 7B) indicate the chemical features responsible for the grouping of the samples along the PC1 and PC2. They can be used to understand how much each wavenumber contributes to the meaningful variation in the data and to interpret variable relationships. Thus, PC1 indicates variations in the whole evaluated region between the mature and juvenile wood, while PC2 presents positive values mainly for lignin bands and negative ones for carbohydrates. Positive bands show an increase in lignin content, while the negative ones indicate a decrease in hemicelluloses content after the thermal treatment.

In addition to PCA, a hierarchical cluster analysis (HCA) was performed, which allowed us to emphasize the natural grouping in the data set and made it possible to visualise the relationships among different groups (Chen et al. 2010; Popescu et al. 2013, 2020).

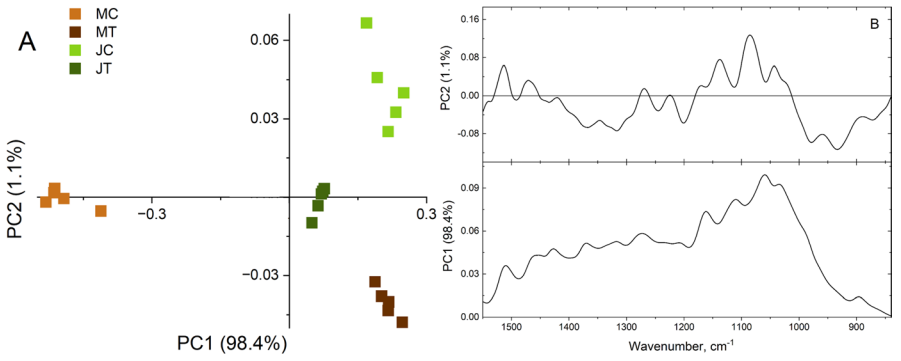

Fig. 7 PC1 versus PC2 scores plot (**A**) and loading plots (**B**) of the control (C) and treated (T) juvenile (J) and mature (M) pine wood

The dendrogram of the analysed wood samples is presented in Fig. 8, showing two main clusters: the MC is in the first one, and the other three samples are in the second one. The second cluster is divided into two other sub-clusters, separating the MT and JC samples from the JT samples. A third sub-cluster separates the MT samples from the JC samples. As observed from the PC scores plot, it was a higher difference between the MC and the other three samples, and further, JT is separated from the other two samples as well.

During thermal modification of wood in moist conditions (depending on water quantity in the surrounding environment), the degradation reactions take place faster than in dry conditions. At the same time, the hydrolysis reactions occur before the oxidation ones. The water molecules act as a catalyst for the activation of the reactions—hydronium-catalysed reactions, with the further generation of acetic acid due to the hydrolysis of acetyl groups from hemicelluloses (Garrote et al. 2001; Popescu et al. 2021). These induce modifications mainly in hemicelluloses but also in lignin and cellulose to some extent and lead to the formation of saturated and unsaturated low-molecular compounds. Moreover, the presence of water molecules can prevent oxidation reactions in favour of hydrolysis. A certain amount of newly formed low-molecular compounds, which vary in quantity and composition, remains trapped in the wood structure.

The modifications observed in the spectra of the mature and juvenile wood indicate the reduction of hydroxyl, as well as the amount of carbonyl/carboxyl groups and an apparent increase of C–O and C–O–C groups from lignin and carbohydrates. The latter can also be due to the presence of these groups in the newly formed low-molecular compounds trapped in the wood structure.

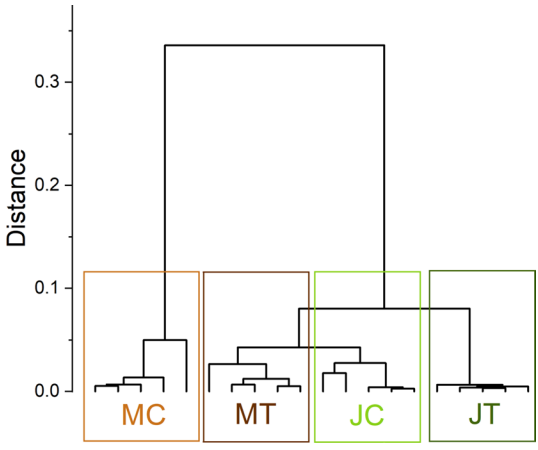

Fig. 8 HCA plots of the control (C) and treated (T) juvenile (J) and mature (M) pine wood

Swelling properties

Kinetics of radial and tangential swelling

The rate and extent of radial and tangential wood swelling are presented in Fig. 9. Generally, for all wood variants, the values of linear swelling were higher in the tangential direction than in the radial direction, which is consistent with the current state of knowledge (Patera et al. 2013; Arzola-Villegas et al. 2019). The tangential swelling of mature wood was higher than that of juvenile wood, but their radial swelling was similar. However, mature wood swelled faster. Thermal treatment considerably reduced the extent of wood swelling and its rate for both wood types measured in both anatomical directions.

Swelling pressure

The maximum swelling pressure recorded for studied pine wood is presented in Fig. 10. Generally, the stress needed to restrain swelling was higher in the T than in the R direction. However, it cannot be explained by unrestricted wood swelling of similar order, as described above (see Sect. "Kinetics of radial and tangential swelling".), because it is known from literature that wood swelling pressure has no direct correlation with the rate of its moisture-induced deformations (Rybarczyk and Ganowicz 1974)—the smallest wood deformations are observed along the grains while swelling pressure in this direction is much higher than across the grains, for which moisture-induced deformations are much more pronounced. For JC and MC samples, swelling pressure was similar in the R direction, but in the T direction, it was higher for mature wood. Thermal treatment increased wood swelling pressure in

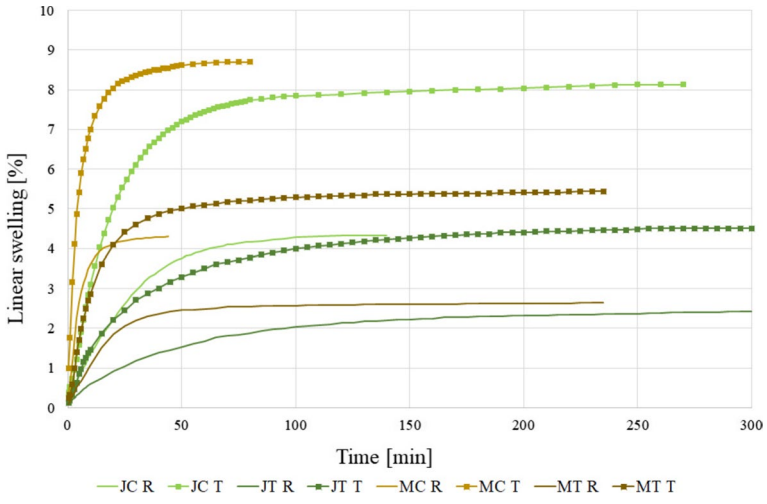

Fig. 9 Kinetics of linear swelling in tangential and radial directions measured for control (C) and thermally modified (T) juvenile (J) and mature (M) pine wood in tangential (T) and radial (R) directions

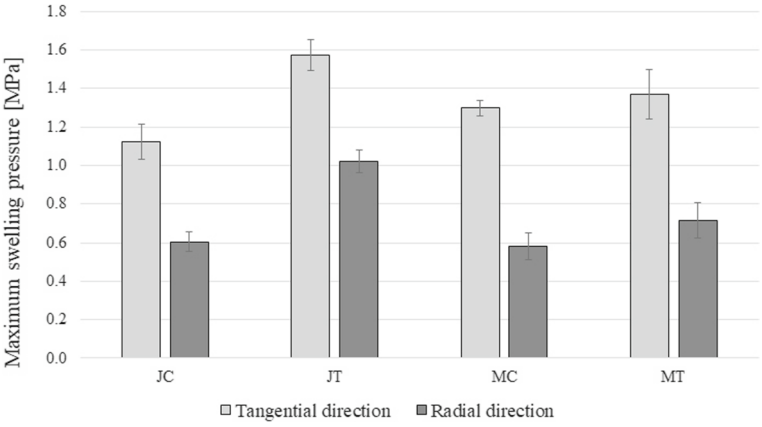

Fig. 10 Maximum swelling pressure in tangential and radial directions measured for control (C) and thermally modified (T) juvenile (J) and mature (M) pine wood; error bars represent the standard deviation

all cases. For juvenile wood, however, the increase was higher than for mature wood, and it was 40% in T and 70% in R compared to 5% in T and 24% in R for mature wood. It is important to note that juvenile wood swells much slower than mature wood (about 7.5 times), and thermally treated wood swells slower than control one (about 3 times for juvenile and 5 times for mature wood). Maximum swelling pressure was recorded after 13 min (R) and 17 min (T) for JC, 45 min (R) and 48 min (T) for JT, 3 min (R) and 2 min (T) for MC, and 16 min (R) and 14 min (T) for MT.

Mechanical properties

Table 3 shows the mechanical parameters of pine wood measured in the compression test. Although there are differences in moisture content between control and thermally treated samples, they do not alter the mechanical parameters much since they all remain in the range of low values (Côté and Kollmann 1984); therefore, they can be neglected in the discussion. The modulus of elasticity (MOE) for JC was 27% lower than for MC. Thermal modification reduced their values for both wood types, but the decrease was less pronounced for juvenile wood (about 10%) than mature wood (27%). The reduced MOE of MT was similar to the initial MOE of JC. No statistically significant differences were observed between JC, JT and MT MOE values. Considering the specific MOE (independent of wood density) of analysed samples, thermal treatment reduced the elasticity of mature wood, but that of juvenile wood was left unaltered.

Stress at the proportionality limit (σ_{pl}) was slightly higher for JC compared to MC. The thermal modification increased its value for both wood types, and the change was again more pronounced for mature wood (an increase of 31% for MT vs 20% for JT). The specific σ_{pl} was also higher for JC than MC, and thermal treatment changed its value by 32% for JT and 38% for MT.

Table 3 Mean values of moisture content (MC), bulk density after conditioning (ρ), modulus of elasticity (MOE), specific modulus of elasticity (sMOE), stress at proportionality limit (σ_{pl}), specific stress at proportionality limit (σ_{pl}), strain at proportionality limit (ε_{pl}), compressive strength (RcL), specific compressive strength (sRcL), strain to failure ($\varepsilon_{(fRcL)}$) for control (C) and treated (T) juvenile (J) and mature (M) pine wood; ±standard deviation (SD)

Wood	MC (%)	ρ (g cm^{-3})	MOE (MPa)	sMOE (MN m kg^{-1})	σ_{pl} (MPa)	sσ_{pl} (kN m kg^{-1})	RcL (MPa)	sRcL (kN m kg^{-1})
JC	7.0	418 ± 8.2^{b}	4752.5 ± 189.9^{a}	11.4	16.4 ± 3.2^{ab}	39.3	43.9 ± 0.8^{a}	104.9
JT	3.0	379 ± 4.7^{a}	4260.0 ± 453.1^{a}	11.3	19.7 ± 2.2^{ab}	52.0	45.1 ± 1.7^{a}	118.9
MC	6.8	451 ± 7.9^{d}	6513.8 ± 391.5^{b}	13.6	15.8 ± 2.3^{a}	35.1	49.1 ± 2.4^{ab}	108.9
MT	4.1	427 ± 15.3^{c}	4755.0 ± 406.8^{a}	11.1	20.7 ± 3.2^{b}	48.5	52.8 ± 4.3^{b}	123.6

^{a,b,c}Different superscripts denote a statistically significant ($p < 0.05$) difference between mean values according to Tukey's honest significant difference (HSD) test

Compressive strength (RcL) for JC was lower than for MC. Thermal modification increased its values by 2% for juvenile and 7% for mature wood, but that increase was not statistically significant. Interestingly, the treatment increased the specific RcL for both wood types by 13%.

Wood hardness along the grains (Table 4) was higher than in the tangential and radial directions; hardness values for individual directions were similar for juvenile and mature wood. Thermal treatment slightly reduced wood hardness in both directions, but differences were not statistically significant.

Discussion

Thermal modification of juvenile and mature pine wood affected all the measured parameters, from chemical composition through swelling behaviour to mechanical properties, showing correlations between them.

In our research on pine wood, we observed a slightly higher mass loss (by 1.5 percentage points) and a higher reduction in wood swelling in the tangential and radial directions (by about 44% for J vs 37–39% for M) for juvenile than mature wood, despite less pronounced changes in its chemical composition. It is known that the degradation of cell wall polymers caused by heat treatment mainly involves the least thermally stable hemicelluloses, but cellulose and lignin can also be affected, depending on the applied temperature and treatment conditions (Hill et al. 2021; Popescu et al. 2021). It results in wood mass loss, a decrease in density, and also a reduced number of hydroxyl groups accessible to water, which are present in wood polymers, most abundantly on hemicelluloses (Repellin and Guyonnet 2005; Hill et al. 2021). Heat treatment also causes a reduction in wood swelling. It is usually attributed to the degradation of hemicelluloses and includes a decrease in hemicellulose absorption sites and also structural modifications in the cell wall due to hemicellulose destruction. However, it is suggested that structural alterations of the cell wall due to hemicellulose degradation, along with chemical changes of lignin, also play an important role in swelling reduction (Repellin and Guyonnet 2005). Summarising, the results obtained show that the correlation between wood chemical composition, mass loss, and swelling is complex and also affected by other factors, e.g., structural features. They also suggest that in the case of juvenile and mature pine wood, the changes in wood swelling behaviour caused by thermal treatment may be

Table 4 Mean values of wood hardness in the longitudinal direction (H_L) and tangential/radial directions ($H_{R/T}$) for control (C) and treated (T) juvenile (J) and mature (M) pine wood; ± standard deviation (SD)

Sample	ρ (g cm^{-3})	H_L (MPa)	$H_{R/T}$ (MPa)
JC	418 ± 8.2	38.4 ± 2.5^{a}	12.3 ± 1.3^{a}
JT	379 ± 4.7	37.4 ± 2.6^{a}	12.0 ± 1.2^{a}
MC	451 ± 7.9	41.3 ± 4.8^{a}	12.2 ± 1.9^{a}
MT	427 ± 15.3	39.0 ± 4.6^{a}	11.8 ± 2.8^{a}

^{a,b,c}Different superscripts denote a statistically significant ($p < 0.05$) difference between mean values according to Tukey's honest significant difference (HSD) test

less attributable to alterations in wood chemical composition than to other factors, including mass loss and structural changes in the cell wall.

Thermal treatment also affected the measured mechanical parameters of juvenile and mature pine wood, such as MOE in compression, compressive strength, stress at proportionality limit (in the longitudinal direction), and hardness along and across the grains (Tables 3 and 4). However, the observed differences between control and treated wood were statistically important only in the case of MOE, σ_{pl} and RcL values for mature wood. It may suggest that the observed changes result mainly from the alterations in the wood chemical composition, which was much more pronounced for mature than juvenile wood. It is known that wood mechanical properties depend on several factors, including chemistry and the arrangement of individual polymers in the cell wall (Salmén et al. 2016; Gaff et al. 2019). Although the arrangement of the main structural wood polymers in the cell wall has still not been fully established, the results obtained using various techniques suggest that glucomannan and xylan from hemicelluloses chains are associated to the cellulose microfibrils while lignin fills the remaining spaces between the cellulose/hemicellulose aggregates and acts as an independent entity (Salmén 2022). Cellulose and the arrangement of cellulose microfibrils are considered responsible for the strength of wood fibre, particularly in the longitudinal direction, and cellulose degradation leads to a reduction in its macro-strength properties (Sweet and Winandy 1999; Salmén et al. 2016), while hemicelluloses contribute to wood elasticity (Berglund et al. 2020). Lignin is thought to affect wood compression stiffness and take part in stress transfer in the cell wall (Salmén et al. 2016; Özparpucu et al. 2019; Serra-Parareda et al. 2020). The recent results of the research where wood polymers were selectively removed from the cell wall suggest that the complementary action of flexible cellulose and rigid lignin is responsible for compressive response of wood; hemicelluloses seem to enhance the interactions between cellulose and lignin and stabilise wood structure without a significant impact on wood compression behaviour (Kurei et al. 2024). In the case of thermally treated mature pine wood, where chemical changes due to the modification were more pronounced than in juvenile wood, the significantly reduced hemicellulose content and structure, along with increased relative lignin content and structure alterations, contributed to the significant decrease in its elasticity, which was reflected in much lower MOE value for MT than MC. The effect of increased lignin content on lowering MOE value has already been observed by other researchers (Xi 2018). Slightly increased values of compressive strength and stress at proportionality limit along the grain after heat treatment for mature wood may result from an increase in the relative amount of lignin and crystalline cellulose due to the degradation of hemicelluloses and amorphous cellulose and the increased cross-linking of lignin acting as a stiffener for cellulose microfibrils (Sweet and Winandy 1999; Boonstra et al. 2007). Since chemical changes in thermally-treated juvenile wood were much smaller, their effect on wood mechanical parameters was not that distinct.

Wood hardness across and along the grains remained unaffected by the applied treatment (Table 4). It is known that wood hardness is determined by various factors, including grain direction, lignin content, wood density and moisture content (Hansson and Antti 2006; Xi 2018). In our research, the combination of various

changes caused by thermal treatment in wood chemistry and structure apparently led to maintaining the hardness values recorded for control wood.

It may seem surprising that thermal modification caused the growth of maximum swelling pressure in wood, particularly for juvenile samples (Fig. 10). Wood swelling pressure is considered a positive function of MOE (Keylwerth 1962) but is not directly linked with the rate of moisture-induced deformations (Rybarczyk and Ganowicz 1974). In our case, we cannot relate the obtained values of swelling pressure to recorded MOE values because they were measured in different anatomical directions. However, considering the fact that water interactions with wood polymers during absorption depend on the elastic energy needed to distort polymers in the cell wall (Bertinetti et al. 2013; Arzola-Villegas et al. 2019) and that "…the potential work of swelling originates from the elastic energy stored in the rigid structure…" of polymers (Nishiyama 2023), it can be stated that the composition, structure and thermodynamics of wood polymers building the cell wall play an important role in creating swelling pressure in wood (Nishiyama 2023). In juvenile wood, the changes in chemical composition caused by thermal treatment were less pronounced than for mature wood. Despite this, its swelling pressure increased more than that of mature wood. Since we do not know the details about the quantitative and qualitative chemical composition of control and treated juvenile and mature pine wood and the effect of the chemical changes on the nanostructure of the cell wall, further more detailed studies in those areas are required to gain more knowledge and explain the phenomenon of the increased swelling pressure of heat-treated wood.

Conclusion

In this research, Scots pine wood of different cambial ages was thermally modified to evaluate if the modification could improve the properties of juvenile wood and make its selected properties equal to those of mature wood so the modified juvenile wood could be used as a fully-fledged raw material for industrial applications.

The results show that thermal treatment caused multiple changes in juvenile and mature pine wood, but the extent of these alterations differed between juvenile and mature wood. Mass loss and the decrease in the swelling rate in the tangential and radial directions were higher for juvenile wood. Swelling pressure increased for both wood types but was more distinct for juvenile wood. Changes in chemical composition due to the heat treatment included reducing carbohydrate content (particularly hemicelluloses) and decreasing the number of hydroxyls. The alterations were more pronounced for mature wood, making it more similar to juvenile both control and treated wood than to control mature wood. Also, more distinct alterations in the mechanical parameters measured in compression were observed.

Based on the above, although the applied thermal modification did not affect much the mechanical performance of juvenile samples while effectively reducing the swelling rate of both studied wood types, making them better suited for use under changeable moisture conditions, it is an inappropriate method to equalise or limit the differences in examined properties between juvenile and mature wood. The results point to the conclusion that structural features may play an important role in

the changes in parameters measured; therefore, to gain more detailed knowledge in this area, we plan to extend research on other wood species, including deciduous species, both ring- and diffuse-porous. Since the results also suggest that changes in wood chemical composition affect wood mechanical properties to a greater extent than its swelling behaviour, these may provide valuable guidance for finding more accurate modification methods to improve juvenile wood performance so it could be used along with mature wood of the same species for a broader range of industrial applications.

Acknowledgements The authors would like to express their gratitude to Anna Rutkowska and Janusz Cegieła for their help in lab work, and to Jerzy Majka for thermal modification of wood samples.

Author contributions M.B., C.-M.P. and E.R. wrote the main manuscript text and prepared figures and tables, C.-M.P., M.B. and K.P. performed experiments and contributed to the description of the results. All authors reviewed the manuscript.

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Adamopoulos S, Passialis C, Voulgaridis E (2007) Strength properties of juvenile and mature wood in black locust (*Robinia Pseudoacacia* L.). Wood Fiber Sci 241–249

Alteyrac J, Cloutier A, Zhang SY (2006) Characterization of juvenile wood to mature wood transition age in black spruce (*Picea mariana* (Mill.) B.S.P.) at different stand densities and sampling heights. Wood Sci Technol 40:124–138. https://doi.org/10.1007/s00226-005-0047-4

Antony F, Schimleck LR, Jordan L et al (2012) Modeling the effect of initial planting density on within tree variation of stiffness in loblolly pine. Ann for Sci 69:641–650. https://doi.org/10.1007/s13595-011-0180-1

Arslan MB, Avcı E, Tozluoğlu A, et al (2021) Comparison of some wood properties of juvenile black pines of different origin planted in the same habitat. Maderas Ciencia y tecnología 23. https://doi.org/10.4067/s0718-221x2021000100466

Arzola-Villegas X, Lakes R, Plaza NZ, Jakes JE (2019) Wood moisture-induced swelling at the cellular scale—Ab intra. Forests 10:996. https://doi.org/10.3390/f10110996

Auty D, Achim A, Macdonald E et al (2014) Models for predicting wood density variation in Scots pine. For Int J for Res 87:449–458. https://doi.org/10.1093/forestry/cpu005

Bal BC, Bektaş İ (2013) The effects of heat treatment on some mechanical properties of juvenile wood and mature wood of eucalyptus grandis. Drying Technol 31:479–485. https://doi.org/10.1080/07373937.2012.742910

Bao FC, Jiang ZH, Jiang XM et al (2001) Differences in wood properties between juvenile wood and mature wood in 10 species grown in China. Wood Sci Technol 35:363–375. https://doi.org/10.1007/s002260100099

Barnett JR, Bonham VA (2004) Cellulose microfibril angle in the cell wall of wood fibres. Biol Rev 79:461–472. https://doi.org/10.1017/S1464793103006377

Berglund J, Mikkelsen D, Flanagan BM et al (2020) Wood hemicelluloses exert distinct biomechanical contributions to cellulose fibrillar networks. Nat Commun 11:4692. https://doi.org/10.1038/s41467-020-18390-z

Bertinetti L, Fischer FD, Fratzl P (2013) Physicochemical basis for water-actuated movement and stress generation in nonliving plant tissues. Phys Rev Lett 111:238001. https://doi.org/10.1103/PhysRevLett.111.238001

Bhat KM, Priya PB, Rugmini P (2001) Characterisation of juvenile wood in teak. Wood Sci Technol 34:517–532. https://doi.org/10.1007/s002260000067

Blackburn D, Huong VD, Thanh ND, Mendham D (2021) Solid wood property variations in early-age *Acacia* plantation trees grown in southern Vietnam. South for J for Sci 83:19–27. https://doi.org/10.2989/20702620.2020.1813645

Boonstra MJ, Van Acker J, Tjeerdsma BF, Kegel EV (2007) Strength properties of thermally modified softwoods and its relation to polymeric structural wood constituents. Ann for Sci 64:679–690. https://doi.org/10.1051/forest:2007048

Brandner R, Flatscher G, Ringhofer A et al (2016) Cross laminated timber (CLT): overview and development. Eur J Wood Prod 74:331–351. https://doi.org/10.1007/s00107-015-0999-5

Candelier K, Thevenon M-F, Petrissans A et al (2016) Control of wood thermal treatment and its effects on decay resistance: a review. Ann for Sci 73:571–583. https://doi.org/10.1007/s13595-016-0541-x

Chen H, Ferrari C, Angiuli M et al (2010) Qualitative and quantitative analysis of wood samples by Fourier transform infrared spectroscopy and multivariate analysis. Carbohyd Polym 82:772–778. https://doi.org/10.1016/j.carbpol.2010.05.052

Chen Z-Q, Abramowicz K, Raczkowski R et al (2016) Method for accurate fiber length determination from increment cores for large-scale population analyses in Norway spruce. Holzforschung 70:829–838. https://doi.org/10.1515/hf-2015-0138

Clark A, Daniels RF, Jordan L (2006) Juvenile/mature wood transition in loblolly pine as defined by annual ring specific gravity, proportion of latewood, and microfibril angle. Wood Fiber Sci 292–299

Cloutier A, Ananias RA, Ballerini A, Pecho R (2007) Effect of radiata pine juvenile wood on the physical and mechanical properties of oriented strandboard. Holz Roh Werkst 65:157–162. https://doi.org/10.1007/s00107-006-0148-2

Corson SR (1984) Influence of wood quality characteristics on TMP and RMP from New Zealand-grown radiata pine. APPITA 37:400–408

Corson SR (1991) Wood characteristics influence pine TMP quality. TAPPI J 74:135–146

Corson SR, Richardson J (2007) Fast-grown PGW fibre for superior communication papers. Appita Technol Innov Manuf Environ 60:144–149. https://doi.org/10.3316/informit.526455377142348

Côté WA, Kollmann FF (1984) Principles of wood science and technology. Solid wood. Springer, Berlin, pp 55–78

Danborg F (1994) Drying properties and visual grading of juvenile wood from fast grown *Picea abies* and *Picea sitchensis*. Scand J for Res 9:91–98. https://doi.org/10.1080/02827589409382817

EN 1534 (2000) Wood and parquet flooring–determination of resistance to indentation (Brinell)–test method

Fabisiak E, Fabisiak B (2021) Relationship of tracheid length, annual ring width, and wood density in Scots pine (*Pinus sylvestris* L.) trees from different social classes of tree position in the stand. BioResources 16:7492–7508. https://doi.org/10.15376/biores.16.4.7492-7508

Faix O, Böttcher JH (1992) The influence of particle size and concentration in transmission and diffuse reflectance spectroscopy of wood. Holz Roh- Werkst 50:221–226. https://doi.org/10.1007/BF02650312

Fengel D, Wegener G (2011) Wood: chemistry, ultrastructure, reactions. Walter de Gruyter, Berlin

Gaff M, Kačík F, Sandberg D et al (2019) The effect of chemical changes during thermal modification of European oak and Norway spruce on elasticity properties. Compos Struct 220:529–538. https://doi.org/10.1016/j.compstruct.2019.04.034

Gapare W, Hathorn A, Kain D et al (2007) Inheritance of spiral grain in the juvenile core of *Pinus radiata*. Can J for Res 37:116–127. https://doi.org/10.1139/x06-202

Garrote G, Domínguez H, Parajó JC (2001) Study on the deacetylation of hemicelluloses during the hydrothermal processing of Eucalyptus wood. Holz Als Roh-Und Werkstoff 59:53–59. https://doi.org/10.1007/s001070050473

Gérardin P (2016) New alternatives for wood preservation based on thermal and chemical modification of wood—a review. Ann for Sci 73:559–570. https://doi.org/10.1007/s13595-015-0531-4

Hannouz S, Collet R, Butaud J-C et al (2015) Mechanical characterization of heat-treated ash wood in relation with structural timber standards. Pro LIGNO-Open Access Sci J Field Wood Eng 11:13

Hannrup B, Cahalan C, Chantre G et al (2004) Genetic parameters of growth and wood quality traits in *Picea abies*. Scand J for Res 19:14–29. https://doi.org/10.1080/02827580310019536

Hansson L, Antti AL (2006) The effect of drying method and temperature level on the hardness of wood. J Mater Process Technol 171:467–470. https://doi.org/10.1016/j.jmatprotec.2005.08.007

Hill CAS (2007) Wood modification: chemical, thermal and other processes. Wiley, Hoboken

Hill C, Altgen M, Rautkari L (2021) Thermal modification of wood—a review: chemical changes and hygroscopicity. J Mater Sci 56:6581–6614. https://doi.org/10.1007/s10853-020-05722-z

Huang Y, Löschke S, Proust G (2021) In the mix: The effect of wood composition on the 3D printability and mechanical performance of wood-plastic composites. Composit Part C Open Access 5:100140. https://doi.org/10.1016/j.jcomc.2021.100140

Hughes M (2015) 4 - Plywood and other veneer-based products. In: Ansell MP (ed) Wood composites. Woodhead Publishing, Sawston, pp 69–89

ISO 13061-2 (2014) Physical and mechanical properties of wood—test methods for small clear wood specimens—part 2: determination of density for physical and mechanical tests

Ivković M, Gapare WJ, Abarquez A et al (2009) Prediction of wood stiffness, strength, and shrinkage in juvenile wood of radiata pine. Wood Sci Technol 43:237–257. https://doi.org/10.1007/s00226-008-0232-3

Jordan L, He R, Hall DB et al (2007) Variation in loblolly pine ring microfibril angle in the southeastern United States. Wood Fiber Sci 39:352–363

Keylwerth R (1962) Untersuchungen über freie und behinderte Quellung von Holz—Erste Mitteilung: freie Quellung [Investigations on free and restraint swelling of wood—Part I: Free swelling]. Holz Roh- Werkst 20:252–259. https://doi.org/10.1007/BF02604681

Kimberley MO, Cown DJ, McKinley RB et al (2015) Modelling variation in wood density within and among trees in stands of New Zealand-grown radiata pine. NZ J for Sci 45:22. https://doi.org/10.1186/s40490-015-0053-8

Kondo T (2005) Hydrogen bonds in cellulose and cellulose derivatives. In: Dumitriu S (ed) Polysaccharides: structural diversity and functional versatility. Marcel Dekker, Inc., New York, pp 69–98

Kretschmann DE, Cramer SM (2007) The role of earlywood and latewood properties on dimensional stability of loblolly pine. In: Proceedings of the compromised wood workshop, 2007 January 29–30 Christchurch, NZ : Wood Technology Research Centre, School of Forestry, University of Canterbury, pp 215–236

Kurei T, Sakai S, Nakaba S et al (2024) Structural and mechanical roles of wood polymer assemblies in softwood revealed by gradual removal of polysaccharides or lignin. Int J Biol Macromol 259:129270. https://doi.org/10.1016/j.ijbiomac.2024.129270

Lachenbruch B, Moore JR, Evans R (2011) Radial variation in wood structure and function in woody plants, and hypotheses for its occurrence. Size Age-Relat Chang Tree Struct Funct 4:121–164. https://doi.org/10.1007/978-94-007-1242-3_5

Lahtela T (2021) ThermoWood® handbook. International Thermowood Association, Helsinki

Larson PR (2001) Formation and properties of juvenile wood in southern pines: a synopsis. US Department of Agriculture, Forest Service, Forest Products Laboratory

Lee JJ, Park JS, Kim KM, Oh JK (2005) Prediction of bending properties for structural glulam using optimized distributions of knot characteristics and laminar MOE. J Wood Sci 51:640–647. https://doi.org/10.1007/s10086-005-0704-0

Mania P, Nowicki M (2020) Nanohardness and elasticity of cell walls of Scots pine (*Pinus sylvestris* L.) juvenile and mature wood. Bull Polish Acad Sci Tech Sci 68:1237–1241. https://doi.org/10.24425/bpasts.2020.134645

Mansfield SD, Parish R, Lucca CMD et al (2009) Revisiting the transition between juvenile and mature wood: a comparison of fibre length, microfibril angle and relative wood density in lodgepole pine. HFSG 63:449–456. https://doi.org/10.1515/HF.2009.069

Mansfield SD, Parish R, Ott PK et al (2016) Assessing the wood quality of interior spruce (*Picea glauca* × *P. engelmannii*): variation in strength, relative density, microfibril angle, and fiber length. Holzforschung 70:223–234. https://doi.org/10.1515/hf-2015-0008

Mantanis GI, Young RA, Rowell RM (1994) Swelling of wood. Wood Sci Technol 28:119–134. https://doi.org/10.1007/BF00192691

Mazzanti P, Colmars J, Gril J et al (2014) A hygro-mechanical analysis of poplar wood along the tangential direction by restrained swelling test. Wood Sci Technol 48:673–687. https://doi.org/10.1007/s00226-014-0633-4

Molinski W, Raczkowski J (1980) Ciśnienie pęcznienia drewna zmodyfikowanego polistyrenem [Swelling pressure of wood modified with polystyrene]. Zeszyty Problemowe Postępów Nauk Rolniczych 231:89–101

Moore JR, Cown DJ (2015) 2 - Processing of wood for wood composites. In: Ansell MP (ed) Wood composites. Woodhead Publishing, pp 27–45

Moore JR, Cown DJ (2017) Corewood (juvenile wood) and its impact on wood utilisation. Curr for Rep 3:107–118. https://doi.org/10.1007/s40725-017-0055-2

Moore J, Achim A, Lyon A et al (2009) Effects of early re-spacing on the physical and mechanical properties of Sitka spruce structural timber. For Ecol Manag 258:1174–1180. https://doi.org/10.1016/j.foreco.2009.06.009

Moore JR, Lyon AJ, Lehneke S (2012) Effects of rotation length on the grade recovery and wood properties of Sitka spruce structural timber grown in Great Britain. Ann for Sci 69:353–362. https://doi.org/10.1007/s13595-011-0168-x

Moore JR, Cown DJ, McKinley RB (2015a) Modelling spiral grain angle variation in New Zealand-grown radiata pine. NZ J for Sci 45:15. https://doi.org/10.1186/s40490-015-0046-7

Moore JR, Cown DJ, McKinley RB, Sabatia CO (2015b) Effects of stand density and seedlot on three wood properties of young radiata pine grown at a dry-land site in New Zealand. NZ J for Sci 45:4. https://doi.org/10.1186/s40490-015-0035-x

Myers GC (2002) Thermomechanical pulping of loblolly pine juvenile wood. Wood Fiber Sci 108–115

Nazerian M, Ghalehno MD, Kashkooli AB (2011) Effect of wood species, amount of juvenile wood and heat treatment on mechanical and physical properties of laminated veneer lumber. J Appl Sci 11:980–987

Nishiyama Y (2023) Thermodynamics of the swelling work of wood and non-ionic polysaccharides: a revisit. Carbohyd Polym 320:121227. https://doi.org/10.1016/j.carbpol.2023.121227

Özparpucu M, Gierlinger N, Cesarino I et al (2019) Significant influence of lignin on axial elastic modulus of poplar wood at low microfibril angles under wet conditions. J Exp Bot 70:4039–4047. https://doi.org/10.1093/jxb/erz180

Paes JB, dos Santos LL, da Silva LF et al (2015) Technological characterization of juvenile wood teak (*Tectona grandis*) to production of furnitures. Revista Brasileira De Ciências Agrárias (agrária) 10:437–442

Pandey KK, Pitman AJ (2003) FTIR studies of the changes in wood chemistry following decay by brown-rot and white-rot fungi. Int Biodeter Biodegr 52:151–160. https://doi.org/10.1016/S0964-8305(03)00052-0

Patera A, Derome D, Griffa M, Carmeliet J (2013) Hysteresis in swelling and in sorption of wood tissue. J Struct Biol 182:226–234. https://doi.org/10.1016/j.jsb.2013.03.003

Pecho R, Ananias RA, Ballerini A, Cloutier A (2005) Influence of radiata pine juvenile wood on the physical and mechanical properties of oriented strand boards (OSB). Rev Bosque 26:123–132

Perkitny T, Kingston RST (1972) Review of the sufficiency of research on the swelling pressure of wood. Wood Sci Technol 6:215–229. https://doi.org/10.1007/BF00351579

Pimentel GC, Sederholm CH (1956) Correlation of infrared stretching frequencies and hydrogen bond distances in crystals. J Chem Phys 24:639–641. https://doi.org/10.1063/1.1742588

Popescu C-M, Popescu M-C, Vasile C (2011) Structural analysis of photodegraded lime wood by means of FT-IR and 2D IR correlation spectroscopy. Int J Biol Macromol 48:667–675. https://doi.org/10.1016/j.ijbiomac.2011.02.009

Popescu M-C, Froidevaux J, Navi P, Popescu C-M (2013) Structural modifications of *Tilia cordata* wood during heat treatment investigated by FT-IR and 2D IR correlation spectroscopy. J Mol Struct 1033:176–186. https://doi.org/10.1016/j.molstruc.2012.08.035

Popescu C, Jones D, Kržišnik D, Humar M (2020) Determination of the effectiveness of a combined thermal/chemical wood modification by the use of FT–IR spectroscopy and chemometric methods. J Mol Struct 1200:127133. https://doi.org/10.1016/j.molstruc.2019.127133

Popescu C-M, Zeniya N, Endo K et al (2021) Assessment of structural differences between water-extracted and non-extracted hydro-thermally treated spruce wood by NIR spectroscopy. Forests 12:1689. https://doi.org/10.3390/f12121689

Pugel AD, Price EW, Hse CY (1990) Composites from southern pine juvenile wood. Part 2. Durability and dimensional stability. For Prod J 40:57–61

Rautkari L, Hill CAS (2014) Effect of initial moisture content on the anti-swelling efficiency of thermally modified Scots pine sapwood treated in a high-pressure reactor under saturated steam. Holzforschung 68:323–326. https://doi.org/10.1515/hf-2013-0078

Repellin V, Guyonnet R (2005) Evaluation of heat-treated wood swelling by differential scanning calorimetry in relation to chemical composition. 59:28–34. https://doi.org/10.1515/HF.2005.005

Roszyk E, Mania P, Iwańska E et al (2020) Mechanical performance of scots pine wood from north-western Poland–a case study. BioResources 15:6781–6794. https://doi.org/10.15376/biores.15.3.6781-6794

Roszyk E, Kropaczewski R, Mania P, Broda M (2024) Swelling Behaviour of Bamboo (*Phyllostachys pubescens*). Forests 15:118. https://doi.org/10.3390/f15010118

Ruano A, García de Ceca JL, Cabrero JC, Hermoso E (2022) Shrinkage pattern assessment for black pine juvenile wood delimitation. Eur J Wood Prod 80:131–138. https://doi.org/10.1007/s00107-021-01736-9

Rybarczyk W, Ganowicz R (1974) A theoretical description of the swelling pressure of wood. Wood Sci Technol 8:233–241. https://doi.org/10.1007/BF00352027

Salmén L (2022) On the organization of hemicelluloses in the wood cell wall. Cellulose 29:1349–1355. https://doi.org/10.1007/s10570-022-04425-9

Salmén L, Stevanic JS, Olsson A-M (2016) Contribution of lignin to the strength properties in wood fibres studied by dynamic FTIR spectroscopy and dynamic mechanical analysis (DMA). Holzforschung 70:1155–1163. https://doi.org/10.1515/hf-2016-0050

Sandberg D, Kutnar A (2016) Thermally modified timber: recent developments in Europe and North America. Wood Fiber Sci 48:28–39

Sarkhad M, Ishiguri F, Nezu I et al (2021) Modeling of radial variations in wood properties and comparison of juvenile and mature wood of four common conifers in Mongolia. Holzforschung 76:14–25. https://doi.org/10.1515/hf-2021-0107

Sedlar T, Sinković T, Trajković J et al (2019) Physical properties of juvenile and mature sycamore maple (*Acer pseudoplatanus* L.) wood from Medvednica region. Drvna Industrija 70:19–26. https://doi.org/10.5552/drvind.2019.1762

Serra-Parareda F, Tarrés Q, Espinach FX et al (2020) Influence of lignin content on the intrinsic modulus of natural fibers and on the stiffness of composite materials. Int J Biol Macromol 155:81–90. https://doi.org/10.1016/j.ijbiomac.2020.03.160

Severo ETD [UNESP, Sansígolo CA [UNESP, Calonego FW [UNESP, Barreiros RM [UNESP (2013) Kraft pulp from juvenile and mature woods of corymbia citriodora. BioResources 1657

Shi JL, Zhang SY, Riedl B (2005) Effect of juvenile wood on strength properties and dimensional stability of black spruce medium-density fiberboard panels. 59:1–9. https://doi.org/10.1515/HF.2005.001

Soares BCD, Lima JT, Rocha MFV et al (2019) Behavior of juvenile and mature *Eucalyptus cloeziana* wood subjected to drastic drying. Floresta Ambient 26:e20170872. https://doi.org/10.1590/2179-8087.087217

Struszczyk H (1986) Modification of Lignins. III. Reaction of lignosulfonates with chlorophosphazenes. J Macromol Sci Part A Chem 23:973–992. https://doi.org/10.1080/00222338608081105

Sweet MS, Winandy JE (1999) Influence of degree of polymerization of cellulose and hemicellulose on strength loss in fire-retardant-treated southern pine. Holzforschung 53:311–317. https://doi.org/10.1515/HF.1999.051

Tjeerdsma BF, Boonstra M, Pizzi A et al (1998) Characterisation of thermally modified wood: molecular reasons for wood performance improvement. Holz Roh- Werkst 56:149–153. https://doi.org/10.1007/s001070050287

Torniainen P, Popescu C-M, Jones D et al (2021) Correlation of studies between colour, structure and mechanical properties of commercially produced ThermoWood® treated norway spruce and scots pine. Forests 12:1165. https://doi.org/10.3390/f12091165

Tumenjargal B, Ishiguri F, Iki T et al (2022) Clonal variations and effects of juvenile wood on lumber quality in Japanese larch. Wood Mat Sci Eng 17:72–81. https://doi.org/10.1080/17480272.2020.1779809

Wagner FG, Gorman T, Pratt KL, Keegan C (2002) Warp, MOE, and grade of structural lumber curve sawn from small-diameter Douglas-fir logs. For Prod J 52:27–31

Wu HX, Ivkovic M, Gapare WJ et al (2008) Breeding for wood quality and profit in *Pinus radiata*: a review of genetic parameter estimates and implications for breeding and deployment. NZ J for Sci 38:56–87

Xi E (2018) Dynamic relationship between mechanical properties and chemical compo sition distribution of wood cell walls. Wood Res 63:179–192

Yildiz S, Gümüşkaya E (2007) The effects of thermal modification on crystalline structure of cellulose in soft and hardwood. Build Environ 42:62–67. https://doi.org/10.1016/j.buildenv.2005.07.009

Zanuttini R, Negro F (2021) Wood-based composites: innovation towards a sustainable future. Forests 12:1717. https://doi.org/10.3390/f12121717

Zhang SY, Ren H, Jiang Z (2021) Wood density and wood shrinkage in relation to initial spacing and tree growth in black spruce (*Picea mariana*). J Wood Sci 67:30. https://doi.org/10.1186/s10086-021-01965-9

Zobel B (1984) The changing quality of the world wood supply. Wood Sci Technol 18:1–17. https://doi.org/10.1007/BF00632127

Zobel BJ, Sprague JR (2012) Juvenile wood in forest trees. Springer, Berlin

Authors and Affiliations

Magdalena Broda[1] · Carmen-Mihaela Popescu[2,3] · Kamil Poszwa[1] · Edward Roszyk[1]

✉ Magdalena Broda
magdalena.broda@up.poznan.pl

[1] Department of Wood Science and Thermal Techniques, Faculty of Forestry and Wood Technology, Poznan University of Life Sciences, ul. Wojska Polskiego 38/42, 60-637 Poznan, Poland

[2] Petru Poni Institute of Macromolecular Chemistry of the Romanian Academy, 41A Grigore Ghica Voda Alley, 700487 Iasi, Romania

[3] School of Computing, Engineering and the Built Environment, Edinburgh Napier University, Unit 1, Seven Hills Business Park, 37 Bankhead Crossway South, Edinburgh EH11 4EP, UK