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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

### ORIGINAL SCIENTIFIC PAPER

#### Izvorni znanstveni rad

Received – prispjelo: 23. 12. 2023.

Accepted – prihvaćeno: 2. 4. 2024.

UDK: 582.681.82; 674.04

<https://doi.org/10.5552/drvind.2024.0180>

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**ABSTRACT** • Twelve elastic constants (Young's modulus ( $E_L$ ,  $E_R$ , and  $E_T$ ), shear modulus ( $G_{LR}$ ,  $G_{LP}$  and  $G_{RT}$ ) and Poisson's ratios ( $\nu_{LR}$ ,  $\nu_{LP}$ ,  $\nu_{RP}$ ,  $\nu_{TR}$ ,  $\nu_{RL}$ , and  $\nu_{TL}$ ) 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  $E_L$ ,  $E_R$ ,  $E_T$ ,  $G_{LR}$ ,  $G_{LP}$ ,  $G_{RP}$ ,  $\nu_{LR}$ ,  $\nu_{LP}$ ,  $\nu_{RP}$ ,  $\nu_{TR}$ ,  $\nu_{RL}$ , and  $\nu_{TL}$  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  $\nu_{RT}$  and  $\nu_{TR}$ , 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 ( $G_{LR}$ ,  $G_{LP}$  i  $G_{RT}$ ) i Poissonovi omjeri ( $\nu_{LR}$ ,  $\nu_{LP}$ ,  $\nu_{RP}$ ,  $\nu_{TR}$ ,  $\nu_{RL}$  i  $\nu_{TL}$ ) 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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$E_T$ ,  $G_{LR}$ ,  $G_{LD}$ ,  $G_{RD}$ ,  $\nu_{LR}$ ,  $\nu_{LD}$ ,  $\nu_{RD}$ ,  $\nu_{TR}$ ,  $\nu_{RL}$  i  $\nu_{TL}$  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 dosegli 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  $\nu_{RT}$  i  $\nu_{TR}$ , 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.

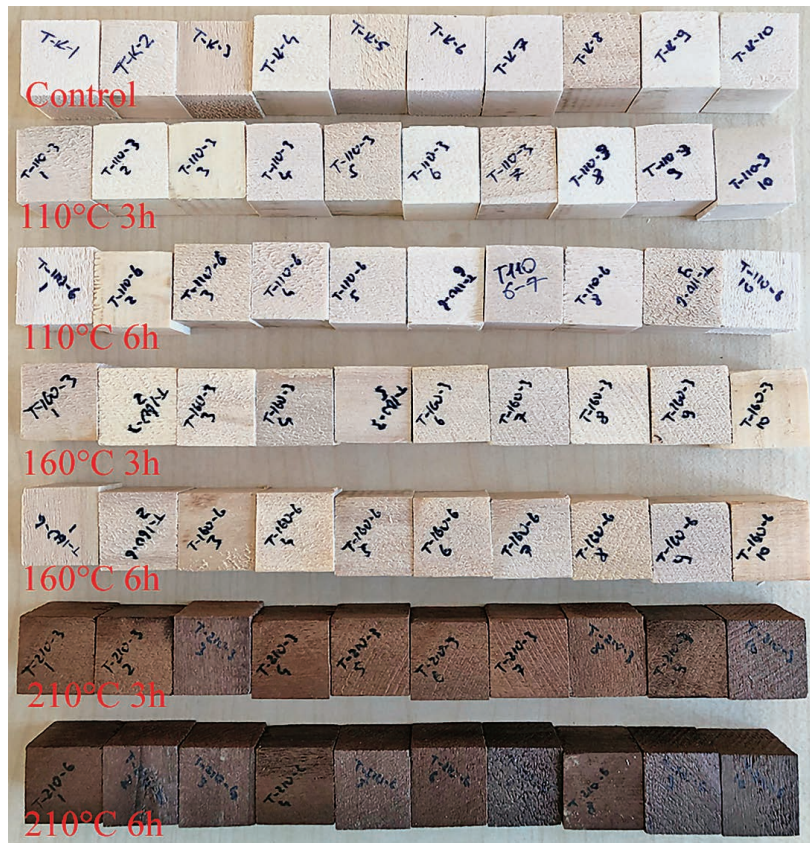
Studies generally reported the  $E_L$  of *Populus deltoids* clones (Narasimhamurthy *et al.*, 2017), poplar (Aydın *et al.*, 2007), *Populus alba* and *Populus nigra* (Monteiro *et al.*, 2019), and *Populus euramericaha* cv. I-69/58 (Guo *et al.*, 2011). The effect of TT on  $E_L$  of *Populus usbekistanica* 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; Villasanté *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 be-

havior 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<br><i>Propagacija – polarizacija</i> | Type of wave<br><i>Vrsta vala</i> | Equation for diagonal and off-diagonal terms<br><i>Jednadžba za dijagonalne i nedijagonalne članove</i> |  |
|---|-----------------------------------|---|--|
| Axis<br>(L, R, and T)   | $V_{LL}$                          | Longitudinal<br><i>uzdužni</i>  | $C_{11} = C_{LL} = \rho V_{LL}^2$  |
|   | $V_{RR}$                          |   | $C_{22} = C_{RR} = \rho V_{RR}^2$  |
|   | $V_{TT}$                          |   | $C_{33} = C_{TT} = \rho V_{TT}^2$  |
|   | $V_{TR/RT}$                       | Shear<br>(Transverse)<br><i>posmični</i><br>( <i>poprečni</i> )   | $C_{44} = C_{RT} = (\rho V_{RT}^2 + \rho V_{TR}^2) / 2$  |
|   | $V_{LT/TL}$                       |   | $C_{55} = C_{LT} = (\rho V_{LT}^2 + \rho V_{TL}^2) / 2$  |
|   | $V_{LR/RL}$                       |   | $C_{66} = C_{RL} = (\rho V_{RL}^2 + \rho V_{LR}^2) / 2$  |
| Off-axis (RT45°)  | $V_{RT/RT}$                       | Quasi-shear<br>(Transverse)<br><i>kvaziposmični</i><br>( <i>poprečni</i> )                              | $(C_{23} + C_{44})n_2n_3 = \pm\sqrt{[(C_{22}n_2^2 + C_{44}n_3^2 - \rho V_{\infty}^2)(C_{44}n_2^2 + C_{33}n_3^2 - \rho V_{\infty}^2)]}$ |
| Off-axis (LT45°)  | $V_{LT/LT}$                       |   | $(C_{13} + C_{55})n_1n_3 = \pm\sqrt{[(C_{11}n_1^2 + C_{55}n_3^2 - \rho V_{\infty}^2)(C_{55}n_1^2 + C_{33}n_3^2 - \rho V_{\infty}^2)]}$ |
| Off-axis (LR45°)  | $V_{LR/LR}$                       |   | $(C_{12} + C_{66})n_1n_2 = \pm\sqrt{[(C_{11}n_1^2 + C_{66}n_2^2 - \rho V_{\infty}^2)(C_{66}n_1^2 + C_{22}n_2^2 - \rho V_{\infty}^2)]}$ |

Where  $\rho$  (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 ob-



tained wave propagation times in  $\mu\text{s}$ . 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 inverting  $[C]$ .

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

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

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

Where  $E$  is Young's modulus,  $G$  is the shear modulus, and  $\nu$  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/m<sup>3</sup> (Casado *et al.*, 2010), 395 kg/m<sup>3</sup> (Papandrea *et al.*, 2022), 405.6 kg/m<sup>3</sup> (Hodoušek *et al.*, 2016), 464 kg/m<sup>3</sup> (Villasante *et al.*, 2021), and 372-468 kg/m<sup>3</sup> (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. x 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 ( $V_{LR45^\circ}$ ), 1210 m/s ( $V_{LT45^\circ}$ ), and 740 m/s ( $V_{RT45^\circ}$ ) for 390 kg/m<sup>3</sup> *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, %**<br>[CoV]*** | Std.<br>Error | 95 % CI for mean<br>(Bounds) |        | Min. | Max. |
|--|------------|----|-----------------------|---------------|------------------------------|--------|------|------|
|  |            |    |                       |               | Lower                        | Upper  |      |      |
| Density, kg/m <sup>3</sup><br>s. (F 6.119,<br>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<br>n.s. (F 0.851, P 0.536)         | 3585 a* [3.2]        | $V_{RR}$ , m/s<br>n.s. (F 1.211, P 0.313)         | 2060 a [3]          | $V_{TT}$ , m/s<br>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<br>s. (F 2.428, P 0.036)           | 1502 bc [2]          | $V_{LT}$ , m/s<br>s. (F 4.636, P 0.001)           | 1210 a [1.3]        | $V_{RT}$ , m/s<br>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<br>s. (F 2.969, P 0.013)           | 1515 bc [1.5]        | $V_{TL}$ , m/s<br>n.s. (F 1.600, P 0.162)         | 1172 ab [3.1]       | $V_{TR}$ , m/s<br>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<br>n.s. (F 1.986, P 0.081) | 1290 ab [5.3]        | $V_{LT45^\circ}$ , m/s<br>n.s. (F 1.760, P 0.122) | 1012 a [5.1]        | $V_{RT45^\circ}$ , m/s<br>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/m<sup>3</sup> 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, %**<br>[CoV] ***   | Property                                   | Mean, %* [CoV]           | Property                                   | Mean, %* [CoV]       |
|------------|--|--------------------------|--|--------------------------|--|----------------------|
| Control    | $E_L$ , MPa<br>s. (F 3.258,<br>P 0.007)    | 4361 ab* [8.3]           | $E_R$ , MP<br>Žs. (F 3.651,<br>P 0.004)    | 1438 ab [6.4]            | $E_T$ , MP<br>s. (F<br>11.172,<br>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)<br>[13.3] |  | 1270 c (-11.7)<br>[12.1] |  | 331 c (-30.4) [16]   |
| Control    | $G_{LR}$ , MPa<br>s. (F 6.176,<br>P 0.000) | 771 ab [4.1]             | $G_{LT}$ , MP<br>s. (F 11.946,<br>P 0.000) | 480 a [3.6]              | $G_{RT}$ , MP<br>s. (F 5.447,<br>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 com-

mon 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  $\nu_{LR}$ ,  $\nu_{LT}$ ,  $\nu_{RT}$ ,  $\nu_{TR}$ ,  $\nu_{RL}$ , and  $\nu_{TL}$  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  $\nu_{RL}$  and  $\nu_{TL}$  are much smaller than other ratios. However, as can be seen in Table 5, this is only valid for  $\nu_{TL}$ . 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    | v <sub>LR</sub><br>n.s.<br>(F 1.514,<br>P 0.188) | 0.795 ab [13.7]        | v <sub>LT</sub><br>n.s.<br>(F 0.884,<br>P 0.512) | 0.296 a [55.8]         | v <sub>RT</sub><br>n.s.<br>(F 1.451,<br>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    | v <sub>RL</sub><br>n.s.<br>(F 1.537,<br>P 0.181) | 0.19 ab [21.6]         | v <sub>TL</sub><br>n.s.<br>(F 0.690,<br>P 0.659) | 0.027 a [57.4]         | v <sub>TR</sub><br>s. (F 3.625,<br>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<sup>2</sup> values corresponding to Figure 1

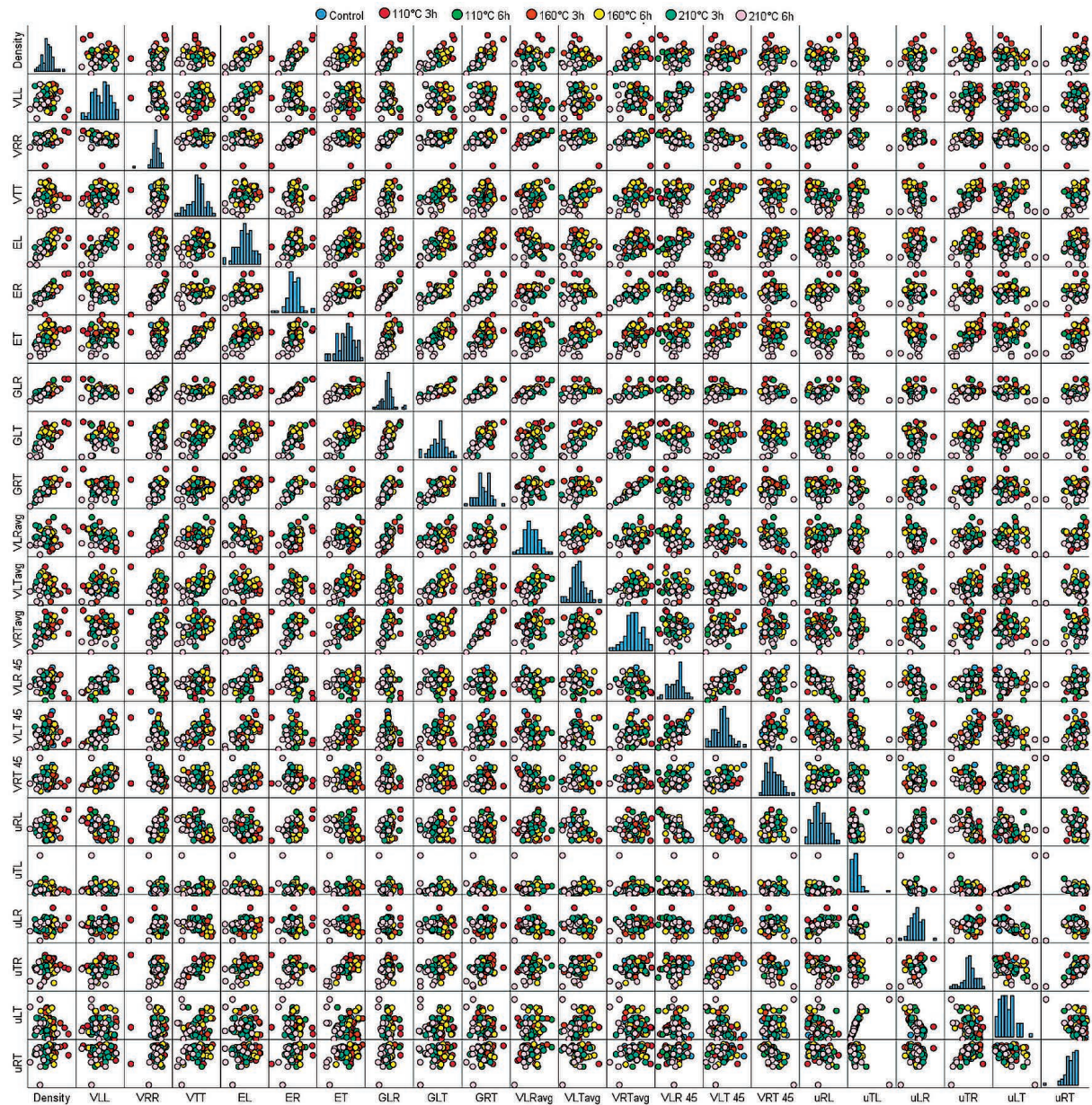
**Tablica 6.** Vrijednosti R<sup>2</sup> linearne regresije koje odgovaraju uzorcima prikazanim na slici 1.

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

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 v<sub>TR</sub>, the influence of TT on Poisson’s ratios is not significant (P<0.05). Contrary to moduli and except for v<sub>RT</sub> and v<sub>TR</sub>, 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 v<sub>TL</sub> but not linearly with the in-

crease in treatment conditions. Moreover, v<sub>TL</sub> 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 v<sub>LT</sub> and v<sub>TL</sub> 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 ( $vLR$  vs  $V_{RR}$  and  $vLT$  vs  $E_T$  or  $G_{LT}$ ) to 0.712 ( $vLT$  vs  $vTL$ ), 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



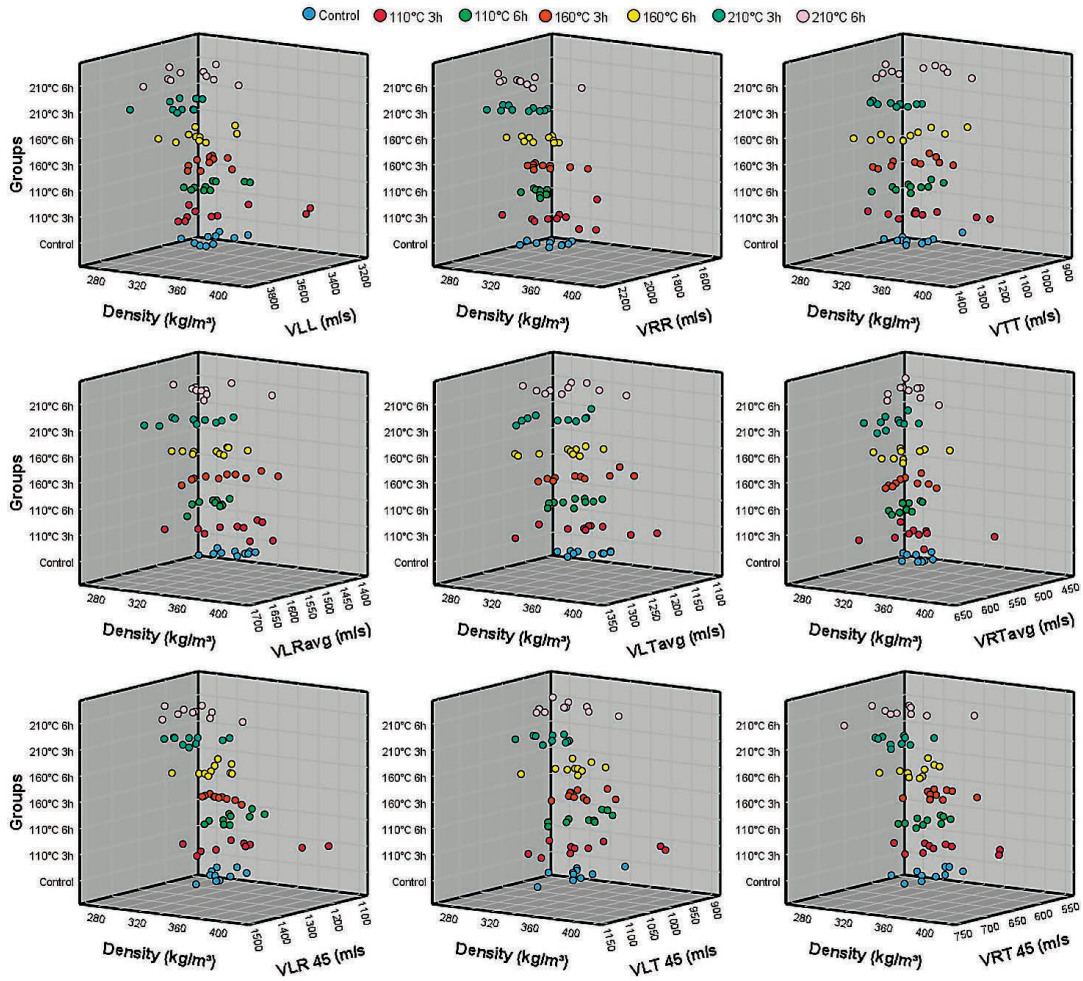


Figure 3 Grouped 3D Scatters for velocities  
Slika 3. Grupirana 3D raspršenja za brzine

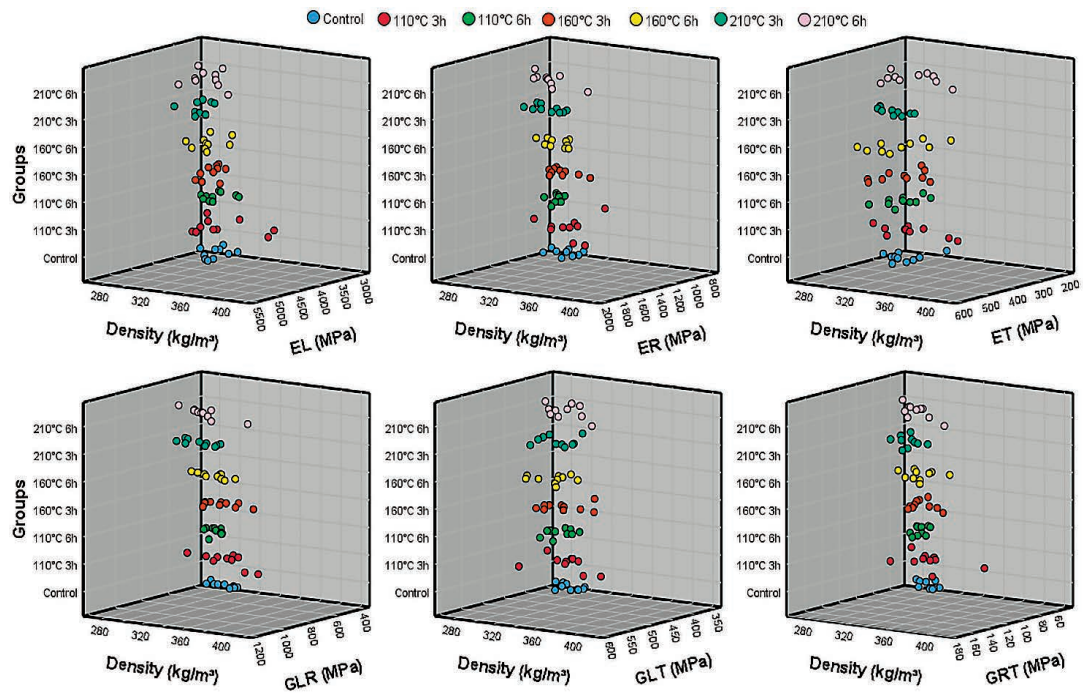
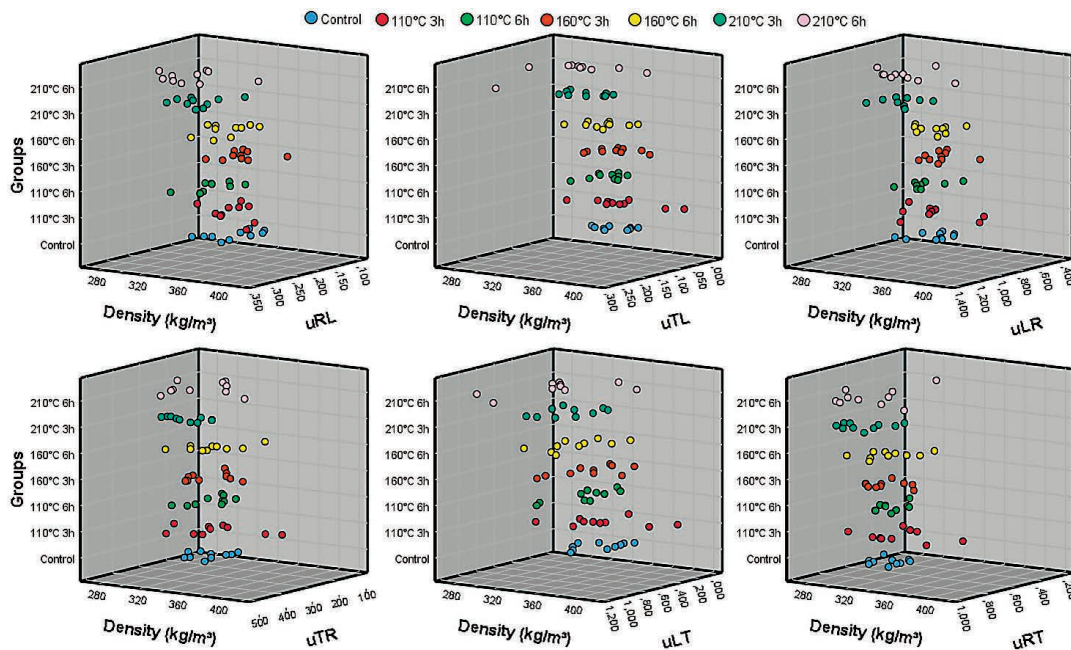


Figure 4 Grouped 3D Scatters for moduli  
Slika 4. Grupirana 3D raspršenja za module



**Figure 5** Grouped 3D Scatters for Poisson's ratios  
**Slika 5** Grupirana 3D raspšenja 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



