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Non-Destructive Evaluation of Thermal Treatment Influence on Elastic Engineering Parameters of Poplar

Ocjena utjecaja toplinske obrade na elastična svojstva drva topole nedestruktivnom metodom

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ABSTRACT • *Twelve elastic constants (Young's modulus (E_L, E_R, and E_T), shear modulus (G_{LR}, G_{LT}, and G_{RT}) and Poisson's ratios (ν_{LR}, ν_{LT}, ν_{RT}, ν_{TR}, ν_{RL}, and ν_{TL})) of Populus canadensis M. were determined by ultrasonic testing and evaluation, and the effect of thermal treatment on these constants was figured out. Samples were modified at 110, 160, and 210 °C for 3 and 6 h. The 2.25 MHz pressure and 1 MHz shear waves were propagated to calculate ultrasonic wave velocities, which were used to dynamically predict the constants. The control values for E_L, E_R, E_T, G_{LR}, G_{LT}, G_{RT}, ν_{LR}, ν_{LT}, ν_{RT}, ν_{TR}, ν_{RL}, and ν_{TL} were 4361 MPa, 1438 MPa, 476 MPa, 771 MPa, 480 MPa, 107 MPa, 0.795, 0.296, 0.863, 0.335, 0.19, and 0.027, respectively. Yet, no data for full elastic constants were reported, and some remarkable differences were observed for moduli and Poisson ratios when compared to other poplar species. Elasticity and shear moduli reached their highest at 160 °C 3h and 110 °C 3h conditions, respectively. The common point of the treatment on moduli was that intense application caused the highest adverse effect, particularly for E_T and G_{RT}. Contrary to moduli, apart from ν_{RT} and ν_{TR}, the lowest values for Poisson's ratios were not obtained at the intense application. In general, none of the properties presented linear-like advancement or worsening by the increase in treatment conditions. Furthermore, not all the properties were significantly influenced by the treatment. Therefore, defining an optimum thermal treatment condition for improving the wood elastic constants is not easy when considering that the response to thermal treatment changes not only between the species but also within the species. Anyhow, preventing extended duration to elevated temperatures provides considerable advances.*

KEYWORDS: *poplar; thermal treatment; elastic constants; ultrasound; nondestructive test*

SAŽETAK • *Ultrazvučnim je ispitivanjem i ocjenjivanjem utvrđeno dvanaest konstanti elastičnosti: Youngov modul (E_L, E_R, i E_T), modul smicanja (G_{LR}, G_{LT}, i G_{RT}) i Poissonovi omjeri (ν_{LR}, ν_{LT}, ν_{RT}, ν_{TR}, ν_{RL} i ν_{TL}) drva Populus canadensis M., a zatim je određen učinak toplinske obrade na te konstante. Uzorci su modificirani na 110, 160 i 210 °C tijekom tri i šest sati. Radi izračunavanja brzina ultrazvučnih valova koji su primijenjeni za dinamičko predviđanje konstanti, propagirani su tlačni valovi od 2,25 MHz i posmični valovi od 1 MHz. Kontrolne vrijednosti za E_L, E_R,*

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E_T, G_{LR}, G_{LT}, G_{RT}, v_{LR}, v_{LT}, v_{RT}, v_{TR}, v_{RL} i v_{TL} bile su 4361 MPa, 1438 MPa, 476 MPa, 771 MPa, 480 MPa, 107 MPa, 0,795, 0,296, 0,863, 0,335, 0,19 i 0,027. Još nisu objavljeni potpuni podatci za elastične konstante, a uočene su i neke značajne razlike za module i Poissonove omjere u usporedbi s drvom drugih vrsta topole. Moduli elastičnosti i smicanja dosegnuli su najviše vrijednosti pri temperaturi modifikacije 160 °C u trajanju tri sata, odnosno pri 110 °C tijekom tri sata. Za sve je uzorke utvrđeno da intenzivna toplinska obrada ima najveći štetni učinak na module, posebice za E_T i G_{RT}. Za razliku od modula, osim v_{RT} i v_{TR}, najniže vrijednosti za Poissonove omjere nisu dobivene pri intenzivnoj toplinskoj obradi. Općenito, nijedno od svojstava nije pokazalo linearno povećanje ili smanjenje s pojačavanjem uvjeta toplinske obrade. Nadalje, toplinska obrada nije značajno utjecala na sva svojstva. Stoga definiranje optimalnih uvjeta toplinske obrade za poboljšanje elastičnih konstanti drva nije jednostavno ako se uzme u obzir da se reakcija na toplinsku obradu mijenja ne samo među različitim vrstama, već i unutar iste vrste drva. Zaključno se može reći da sprječavanje produljenog trajanja toplinske obrade pri povišenim temperaturama ima znatne prednosti.

KLJUČNE RIJEČI: *drvo topole; toplinska obrada; elastične konstante; ultrazvuk; nedestruktivno ispitivanje*

1 INTRODUCTION
1. UVOD

External factor-related alterations should be known to ensure proper utilization of a biodegradable material (Kubovský *et al.,* 2020). Biomaterials such as wood do interact with environmental factors, which may cause significant changes in both physical and mechanical properties. As a result, due to the alterations that occurred in the structure, the life cycle of the material can be shortened. To prevent such adverse effects of environmental factors on the elements, lots of modification methods are in use. One of them is thermal treatment (TT), commonly used to advance some properties of wood. Shrinkage and swelling of the wood become stabilized by TT, and resistance to the degradation caused by biological attacks is increased. The fact remains that mechanical properties decrease, and so thermally treated wood is not suited for structural uses.

Studies generally reported the E_L of *Populus deltoids* clones (Narasimhamurthy *et al.,* 2017), poplar (Aydın *et al.,* 2007), *Populus alba* and *Populus nigra* (Monteiro *et al.,* 2019), and *Populus euramericaha* cv. I-69/58 (Guo *et al.,* 2011). The effect of TT on E_L of *Populus usbekistanica* was investigated by Sözbir *et al.* (2019). Orhan and Bal (2021) figured out the impact of TT on the mechanical features of *Populus subsps*. The influence of TT on the physical properties (Bytner *et al.,* 2022; Meija *et al.,* 2020; Taraborelli *et al.,* 2022; Villasante *et al.,* 2021, Yao *et al.,* 2023), modulus of elasticity (MOE) or modulus of rupture (MOR) (Bak and Nemeth, 2012; Bytner *et al.,* 2022; Goli *et al.,* 2015; Sözbir *et al.,* 2019; Todaro *et al.,* 2021), and tensile strength (Meija *et al.,* 2020) for solid wood obtained from different poplar species was evaluated. However, neither the twelve elastic constants nor the influence of TT on them were figured out for the *Populus x canadensis.* Advanced tool and method requirements are some of the obstacles that steer the researchers' focus on strength evaluation rather than orthotropic elastic behavior investigation. However, this study aimed to determine full elastic engineering parameters as a function of TT.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Poplar (*Populus x canadensis* Moench.) was used in this study. Logs were obtained from the Atabey District of Isparta City of Türkiye and then sawn. Timbers were air dried and then defect-free samples were prepared. Thermal treatment was done using FN 500 (Nüve Co., Ankara, Türkiye) laboratory type oven operating in ambient air. Before separately placing each sample group, the oven was heated to experimental temperature levels (110, 160, and 210 °C) and samples were treated for exactly 3 and 6 h. Considering the oven drying temperature (103±2) °C, 110 °C was defined as the starting point of the treatment with 50 °C increments, which were within the range of the reported treatment temperatures. The temperature of approximately 220 °C is required for 2-4 h for a successful treatment, and the duration of heating up and cooling down changes according to wood dimension (Rapp and Sailer, 2001). Not only heating up but also cooling regimes cause additional treatment of wood particularly at high temperatures (Johansson, 2008). Furthermore, cooling down from higher temperatures extends this additional treatment. To evaluate the effects of exact exposure duration on elastic constants, pre-heating and equipment assisted cooling with remoistening was not performed as in industrial practice. Heat transfer and equilibration following the treatment took place in ambient air. The control samples were unmodified. Particularly for the samples treated at intense configurations, surfaces were controlled against the defects such as cracks, etc., and defected samples were not tested. Furthermore, samples presented with abnormal velocities were neglected due to assumption of inner faults.

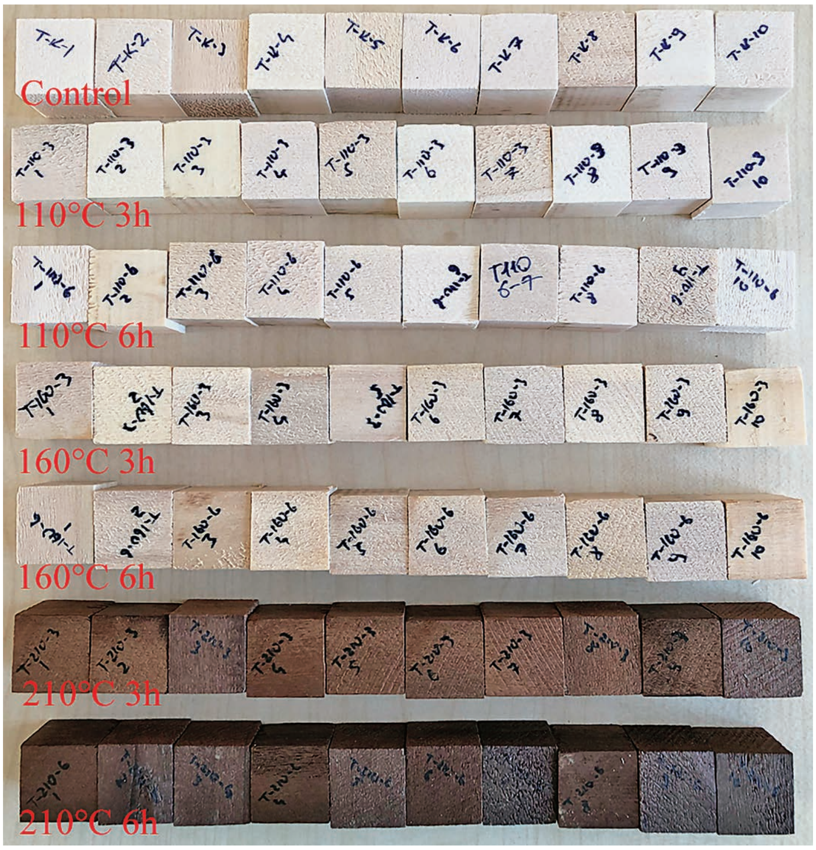

Figure 1 Samples and color changes regarding thermal treatment
Slika 1. Uzorci i promjene boje nakon toplinske obrade

Table 1 Equations for determining matrix elements (Gonçalves *et al.,* 2014; Ozyhar *et al.,* 2013)
Tablica 1. Jednadžbe za određivanje elemenata matrice (Gonçalves *et al*., 2014.; Ozyhar *et al*., 2013.)

Propagation – Polarization *Propagacija – polarizacija*	**Type of wave** *Vrsta vala*		**Equation for diagonal and off-diagonal terms** *Jednadžba za dijagonalne i nedijagonalne članove*
Axis (L, R, and T)	V_{LL}	Longitudinal *uzdužni*	$C_{11} = C_{\mathrm{LL}} = \rho V_{\mathrm{LL}}^2$
	V_{RR}		$C_{22} = C_{\mathrm{RR}} = \rho V_{\mathrm{RR}}^2$
	V_{TT}		$C_{33} = C_{\mathrm{TT}} = \rho V_{\mathrm{TT}}^2$
	$V_{\mathrm{TR/RT}}$	Shear (Transverse) *posmični (poprečni)*	$C_{44} = C_{\mathrm{RT}} = (\rho V_{\mathrm{RT}}^2 + \rho V_{\mathrm{TR}}^2) / 2$
	$V_{\mathrm{LT/TL}}$		$C_{55} = C_{\mathrm{LT}} = (\rho V_{\mathrm{LT}}^2 + \rho V_{\mathrm{TL}}^2) / 2$
	$V_{\mathrm{LR/RL}}$		$C_{66} = C_{\mathrm{RL}} = (\rho V_{\mathrm{RL}}^2 + \rho V_{\mathrm{LR}}^2) / 2$
Off-axis (RT45°)	$V_{\mathrm{RT/RT}}$	Quasi-shear (Transverse) *kvaziposmični (poprečni)*	$\left(C_{23} + C_{44}\right) n_2 n_3 = \pm\sqrt{[(C_{22} n_2^2 + C_{44} n_3^2 - \rho V_{\propto}^2)(C_{44} n_2^2 + C_{33} n_3^2 - \rho V_{\propto}^2)]}$
Off-axis (LT45°)	$V_{\mathrm{LT/LT}}$		$\left(C_{13} + C_{55}\right) n_1 n_3 = \pm\sqrt{[(C_{11} n_1^2 + C_{55} n_3^2 - \rho V_{\propto}^2)(C_{55} n_1^2 + C_{33} n_3^2 - \rho V_{\propto}^2)]}$
Off-axis (LR45°)	$V_{\mathrm{LR/LR}}$		$\left(C_{12} + C_{66}\right) n_1 n_2 = \pm\sqrt{[(C_{11} n_1^2 + C_{66} n_2^2 - \rho V_{\propto}^2)(C_{66} n_1^2 + C_{22} n_2^2 - \rho V_{\propto}^2)]}$

Where ρ (kg/m) is density, V_{II} is longitudinal UWV (m/s), V_{IJ} or V_{JI} is transverse UWV (m/s), and $V\alpha$ is quasi-transverse UWV (m/s) (Vázquez *et al.,* 2015), $n_1 = \cos\alpha$; $n_2 = \sin\alpha$, and $n_3 = 0$ for C_{23}, $n_1 = \cos\alpha$; $n_3 = \sin\alpha$, and $n_2 = 0$ for C_{13}, and $n^2 = \cos\alpha$; $n_3 = \sin\alpha$, and $n_1 = 0$ for C_{12} (Gonçalves *et al.,* 2014).

Following the TT and cooling down, 20 mm × 20 mm × 20mm (through L, R, and T directions, and LR45°, LT45°, and RT45° off-axis planes) samples (Figure 1) were conditioned at 20±1°C and 65 % relative humidity using a laboratory-type chamber (Memmert Gmbh+Co. KG, Schwabach, Germany). To avoid the influence of ambient air, samples were stored in a desiccator for density determination and ultrasonic measurements. The density of the samples was determined according to TS ISO 13061-2 (2021) standard.

The ultrasonic wave velocity (UWV), required for elastic constant prediction, were calculated by obtained wave propagation times in µs. Two different wave types, longitudinal or pressure (2.25 MHz) and transverse or shear (1MHz), were propagated through the essential directions (L, R, and T) and planes (LR, LT, and RT, and 45° off-axis-planes), respectively. The EPOCH 650 (Olympus NDT, USA) ultrasonic flaw detector, contact type piezoelectric transducers (Panametrics A133S-RM and V153-RM for pressure and shear waves, respectively), and ultrasonic couplants were used for propagation. For longitudinal waves, only propagation directions (L, R, and T) were used without polarization. However, for transverse waves, polarization with the propagation directions was used, which provided transmission through LR, LT, RT, RL, TL, and TR planes including 45° off-axis. The calculated UWVs were used to determine the stiffness matrix [*C*] (Eq. 1) elements using the equations presented in Table 1. Then compliance matrix [*S*] (Eq. 2) was calculated by inversing [*C*].

$$[C]=\begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \tag{1}$$

Where C_{ii} are the diagonal and C_{ij} and C_{ji} are the off-diagonal terms.

$$[S]=\begin{bmatrix} \frac{1}{E_L} & -\frac{\upsilon_{21}}{E_R} & -\frac{\upsilon_{31}}{E_T} & 0 & 0 & 0 \\ -\frac{\upsilon_{12}}{E_L} & \frac{1}{E_R} & -\frac{\upsilon_{32}}{E_T} & 0 & 0 & 0 \\ -\frac{\upsilon_{13}}{E_L} & -\frac{\upsilon_{23}}{E_R} & \frac{1}{E_T} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{RT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{LT}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{LR}} \end{bmatrix} \tag{2}$$

Where *E* is Young's modulus, *G* is the shear modulus, and **ν** is Poisson's ratio.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The averages for the density are given in Table 2. Reported values for unmodified *Populus x canadensis* solid wood are 334-374 kg/m³ (Casado *et al.,* 2010), 395 kg/m³ (Papandrea *et al.,* 2022), 405.6 kg/m³ (Hodoušek *et al.,* 2016), 464 kg/m³ (Villasante *et al.,* 2021), and 372-468 kg/m³ (YingJie *et al.,* 2017), and averages of this study are comparable. As seen in the table, around 8.9 % decrease was observed for intensive treatment. Taraborelli *et al.* (2022) reported 2.5 % and 10 % decreases for *P.* × *canadensis* 'I-214' heat-treated at 160 °C for 3h and 200 °C for 45 min, respectively. However, in this study, a 0.7 % increase was observed for the same treatment level, while the adverse effect of intensive treatment is comparable. The means of the intensive treatment groups presented statistically significant differences from others.

The averages for the UWVs are presented in Table 3. No study reported all the UWVs required for full elastic characterization of *Populus x canadensis* solid wood. However, Aydın and Aydın (2023) noted 2, 4 and 6 annual rings related V_{RR} (1607, 1782, and 1850 m/s), V_{LR} (1463, 1494, and 1501 m/s), V_{RL} (1491, 1567, and 1588 m/s), V_{RT} (532, 536, and 565 m/s), and V_{TR} (504, 512, and 522 m/s), respectively. The differences between the averages of the (Aydın and Aydın, 2023) and control values of this study are around 18 %, 1.1 %, -2.2 %, 3.5 %, and 9.2 %, respectively. Such diffractions are normal for wood material even for the same species. Zahedi *et al.* (2022) reported 3360 m/s (V_{LL}), 1850 m/s (V_{RR}), 1380 m/s (V_{TT}), 1370 m/s (V_{LR}), 1250 m/s (V_{RL}), 1140 m/s (V_{LT}), 1350 m/s (V_{TL}), 670 m/s (V_{RT}), 650 m/s (V_{TR}), 1510 m/s ($V_{LR\ 45°}$), 1210 m/s ($V_{LT\ 45°}$), and 740 m/s ($\mathrm{V}_{RT\ 45°}$) for 390 kg/m³ *populus deltoides*. When compared, UWVs are generally comparable but Ettelaei *et al.* (2019) reported 5433-5887 m/s for V_{LL} of *Populus Euroamericana* and around 35.2 % to 40.2 % diffractions between the lowest velocity and lower and upper bounds. Furthermore, 3877 to 4761 m/s V_{LL} for the I-214 clone obtained by stress wave speed was reported (Casado *et al.,* 2010; Papandrea *et al.,* 2022). Contrary to (Ettelaei *et al.,* 2019), the lower bound (8.1 %) of stress wave velocity is comparable to this study.

In general, the UWVs oscillated instead of linearly increasing or decreasing with the treatment progress. The same fluctuations were reported for some UWVs of heat-treated Taurus cedar (Yılmaz Aydın, 2021), oak (Aydın, 2020; Yılmaz Aydın and Aydın, 2020), red pine (Aydın, 2022), and beech (Yılmaz Aydın and Aydın, 2018a). Furthermore, treatment levels caused different influences as seen in Table 3. Therefore, it is not possible to define a certain treatment level for optimum advancement through all the UWVs. However, except for quasi-shear wave velocities, the highest adverse effect was obviously observed for the prolonged duration at 210 °C. Furthermore, according to ANOVA results presented in Table 3, the influence of treatment is significant (P<0.05) for V_{TT}, V_{LR}, V_{RL}, V_{LT}, V_{RT}, and V_{TR}. Particularly the means of the intensively treated groups presented statistically significant diffractions.

The averages for moduli are presented in Table 4. Full elastic constants for unmodified *Populus x*

Table 2 Statistics for density
Tablica 2. Statističke vrijednosti za gustoću

Property	Groups	*N*	Mean, %** [CoV]***	Std. Error	95 % CI for mean (Bounds)		Min.	Max.
					Lower	Upper		
Density, kg/m³ s. (F 6.119, P 0.000)	Control	10	339 a* [3,9]	4.225	329.27	348.38	316	353
	110 °C 3 h	10	346 a (2.3) [8,6]	9.434	325.13	367.81	301	403
	110 °C 6 h	10	335 a (-1.2) [3.2]	3.387	327.24	342.56	321	351
	160 °C 3 h	10	341 a (0.7) [4.6]	5.001	329.88	352.50	324	375
	160 °C 6 h	10	333 a (-1.7) [4.7]	4.976	321.92	344.43	307	355
	210 °C 3 h	10	310 b (-8.5) [5.4]	5.248	298.14	321.89	288	330
	210 °C 6 h	10	309 b (-8.9) [8.2]	8.032	290.43	326.77	270	364

s – significant, *Duncan's homogeneity groups, ** % diffraction from the average of the control group, *** coefficient of variation
*s – značajan, *Duncanove grupe homogenosti, ** postotak difrakcije od prosječne vrijednosti kontrolne skupine, *** koeficijent varijacije*

Table 3 Statistics for ultrasonic wave velocities
Tablica 3. Statističke vrijednosti za brzine ultrazvučnih valova

Groups	Property	Mean, %** [CoV]***	Property	Mean, % [CoV]	Property	Mean, % [CoV]
Control	V_{LL}, m/s n.s. (F 0.851, P 0.536)	3585 a* [3.2]	V_{RR}, m/s n.s. (F 1.211, P 0.313)	2060 a [3]	V_{TT}, m/s s. (F 5.945, P 0.000)	1184 a [5.7]
110 °C 3 h		3565 a (-0.6) [5.1]		2062 a (0.1) [9]		1182 a (-0.2) [4.1]
110 °C 6 h		3564 a (-0.6) [3.0]		2110 a (2.4) [2.9]		1180 a (-0.4) [6.5]
160 °C 3 h		3628 a (1.2) [3.3]		2103 a (2.1) [2.3]		1203 a (1.6) [7.4]
160 °C 6 h		3632 a (1.3) [3.8]		2102 a (2.1) [2.7]		1191 a (0.6) [9.1]
210 °C 3 h		3605 a (0.6) [3.4]		2059 a (0) [2.8]		1149 a (-3) [2.2]
210 °C 6 h		3522 a (-1.8) [4.3]		2026 a (-1.6) [3.4]		1034 b (-12.6) [7.6]
Control	V_{LR}, m/s s. (F 2.428, P 0.036)	1502 bc [2]	V_{LT}, m/s s. (F 4.636, P 0.001)	1210 a [1.3]	V_{RT}, m/s s. (F 5.107, P 0.000)	563 a [3.8]
110 °C 3 h		1536 ab (2.3) [3.8]		1223 a (1.1) [1.8]		583 a (3.6) [6.9]
110 °C 6 h		1554 a (3.5) [3.7]		1240 a (2.5) [2.7]		579 a (2.9) [4]
160 °C 3 h		1531 abc (1.9) [3.9]		1234 a (2) [3]		585 a (3.9) [4.8]
160 °C 6 h		1545 ab (2.8) [2.5]		1244 a (2.8) [2.5]		583 a (3.6) [4.7]
210 °C 3 h		1524 abc (1.4) [3.3]		1221 a (0.9) [4.7]		561 a (-0.5) [5.7]
210 °C 6 h		1485 c (-1.1) [2.8]		1174 b(-3) [2.8]		528 b (-6.2) [4.9]
Control	V_{RL}, m/s s. (F 2.969, P 0.013)	1515 bc [1.5]	V_{TL}, m/s n.s. (F 1.600, P 0.162)	1172 ab [3.1]	V_{TR}, m/s s. (F 2.749, P 0.019)	560 a [5.3]
110 °C 3 h		1530 abc (1) [4.6]		1197 ab (2.2) [5.5]		572 a (2.1) [8.8]
110 °C 6 h		1555 ab (2.7) [2.6]		1188 ab (1.4) [3.9]		573 a (2.4) [7.9]
160 °C 3 h		1545 ab (2) [3.3]		1191 ab (1.6) [6.1]		585 a (4.5) [5.8]
160 °C 6 h		1562 a (3.1) [2.1]		1222 a (4.3) [4.7]		565 a (0.9) [7.9]
210 °C 3 h		1555 ab (2.7) [2.5]		1164 b (-0.6) [3.4]		548 ab (-2.2) [9.2]
210 °C 6 h		1496 c (-1.3) [3.1]		1157 b (-1.3) [5.2]		512 b (-8.6) [11.7]
Control	$V_{LR45^{\circ}}$, m/s n.s. (F 1.986, P 0.081)	1290 ab [5.3]	$V_{LT45^{\circ}}$, m/s n.s. (F 1.760, P 0.122)	1012 a [5.1]	$V_{RT45^{\circ}}$, m/s n.s. (F 0.6989 P 0.659)	639 a [5.9]
110 °C 3 h		1245 ab (-3.5) [6.5]		1008 a (-0.4) [5.6]		633 a (-1) [4.0]
110 °C 6 h		1232 b (-4.5) [5.9]		985 ab (-2.6) [5.1]		638 a (-0.2) [4.4]
160 °C 3 h		1303 a (1.0) [1.4]		1006 a (-0.6) [3.2]		628 a (-1.8) [3.9]
160 °C 6 h		1298 a (0.6) [5.1]		1006 a (-0.6) [4.1]		653 a (2.1) [5.9]
210 °C 3 h		1286 ab (-0.4) [3.5]		1004 a (-0.8) [2.4]		645 a (0.9) [3.9]
210 °C 6 h		1271 ab (-1.5) [4.1]		961 b (-5) [3.6]		633 a (-1) [6.3]

n.s. – not significant, s – significant, *Duncan's homogeneity groups, ** % diffraction from the average of the control group, and *** coefficient of variation
*n.s. – nije značajno, s – značajno, *Duncanove grupe homogenosti, ** postotak difrakcije od prosječne vrijednosti kontrolne skupine, *** koeficijent varijacije*

canadensis solid wood are not available. However, Aydın and Aydın (2023) evaluated the influence of growth ring on E_R, G_{LR}, and G_{RT} of *Populus x canadensis* (345-354 kg/m³ density) and reported 899-1211 MPa, 772-876 MPa, and 93-111 MPa, respectively. When compared, shear moduli are in harmony with the reported values. However, the control value for E_R is around 18.8 % higher than the reported upper bound. Except for density, differences between the calculation methods of the studies may cause such diffractions as described in the materials and method headings. Due to a lack of full elastic properties for unmodified or thermally treated *Populus x canadensis* in the literature, results were compared to poplar subspecies. For exam-

Table 4 Statistics for moduli
Tablica 4. Statističke vrijednosti za module

Groups	Property	Mean, %** [CoV] ***	Property	Mean, %* [CoV]	Property	Mean, %* [CoV]
Control	E_L, MPa s. (F 3.258, P 0.007)	4361 ab* [8.3]	E_R, MP Žs. (F 3.651, P 0.004)	1438 ab [6.4]	E_T, MP s. (F 11.172, P 0.000)	476 a [10.8]
110 °C 3 h		4398 ab (0.9) [9.7]		1493 a (3.9) [21.6]		483 a (1.4) [7.5]
110 °C 6 h		4256 ab (-2.4) [6.1]		1493 a (3.9) [8.4]		467 a (-1.8) [12.7]
160 °C 3 h		4504 a (3.3) [10.2]		1508 a (4.9) [5.3]		495 a (4) [14]
160 °C 6 h		4404 ab (1) [9.5]		1473 a (2.5) [7.2]		474 a (-0.4) [15.8]
210 °C 3 h		4037 bc (-7.4) [9.9]		1313 bc (-8.6) [6.2]		409 b (-14) [6]
210 °C 6 h		3841 c (-11.9) [13.3]		1270 c (-11.7) [12.1]		331 c (-30.4) [16]
Control	G_{LR}, MPa s. (F 6.176, P 0.000)	771 ab [4.1]	G_{LT}, MP s. (F 11.946, P 0.000)	480 a [3.6]	G_{RT}, MP s. (F 5.447, P 0.000)	107 ab [10]
110 °C 3 h		817 a (5.9) [13]		507 a (5.5) [8.4]		116 a (8.6) [18.2]
110 °C 6 h		811 a (5.2) [8.4]		494 a (2.8) [5.9]		112 a (4.4) [13.5]
160 °C 3 h		807 a (4.6) [5.4]		501 a (4.4) [5.8]		117 a (9.5) [11.9]
160 °C 6 h		804 a (4.2) [4.7]		506 a (5.4) [5.1]		110 ab (2.9) [13.6]
210 °C 3 h		734 ab (-4.8) [5.1]		441 b (-8.2) [7.3]		96 bc (-10.4) [17.1]
210 °C 6 h		687 b (-11) [10.7]		419 b (-12.7) [9.5]		85 c (-21.1) [21.8]

n.s. – not significant, s – significant, *Duncan's homogeneity groups, ** % diffraction from the average of the control group, and *** coefficient of variation
*n.s. – nije značajno, s – značajno, *Duncanove grupe homogenosti, ** postotak difrakcije od prosječne vrijednosti kontrolne skupine, *** koeficijent varijacije*

ple, Zahedi *et al.* (2022) determined E_L, E_R, E_T, G_{LR}, $G_{LT,}$ and G_{RT} of *Populus deltoides* by ultrasonic tests as follows: 4.52, 1.37, 0.74, 0.69, 0.62, and 0.17 GPa, respectively. When compared to the results of this study, differences between the moduli are -3.5 %, 5.0 %, -35.7 %, 11.7 %, -22.6 %, and -37.1 %, respectively. Considering the internal or external factors affecting wood properties, such differences are comparable.

The influence of treatment on both elasticity and shear moduli was significant ($P<0.05$). However, as can be seen in Table 4, a linear-like influence either positive or negative was not observed for moduli. Indeed, the fluctuation was the fact. As illustrated in Appendix 1, the treatment at 160 °C for 3 h provided the highest advancements in all elasticity modulus values. The positive impact of relatively low-level TT on E_L of wood was reported by (Aydın, 2020; Güntekin *et al.,* 2017; Yılmaz Aydın, 2021; Yılmaz Aydın and Aydın, 2018a; Yılmaz Aydın and Aydın, 2020). The negative effect of TT even at a low-temperature level (110 °C) on some *E* and *G* of red pine was also reported (Aydın, 2022).

Considering the shear moduli, a common treatment condition for the highest advancement was not achieved because G_{LR} and G_{LT} reached their maximum value at 110 °C 3h, while G_{RT} presented the highest values at 160 °C 3h treatment levels, contradicting the adverse effect of moderate treatment (Aydın, 2022).

Yue *et al.*, (2023) reported that modification at 160-170 °C caused insignificant discrepancies in the mechanical properties of Chinese poplar, while 180 °C and further levels caused differences. As seen in Table 4, elastic and shear moduli reached their highest values at different moderate temperature levels but the common point between them is that the intense treatment conditions caused the highest adverse effect. Therefore, extended exposure duration at high temperatures following 160 °C should be avoided so as not to weaken the moduli of wood.

The averages for Poisson ratios are presented in Table 5. In the literature, there is limited data for the Poisson ratio for poplar species. Furthermore, neither untreated nor heat-treated Poisson ratios of *Populus canadensis* were reported. The reported ν_{LR}, ν_{LT}, ν_{RT}, ν_{TR}, ν_{RL}, and ν_{TL} ranges for hardwood species are 0.297-0.495, 0.374-0.651, 0.560-0.912, 0.213-0.496, 0.018-0.086, and 0.009-0.051, respectively (Kretschmann, 2010), and ν_{RL} and ν_{TL} are much smaller than other ratios. However, as can be seen in Table 5, this is only valid for ν_{TL}. Furthermore, there are remarkable numerical differences between the reported LR and RL ratios and the results of this study. Moreover, Aydın (2022) reported -45 % to 109 % differences between the Poisson's ratios of heat-treated red pine. However, it should be taken into consideration that Poisson's ratios vary within and between species (Kretschmann, 2010) and there is no information about Poisson's ratio in the standards (Obara, 2018). Therefore, such numerically huge discrepancies in the literature are meaningful.

As for moduli, a stable behavior of ratios against the treatment progress was not observed as (Aydın, 2022) reported for red pine. Furthermore, among the properties, the highest adverse effect of the treatment was observed for ratios. In the literature, it was reported that Poisson's ratios are less sensitive (Yılmaz Aydın *et al.,* 2016) and insensitive (Luis Gómez-Royuela *et al.,* 2021) to TT. Furthermore, Al-musawi *et al.* (2023)

Table 5 Statistics for Poisson's ratios
Tablica 5. Statističke vrijednosti za Poissonove omjere

Groups	Property	Mean, %** [CoV]***	Property	Mean, %* [CoV]	Property	Mean, %* [CoV]
Control	ν_{LR} n.s. (F 1.514, P 0.188)	0.795 ab [13.7]	ν_{LT} n.s. (F 0.884, P 0.512)	0.296 a [55.8]	ν_{RT} n.s. (F 1.451, P 0.210)	0.863 ab [9.1]
110 °C 3 h		0.864 a (8.7) [17.3]		0.347 a (17.2) [50.6]		0.845 ab (-2.1) [14.5]
110 °C 6 h		0.843 ab (6.1) [14]		0.405 a (36.8) [68.8]		0.815 ab (-5.5) [13]
160 °C 3 h		0.749 ab (-5.8) [17.2]		0.431 a (45.5) [57]		0.905 a (4.9) [8.3]
160 °C 6 h		0.733 b (-7.8) [14.6]		0.499 a (68.6) [51]		0.821 ab (-4.8) [13.2]
210 °C 3 h		0.818 ab (2.9) [14.7]		0.312 a (5.5) [65]		0.83 ab (-3.7) [10.8]
210 °C 6 h		0.773 ab (-2.8) [16.8]		0.423 a (42.8) [78.9]		0.754 b (-12.6) [28.5]
Control	ν_{RL} n.s. (F 1.537, P 0.181)	0.19 ab [21.6]	ν_{TL} n.s. (F 0.690, P 0.659)	0.027 a [57.4]	ν_{TR} s. (F 3.625, P 0.004)	0.335 a [13.2]
110 °C 3 h		0.211 ab (11.2) [25.4]		0.034 a (24.7) [48.3]		0.338 a (1.1) [15.6]
110 °C 6 h		0.225 a (18.5) [18.5]		0.042 a (54.2) [75.4]		0.310 a (-7.4) [20]
160 °C 3 h		0.178 b (-6.7) [18.1]		0.038 a (40.8) [61.6]		0.337 a (0.7) [16.5]
160 °C 6 h		0.192 ab (0.9) [24.4]		0.048 a (74.1) [55]		0.301 a (-10.2) [18.5]
210 °C 3 h		0.202 ab (6.1) [17.6]		0.028 a (3.7) [65.1]		0.307 a (-8.4) [6.8]
210 °C 6 h		0.214 ab (12.4) [17.5]		0.053 a (93.3) [148.7]		0.245 b (-26.7) [30.1]

n.s. – not significant, s – significant, *Duncan's homogeneity groups, ** % diffraction from the average of the control group, and *** coefficient of variation
*n.s. – nije značajno, s – značajno, *Duncanove grupe homogenosti, ** postotak difrakcije od prosječne vrijednosti kontrolne skupine, *** koeficijent varijacije*

Table 6 Linear regression R^2 values corresponding to Figure 1
Tablica 6. Vrijednosti R^2 linearne regresije koje odgovaraju uzorcima prikazanima na slici 1.

	Density	V_{LL}	V_{RR}	V_{TT}	E_L	E_R	E_T	G_{LR}	G_{LT}	G_{RT}	V_{LR}	V_{LT}	V_{RT}	V_{LR45}	V_{LT45}	V_{RT45}	ν_{RL}	ν_{TL}	ν_{LR}	ν_{TR}	ν_{LT}	ν_{RT}
Density	-	.010	.079	.011	.498	.593	.224	.575	.477	.626	.002	.004	.332	.001	.017	.002	.019	.058	.041	.028	.074	.045
V_{LL}		-	.081	.103	.598	.026	.106	.045	.032	.004	.165	.023	.005	.374	.492	.118	.240	.041	.008	.054	.012	.001
V_{RR}			-	.005	.001	.679	.027	.279	.024	.048	.247	.004	.026	.011	.113	.010	.190	.017	.000	.008	.008	.167
V_{TT}				-	.085	.010	.849	.059	.205	.054	.079	.269	.088	.018	.295	.004	.280	.001	.028	.616	.007	.134
E_L					-	.136	.283	.101	.311	.302	.078	.004	.172	.207	.337	.076	.071	.085	.034	.072	.061	.012
E_R						-	.144	.661	.265	.378	.146	.004	.202	.008	.028	.002	.149	.047	.012	.001	.043	.147
E_T							-	.251	.445	.251	.066	.192	.223	.019	.281	.001	.182	.009	.008	.556	.000	.149
G_{LR}								-	.551	.484	.466	.066	.323	.019	.001	.015	.046	.039	.005	.046	.022	.124
G_{LT}									-	.502	.143	.462	.396	.000	.092	.000	.012	.014	.001	.122	.000	.040
G_{RT}										-	.036	.029	.902	.001	.026	.000	.001	.049	.024	.079	.041	.076
V_{LR}											-	.229	.059	.047	.026	.061	.025	.004	.010	.028	.003	.108
V_{LT}												-	.079	.002	.082	.005	.081	.004	.020	.099	.077	.005
V_{RT}													-	.001	.034	.001	.001	.036	.013	.105	.022	.076
V_{LR45}														-	.337	.079	.451	.022	.167	.009	.004	.042
V_{LT45}															-	.091	.280	.103	.023	.335	.147	.009
V_{RT45}																-	.008	.091	.011	.214	.010	.506
ν_{RL}																	-	.017	.338	.244	.082	.074
ν_{TL}																		-	.382	.144	.712	.301
ν_{LR}																			-	.028	.516	.001
ν_{TR}																				-	.097	.426
ν_{LT}																					-	.098
ν_{RT}																						-

noted no obvious correlation between Poisson's ratios and intensity of the TT determined by ultrasonic tests. As can be seen in Table 5, except for ν_{TR}, the influence of TT on Poisson's ratios is not significant ($P<0.05$). Contrary to moduli and except for ν_{RT} and ν_{TR}, the lowest values were not observed at intensive treatment conditions. Furthermore, Yang *et al.* (2021) stated that Poisson's ratios of the bamboo slivers increased after the TT due to a decrease in the ductility in the loading direction and an increase in the transverse shrinkage. In this study, such an increase regarding the treatment was only observed for ν_{TL} but not linearly with the increase in treatment conditions. Moreover, ν_{TL} presented the highest value among the ratios at 210 °C applied for 6h. In the literature, small differences in the ratios between the unmodified and heat-treated samples were reported (Luis Gómez-Royuela *et al.,* 2021; Wetzig *et al.,* 2011). However, as seen in Table 5, the numerical differences between the control and modified means (-26.7 % to 93.3 %) are remarkably wide. Furthermore, variations in the ratios are high, particularly for ν_{LT} and ν_{TL} but this is not unusual as Luis Gómez-Royuela *et al.* (2021) state that it is a fact for wood material.

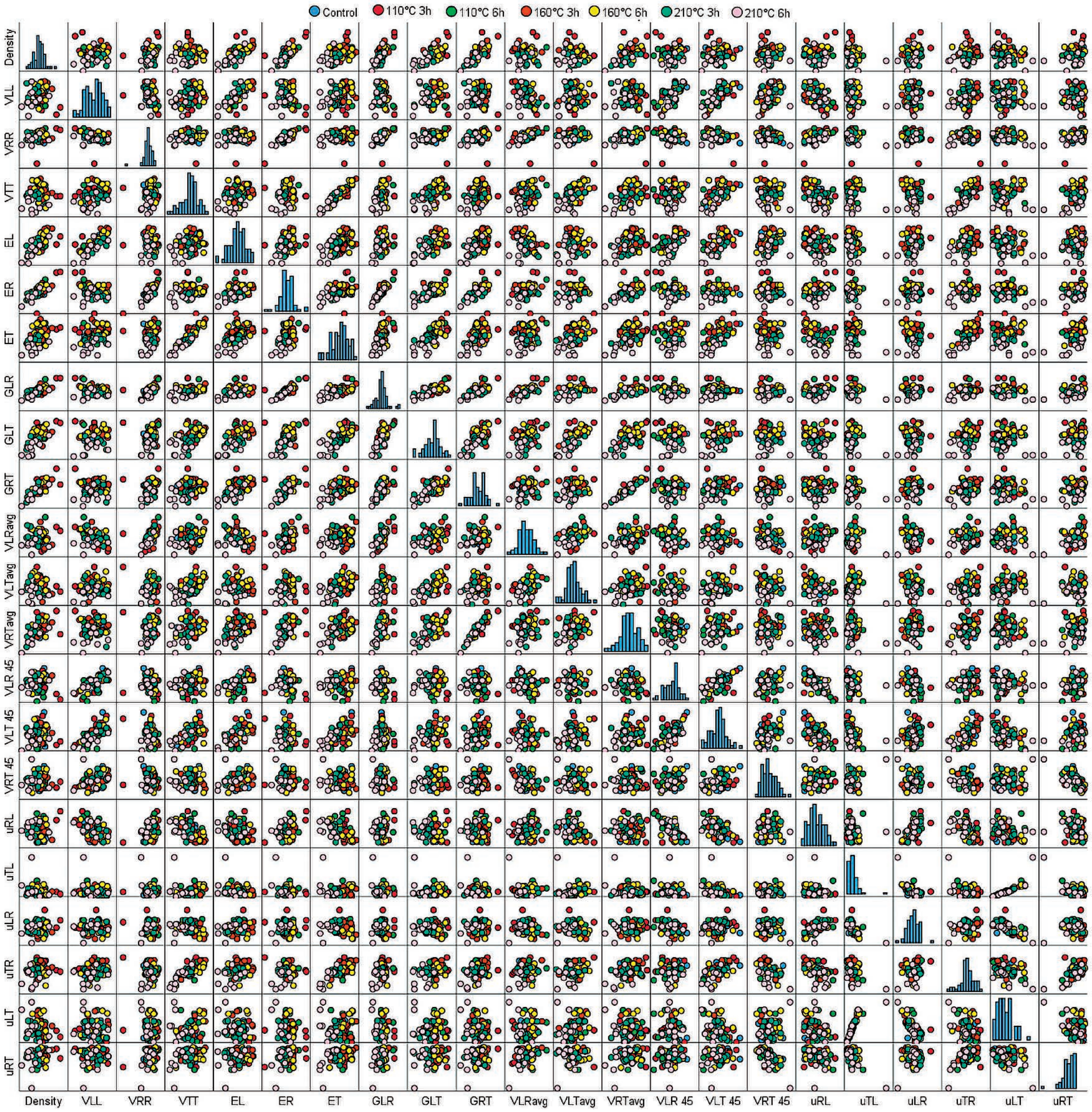

Figure 2 Scatterplot matrix for all measured properties
Slika 2. Matrica dijagrama raspršenja za sva izmjerena svojstva

It is not evident from any of the above papers that Poisson's ratios and density or other elastic constants are highly correlated (Sliker and Yu, 1993). As can be seen in Table 6, R^2 values between the variables ranged from 0.001 (V_{RR} *vs* E_L) to 0.849 (V_{TT} *vs* E_T) for elasticity modulus, 0.004 (V_{LL} *vs* G_{RT}) to 0.661 (E_R *vs* G_{LR}) for shear modulus, 0.000 (νLR *vs* V_{RR} and νLT *vs* E_T or G_{LT}) to 0.712 (νLT *vs* νTL), and 0.001 (V_{LL} *vs* density) to 0.593 (density *vs* E_R) for density. However, much higher R^2 values (0.64 to 0.91) for V_{LL} *vs* density were reported (Yılmaz Aydın and Aydın, 2018b; Yılmaz Aydın and Aydın, 2018; Yılmaz Aydın and Aydın, 2018c). The scatterplot matrix illustrates the interaction between the variables with histograms in terms of treatment groups. Also, the interactions between the density vs UWVs and elastic constants are illustrated in Figures 2-4 by 3D scatters grouped by treatment conditions.

Changes in the structure of wood by TT are comprehensively reported in the literature and advertency is avoided so as not to fall into repetition. However, it should be kept in mind that one of the key points for the reduction in the mechanical properties is the degradation of hemicellulose (Yue *et al.,* 2023).

Apart from elastic constants, Kaymakçı and Bayram (2021) reported 7356 MPa (210 °C 4h) and 10231 MPa (untreated) *MOE* values for *Populus alba* L., and the decrease was linear instead of oscillating. Sözbir *et al.* (2019) heat-treated *Populus usbekistanica* and reported 5693 MPa *MOE* for untreated samples, while the *MOE* averages oscillated with the progress in TT

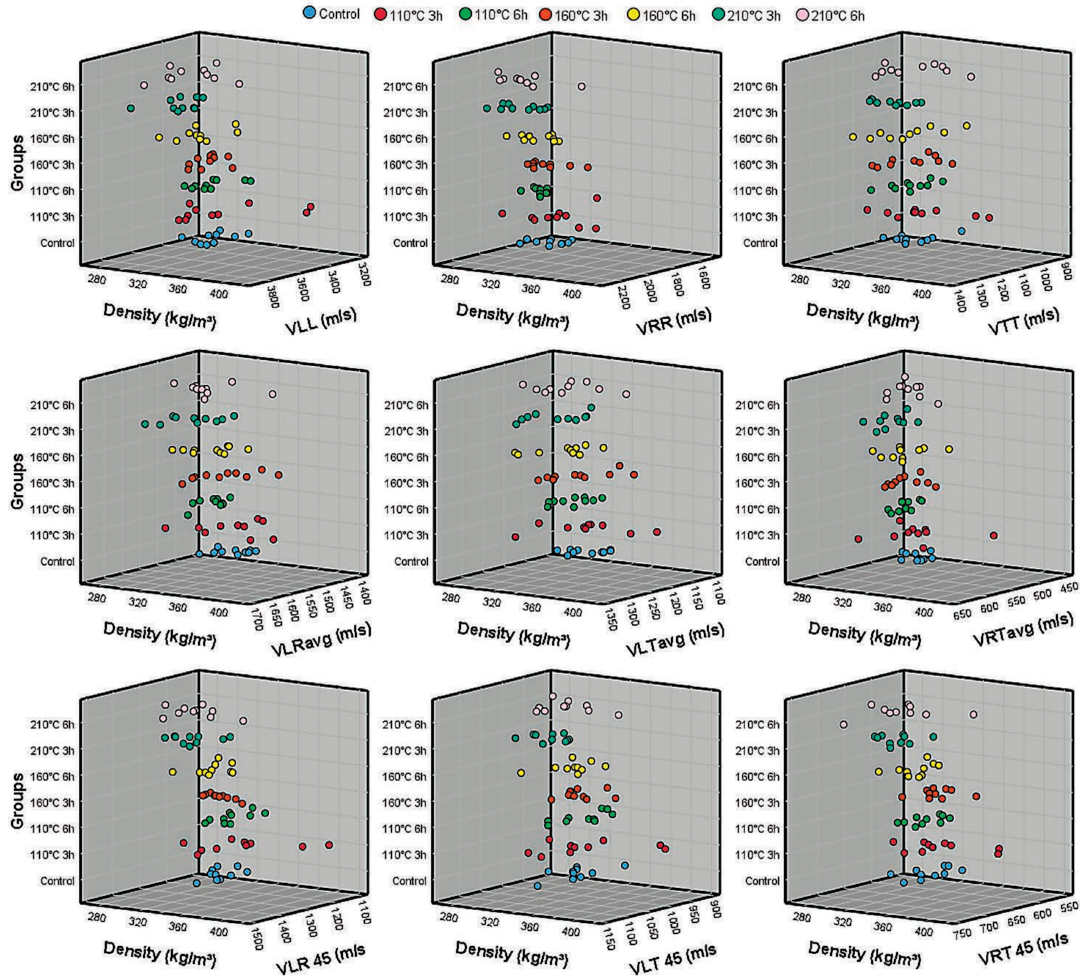

Figure 3 Grouped 3D Scatters for velocities
Slika 3. Grupirana 3D raspršenja za brzine

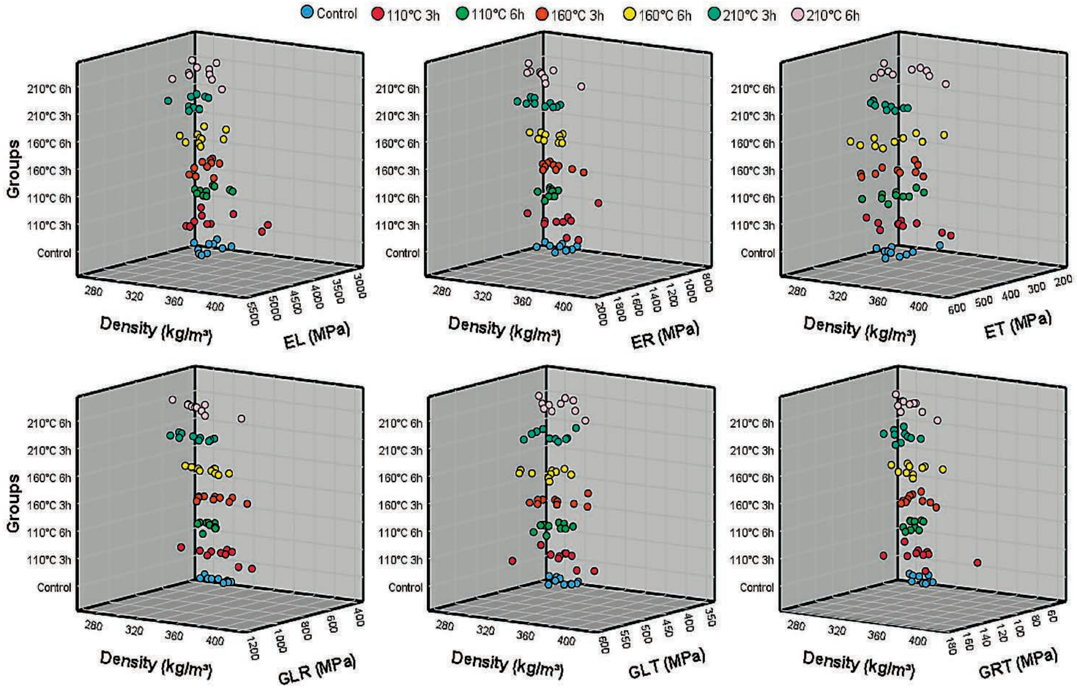

Figure 4 Grouped 3D Scatters for moduli
Slika 4. Grupirana 3D raspršenja za module

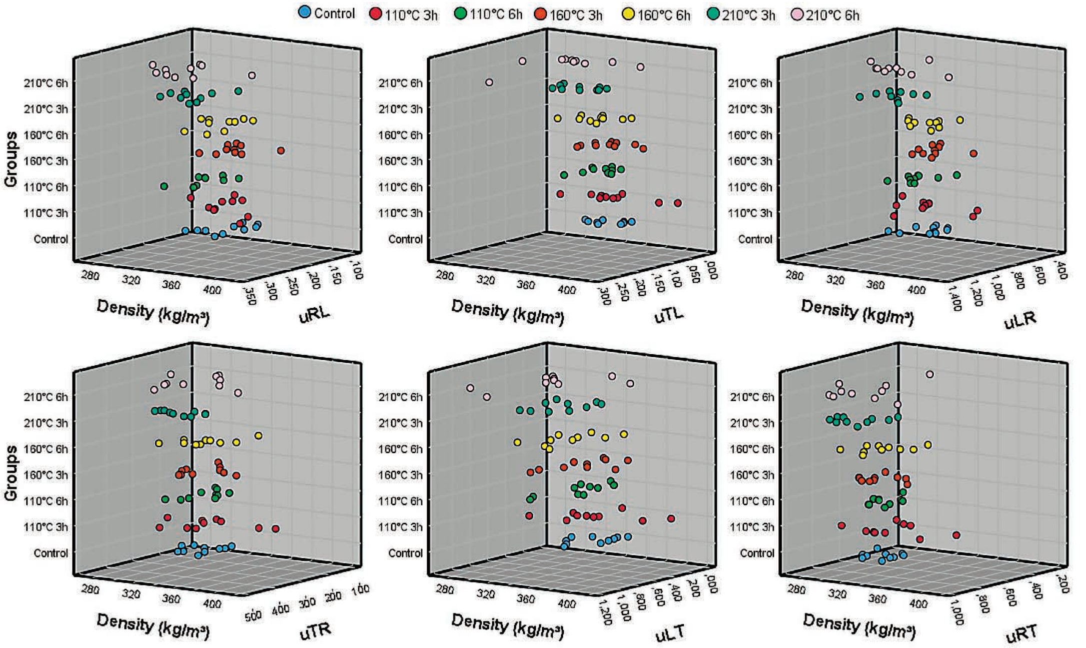

Figure 5 Grouped 3D Scatters for Poisson's ratios
Slika 5 Grupirana 3D raspršenja za Poissonove omjere

(120, 160, and 200 °C for 1 and 3h) and no statistically significant differences were found. For full elastic constants, fluctuation is the fact of this study. Therefore, the results of each study are generally unique or partially the same at moderate temperature levels but almost the same at intense conditions.

4 CONCLUSIONS
4. ZAKLJUČAK

Due to the polar orthotropic nature of wood, it is not an easy task to define factor-related properties, particularly for elastic properties through essential axes or planes. The reason is that not only specific tools are required but also a complex sample preparation due to anatomic complexity and inhomogeneous structure formation by the alignment of elements. Furthermore, samples used for the test are not similar even when prepared using the same laths.

Even though it was obvious that TT significantly affected the elastic characteristics of wood, a common expression of certain effects of TT on wood elastic constants should be avoided because the elastic engineering parameters were non-linearly and differently influenced by the treatment process. Moderate treatment conditions provided considerable advancements in the moduli of wood. However, intense treatment caused the highest decreases in moduli, while the same is not true for some Poisson's ratios. Common treatment conditions did not provide the highest improvements in all elastic constants. Therefore, prioritization should be taken into consideration for defining the application parameters.

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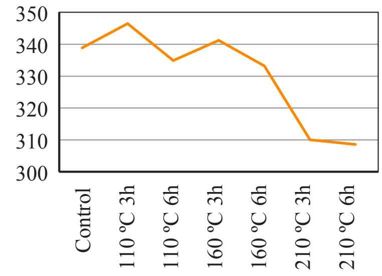
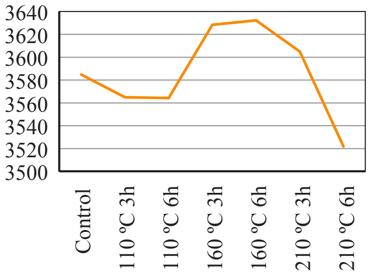
APPENDIX
DODATAK

A.1 Tendency illustration regarding treatment conditions
A.1. Prikaz trendova s obzirom na uvjete toplinske obrade

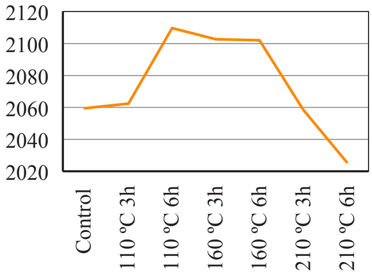
Density / *gustoća*, kg/m³



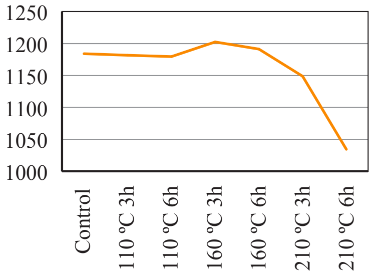
V_{LL}, m/s



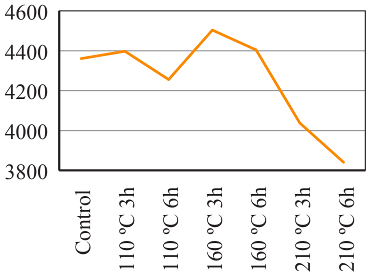
V_{RR}, m/s



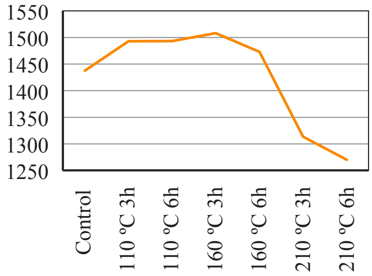
V_{TT}, m/s



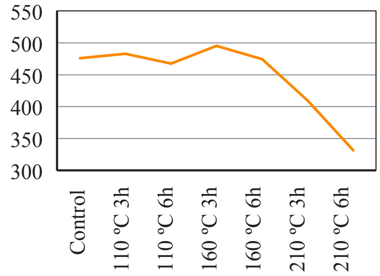
E_L, MPa



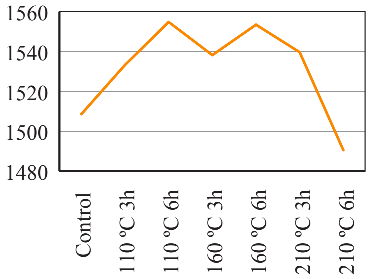
E_R, MPa



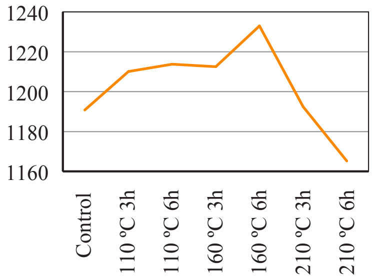
E_T, MPa



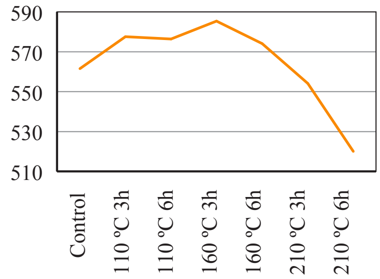
V_{LRavg}, m/s



V_{LTavg}, m/s



V_{RTavg}, m/s




G_{LR}, MPa
850
800
750
700
650
G_{LT}, MPa
520
500
480
460
440
420
400
G_{RT}, MPa
120
110
100
90
80
$V_{LR\ 45°}$, m/s
1320
1300
1280
1260
1240
1220
$V_{LT\ 45°}$, m/s
1020
1010
1000
990
980
970
960
950
$V_{RT\ 45°}$, m/s
655
650
645
640
635
630
625
μ_{RL}
0.230
0.210
0.190
0.170
0.150
μ_{TL}
0.055
0.050
0.045
0.040
0.035
0.030
0.025
0.020
μ_{TR}
0.360
0.340
0.320
0.300
0.280
0.260
0.240
0.220
μ_{LR}
0.900
0.850
0.800
0.750
0.700
μ_{LT}
0.550
0.500
0.450
0.400
0.350
0.300
0.250
μ_{RT}
0.950
0.900
0.850
0.800
0.750
0.700
Control
110 °C 3h
110 °C 6h
160 °C 3h
160 °C 6h
210 °C 3h
210 °C 6h