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Auxeticity and Wood

Auksetičnost i drvo

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ABSTRACT • *Poisson's ratio, one of the elastic constants, describes the ratio of lateral strain to axial strain when a material is subjected to stress. The range of Poisson's ratios greatly varies in terms of material types and their structures. Furthermore, some materials present negative Poisson's ratios which are attributed to auxeticity. Wood material has six Poisson's ratios corresponding to the neighboring planes of the essential axes of Longitudinal, Radial, and Tangential. Due to the polar orthotropic nature of wood, six of them are different, and generally reported Poisson's ratios are positive. Limited studies focused on the auxetic behavior of wood. This study was focused on the auxeticity evaluation of poplar wood by ultrasonic testing over annual ring inclinations (30°, 45°, and 60°). The elasticity (E_L, E_R, and E_T), and shear (G_{LR}, G_{LT}, and G_{RT}) moduli and Poisson's ratios (μ_{LR}, μ_{LT}, μ_{RL}, μ_{RT}, μ_{TL}, and μ_{TR}) were calculated. According to the results, auxetic behavior was not observed for 30° samples. Furthermore, negative Poisson's ratios were not seen in μ_{TR} and μ_{RT} in all inclinations. However, μ_{LT} and μ_{TL} in 45° and μ_{LR} and μ_{RL} in 60° presented auxetic behavior. Furthermore, higher than 1 Poisson's ratio values were also observed, which is not common for wood material. Also, moduli were determined using a simple formula and stiffness tensor. Considerable differences were observed in elasticity moduli (up to -70 % for E_T), while shear moduli were almost the same. By the increase in inclination, ultrasonic wave velocities were differently affected in terms of increases, decreases, and oscillations. However, the impact of inclination on velocities, and all elastic constants were statistically significant. The coefficients of determination between density and Poisson's ratios were close to zero.*

KEYWORDS: *negative Poisson's ratio; Populus canadensis; ultrasonic; auxeticity*

SAŽETAK • *Poissonov omjer, jedna od konstanti elastičnosti, opisuje omjer bočne i aksijalne deformacije kada je materijal izložen naprezanju. Raspon Poissonovih omjera uvelike varira ovisno o vrsti materijala i njegovoj strukturi. Nadalje, neki materijali pokazuju negativne Poissonove omjere, koji se pripisuju auksetičnosti. Drvni materijal ima šest Poissonovih omjera koji odgovaraju susjednim ravninama glavnih osi – uzdužne, radijalne i tangencijalne. Zbog polarne ortotropne prirode drva, šest Poissonovih omjera ima različite vrijednosti i uglavnom se navodi da su one pozitivne. Ograničen broj istraživanja usmjeren je na auksetično ponašanje drva. Ovo je istraživanje bilo usmjereno na procjenu auksetičnosti drva topole ultrazvučnim ispitivanjem pri kutu otklona godova od 30°, 45° i 60°. Izračunani su moduli elastičnosti (E_L, E_R i E_T), moduli smicanja (G_{LR}, G_{LT} i G_{RT}) i Poissonovi omjeri (μ_{LR}, μ_{LT}, μ_{RL}, μ_{RT}, μ_{TL} i μ_{TR}). Prema rezultatima, auksetično ponašanje nije primijećeno na uzorcima s kutom otklona godova od 30°. Nadalje, negativni Poissonovi omjeri nisu zabilježeni za Poissonove omjere μ_{TR} i μ_{RT} pri svim kutovima otklona godova. Međutim, Poissonovi omjeri μ_{LT} i μ_{TL} pri 45° te Poissonovi omjeri μ_{LR} i μ_{RL} pri 60° pokazali su auksetično ponašanje. Nadalje, primijećene su i vrijednosti Poissonova omjera veće od 1, što nije uobičajeno za drvni materijal. Moduli su određeni uz pomoć jednostavne formule i tenzora krutosti. Uočene su*

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značajne razlike u modulima elastičnosti (do -70 % za E_T), dok su moduli smicanja bili gotovo jednaki. Povećanje kuta otklona godova različito je utjecalo na brzine ultrazvučnih valova u obliku povećanja, smanjenja i oscilacija. Utjecaj kuta otklona godova na brzine i sve elastične konstante bio je statistički značajan. Koeficijenti determinacije između gustoće i Poissonovih omjera bili su blizu nule.

KLJUČNE RIJEČI: *negativan Poissonov omjer; Populus canadensis; ultrazvučni; auksetičnost*

1 INTRODUCTION
1. UVOD

The auxeticity refers to the property of certain materials to exhibit a negative Poisson's ratio, meaning they expand in transverse directions when stretched. In other words, instead of contracting in the transverse direction as typical materials do, auxetic materials widen or increase in thickness. This unique behavior is a result of the internal structure or arrangement of the constituent elements in the material. Auxetic materials often have a specific geometric or structural pattern that allows them to exhibit this counterintuitive property. This can include structures such as specialized cellular, chiral, origami-inspired, and engineered structures, reentrant honeycombs (HC), certain woven or knitted fabrics, certain foams, and crystals.

The auxetic property of materials has attracted interest in various fields, including engineering, materials science, textiles, and biomedical applications. It offers potential advantages such as enhanced impact resistance, improved energy absorption, and increased flexibility in certain applications. However, it is important to note that not all materials possess auxeticity, and the property is specific to certain structures or compositions.

The formation of auxetic materials or structures involves creating a geometric or structural arrangement that exhibits a negative Poisson's ratio, allowing for expansion in transverse directions when subjected to stretching or deformation. The following are a few common approaches to auxetic formation: geometric reconfiguration, material manipulation, origami and kirigami techniques, and additive manufacturing (AM) or 3D printing. The formation of auxetic materials often requires careful design, analysis, and fabrication techniques to achieve the desired properties. By leveraging the unique properties of auxetic structures, innovative designs, and materials can be developed for diverse purposes. Researchers and engineers continue to explore novel methods and materials to create auxetic structures with enhanced functionalities for various applications. For example, composite seat with auxetic springs (Smardzewski, 2013a; Smardzewski *et al*., 2014), auxetic dowels for furniture joints *(Kasal et al*., 2020; Kuşkun *et al.,* 2023, 2021), elastic properties of auxetic cells (Wojnowska *et al.,* 2017), AM of auxetic lattice truss cores (Smardzewski *et al.,* 2018), sandwich panels (SP) with auxetic lattice truss cores (Smardzewski *et al.,* 2021), seat of auxetic spring skeleton (Janus-Michalska *et al.,* 2013), auxetic structure of seat skeleton (Jasińska *et al.,* 2012) elastic features of wood boards with auxetic cores (Smardzewski, 2013b), two dimensional (2D) numerical simulation of auxetic foams (Pozniak *et al.,* 2013), synclastic SP with auxetic wood-based HC cores (Peliński and Smardzewski, 2022), auxetic spring elements for elastically supporting a sitting or lying (Smardzewski and Majewski, 2011), synclastic wood-based auxetic SP' stiffness (Peliński *et al.,* 2020), bending performance of auxetic cellular cored lightweight wood-based sandwich beams (Peliński and Smardzewski, 2020), the preparation of auxetic foams by three dimensional (3D) printing and their features (Critchley *et al.,* 2013), determining the rigidity, strength and energy absorbing capacity in novel SP with HC core produced using wood which has oval cells in the auxetic core (Smardzewski, 2019).

Apart from the abovementioned studies, the auxetic behavior of wood material was evaluated by limited studies for limited species. Marmier *et al.* (2018) evaluated the auxetic behavior of *Pinus strobus* by off-axis compression test and comparison with the finite element analysis. The authors reported -0.02 and -0.74 negative Poisson's ratios (NPR) in H (R 45°) direction but the proof for the auxeticity in wood was weak and scattered. Marmier *et al*. (2023) evaluated the NPR of *Picea* spp, *Pinus densiflora*, *Pseudotsuga menziesii*, *Taxus baccata*, *Ochroma pyramidale*, *Betula platyphylla*, *Fraxinus excelsior*, *Fagus* sp., *Quercus gilva*, and *Goupia glabra*. The authors noticed that NPR, ranging from -2.98 (*Picea Jezoensis* in RTL direction) to 0.07 (*Goupia glabra* +T direction)), were observed in off-axis directions, and that almost all woods with the density lower than 800 kg/m³ were auxetic. In the literature, the NPR was generally related to off-axis characteristics of wood. For example, Yamani (1957) found -0.42 NPR for *Cryptomeria Japonica* at 30° off the L axis. For the same inclination, Kawahara (Kawahara *et al*., 2015) reported -0.22 NPR for *Japanese cypress* and -0.05 NPR for Kalopanax. Sliker and Yu (1993) reported -0.37 NPR for Basswood in the 20° off-axis. Bucur and Najafi (2003) found higher (-0.95) NPR for Douglas fir determined by ultrasonic measurements. However, the authors did not mention the propagation angle or inclination with the essential axes. Therefore, auxetic behavior can be observed in both softwood and hardwood species.

When subjected to tensile stress, wood contracts in the transverse direction and elongates in the axial direction, following the conventional behavior of most materials. Since a few NPR have been reported for limited species, the auxetic behavior of wood needs to be further evaluated. Therefore, figuring out the possible auxetic behavior of wood related to its grain angle was the main motivation of this study particularly using the poplar species. The influence of ring angle on elastic constants of poplar, which has not been reported before, was also determined.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Populus x canadensis Moench wood was used. As can be seen in Figure 1, rings with 30°, 45°, and 60° were marked and samples were cut. Flawless samples (20 for each group) were conditioned at (20 ± 1) °C and 65 % relative humidity till their weight became constant. Following the equilibration, the density of the samples was calculated according to TS ISO 13061-2 (2021).

The elasticity (E_L, E_R, and E_T) and shear (G_{LR}, G_{LT}, and G_{RT}) moduli, and Poisson's ratios (µLR, µLT, µRT, µRL, µTL, and µTR) were dynamically determined by ultrasonic wave propagation. EPOCH 650 (Olympus, USA) ultrasonic flaw detector was used for propagation time measurements. Two types of waves, shear and longitudinal, were transmitted using V153-RM (1 MHz) and A133S-RM (2.25 MHz) contact-type transducers (Panametrics NDT, USA) in through transmission mode. Obtained times in µs were used to calculate axis and off-axis ultrasonic wave velocities (UWV) presented in Table 1. Stiffness matrix' terms (Eq. 1) were calculated and inversed to determine the compliance matrix (Eq. 2) that estimates the elastic constants.

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

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

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

Where: E_i is Young's modulus, G_{ij} is shear modulus, and v_{ij} and v_{ji} are Poisson's ratios.

To figure out the influence of the calculation method, elasticity, and shear moduli were also determined using the following formulas and compared to matrix results.

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*	$C_{11}=C_{LL}=\rho V_{LL}^2$
	V_{RR}		$C_{22}=C_{RR}=\rho V_{RR}^2$
	V_{TT}		$C_{33}=C_{TT}=\rho V_{TT}^2$
	$V_{TR/RT}$	Shear (Transverse) *smicanje (poprečno)*	$C_{44}=C_{RT}=(\rho V_{RT}^2+\rho V_{TR}^2)/2$
	$V_{LT/TL}$		$C_{55}=C_{LT}=(\rho V_{LT}^2+\rho V_{TL}^2)/2$
	$V_{LR/RL}$		$C_{66}=C_{RL}=(\rho V_{RL}^2+\rho V_{LR}^2)/2$
Off-axis (RT 45°)	$V_{RT/RT}$	Quasi-shear (Transverse) *kvazismicanje (poprečno)*	$(C_{23}+C_{44})n_2n_3=\pm\sqrt{[(C_{22}n_2^2+C_{44}n_3^2-\rho V_{\propto}^2)(C_{44}n_2^2+C_{33}n_3^2-\rho V_{\propto}^2)]}$
Off-axis (LT 45°)	$V_{LT/LT}$		$(C_{13}+C_{55})n_1n_3=\pm\sqrt{[(C_{11}n_1^2+C_{55}n_3^2-\rho V_{\propto}^2)(C_{55}n_1^2+C_{33}n_3^2-\rho V_{\propto}^2)]}$
Off-axis (LR45°)	$V_{LR/LR}$		$(C_{12}+C_{66})n_1n_2=\pm\sqrt{[(C_{11}n_1^2+C_{66}n_2^2-\rho V_{\propto}^2)(C_{66}n_1^2+C_{22}n_2^2-\rho V_{\propto}^2)]}$

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

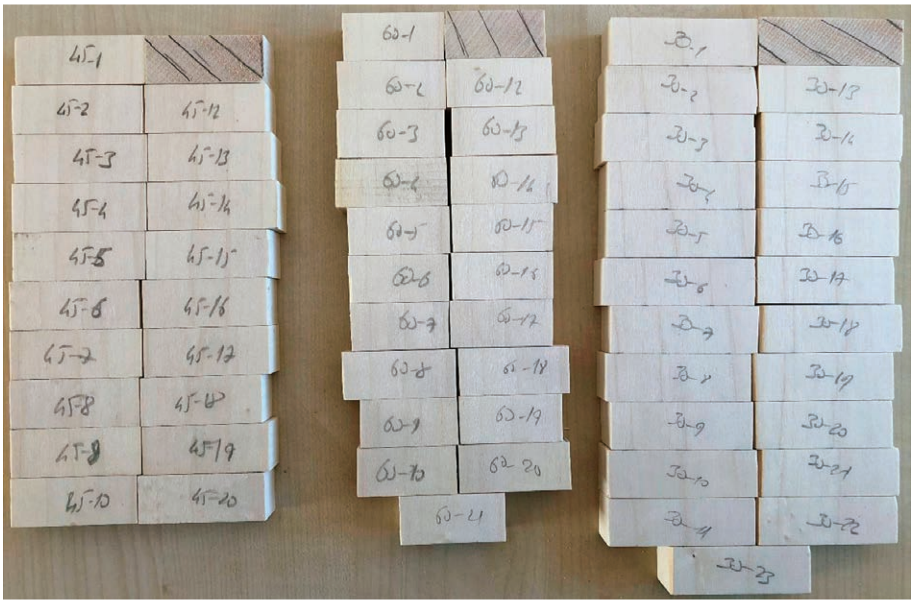

Figure 1 30°, 45°, and 60° samples
Slika 1. Uzorci od 30°, 45° i 60°

$$E_i = \rho\ V_{ii}^2\ 10^{-6} \qquad (3)$$

Where: E_i is elasticity modulus (MPa) in the I direction, ρ is sample density (kg/m³), and V_{II} is longitudinal UWV (m/s).

$$G_{IJ} = \rho\ ((V_{ij} + V_{ji})/2)^2\ 10^{-6} \qquad (4)$$

Where G_{IJ} is shear modulus (MPa) in IJ planes, ρ is sample density (kg/m³), and $V_{IJ} \neq V_{JI}$ is transverse UWV (m/s) in I or J direction with J or I polarization. The means were compared by one-way ANOVA and post hoc multiple comparison (Duncan) was performed.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The density of the samples ranged from 332 to 354 kg/m³. The reported means of *Populus x canadensis* solid wood are 334-374 kg/m³ (Casado *et al.,* 2010), 345-354 kg/m³ (Aydın and Yılmaz Aydın, 2023), 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). As can be seen in Table 2, the means are in harmony with the reported averages and no statistically significant differences in the means were observed.

The averages and statistics for UWVs are presented in Table 2, and as can be seen, V_{RR}, $V_{LR,}$ and V_{RL} were increased with the increase in ring angle, while others fluctuated. The increase in ring angle did not cause the same influences on the UWVs. Furthermore, the ANOVA results reflected these differentiations as ring inclination caused statistically significant differences ($P < 0.05$) in the means. Increases (V_{RR}, V_{LR}, and V_{RL}), decreases (V_{LL}), and increases and then decreases (V_{TT}, V_{LT}, V_{TL}, V_{TR}, and V_{RT}) were observed when the angle increased from 30° to 45° and 60°. Espinoza *et al*. (2018) reported 1193 to 1745 m/s UWV for yellow poplar and figured out that UWV decreases when the angle increases from 0° (radial direction) to 90° (tangential direction) but the decreasing tendency is higher through 30° to 60°. However, such decreases and then increases as in this study were also reported for some other wood species.

The 1782-1850 m/s (V_{RR}), 1463-1501 m/s (V_{LR}), 1491-1588 m/s (V_{RL}), 532-565 m/s (V_{RT}), and 504-522 m/s (V_{TR}) (Aydın and Yılmaz Aydın, 2023) are the reported UWVs for *Populus canadensis*. The 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 ($V_{RT\ 45°}$) for *Populus deltoides* (Zahedi *et al.,* 2022), and 5433-5887 m/s (V_{LL}) for *Populus Euroamericana* (Ettelaei *et al.,* 2019) are the reported UWVs for other poplar species. Saadatnia *et al.* (2016) reported L, R, and T direction UWVs of *Populus deltoids* as 2900-4100 m/s (normal wood) and 3400 to 4200 m/s (tension wood), 1500 m/s, and 1000 m/s, respectively. In general, the UWVs of this study are comparable to the reported velocities.

Elasticity and shear moduli averages and statistics are presented in Table 3. The 899-1211 MPa (E_R), 772-876 MPa (G_{LR}), and 93-111 MPa (G_{RT}) values were reported for *Populus x canadensis* (Aydın and Yılmaz Aydın, 2023). As can be seen in Table 3, when the propagation direction inclined from the essential axes, moduli values dramatically differed (-76 % to -22 % for E_R, -33.4 % to 6.5 % for G_{LR}, and 696.8 % to 377.5 % for G_{LT}) in comparison to (Aydın and Yılmaz Aydın, 2023). Based on outstanding differences of $G_{LT,}$ it can be assumed that the propagation properties of a transverse

Table 2 Descriptives and statistics for density and UWVs
Tablica 2. Statistička analiza rezultata za gustoću i brzinu ultrazvučnih valova

Properties *Svojstva*	**Groups** *Skupine*	**Mean** *Srednja vrijednost*	**Std. Dev.** *Standardna devijacija*	**ANOVA**	
				F.	**Sig.**
Density, kg/m³ *gustoća*, kg/m³	30°	340 a*	2.822	2.336	0.106
	45°	342 a (0.6)**	3.572		
	60°	339 a (-0.3)	5.665		
V_{LL}, m/s	30°	4176 a	169.515	20.522	0.000
	45°	4074 b (-2.4)	28.263		
	60°	3960 c (-5.2)	68.162		
V_{RR}, m/s	30°	1204 b	66.907	114.622	0.000
	45°	1227 b (1.9)	65.274		
	60°	1448 a (20.3)	28.595		
V_{TT}, m/s	30°	1329 b	32.601	146.715	0.000
	45°	1428 a (7.4)	39.545		
	60°	1238 c (-6.8)	32.436		
V_{LR}, m/s	30°	1453 c	10.280	40.698	0.000
	45°	1496 b (3.0)	41.383		
	60°	1543 a (6.2)	34.703		
V_{LT}, m/s	30°	1447 b	10.137	498.816	0.000
	45°	1515 a (4.7)	38.993		
	60°	1249 c (-13.7)	25.733		
V_{TL}, m/s	30°	1410 a	25.483	130.959	0.000
	45°	1427 a (1.2)	21.991		
	60°	1268 b (-10.1)	48.752		
V_{TR}, m/s	30°	633 c	11.403	19.220	0.000
	45°	667 a (5.4)	8.097		
	60°	655 b (3.5)	27.425		
V_{RT}, m/s	30°	601 b	16.370	222.621	0.000
	45°	683 a (13.6)	5.202		
	60°	593 b (-1.3)	19.155		
V_{RL}, m/s	30°	1167 c	10.927	5200.206	0.000
	45°	1463 b (25.4)	14.328		
	60°	1592 a (36.4)	14.901		

*Duncan homogeneity groups, ** difference from 30° group (%)
**Duncanove grupe homogenosti, **razlika od skupine 30° (%)*

wave are in tune with radial direction and tangential polarization which provided similar moduli values.

Comparison of all moduli for *Populus canadensis* was not possible due to the lack of reported data. However, 4.52 GPa E_L, 1.37 GPa E_R, 0.74 GPa E_T, 0.69 GPa G_{LR}, 0.62 GPa G_{LT}, and 0.17 GPa G_{RT} (Zahedi *et al.,* 2022) values of *Populus deltoides,* determined by ultrasonic measurements, and 1103 MPa (E_R), 516 MPa (E_T), and 132 MPa (G_{RT}) values for yellow poplar (Espinosa *et al*., 2018) show somewhat similarity with the results of this study except for E_R. Furthermore, the results of this study can be compared to E_L, $G_{LR,}$ and G_{RT} of *Populus* as reported by Roohnia *et al*. (2010).

The calculation methods have considerable numerical differences in the elasticity moduli, while the shear moduli are almost the same as presented in Table 3 and illustrated in Figure 2. However, dramatic differences were observed between the 60° groups, particularly for E_L and E_T. The longitudinal waves do not have polarization and through the L direction of the wood, V_{LL} decreased only 5.2 %, which was not such a dramatic decrease. The simple formula supports such an assumption. Therefore, the interaction of the other UWVs in the complex formulation in the matrixes caused such a diffraction.

According to ANOVA results, inclination has statistically significant influences on the moduli. Furthermore, as illustrated in Figure 2, different tendencies with the increase in angle were observed instead of stable behavior, particularly for elasticity modules. Moreover, Figures 4 and 5 show the relationships between ring angle, UWV, and moduli.

The Poisson's ratio ranges for hardwood are 0.297-0.495 (μ_{LR}), 0.374-0.651 (μ_{LT}), 0.560-0.912 (μ_{RT}), 0.213-0.496 (μ_{TR}), 0.018-0.086 (μ_{RL}), and 0.009-0.051 (μ_{TL}) and there are considerable variations within and between species (Kretschmann, 2010) and higher than one and negative values are not common for wood material. For isotropic 2D and 3D materials in the elasticity theory, Poisson's ratios range from -1 to 1 (Wojciechowski, 2003) and -1 to 0.5 (Mott and Roland, 2013), respectively. However, large positive or negative Poisson's ra-

Table 3 Descriptives and statistics for moduli
Tablica 3. Statistička analiza rezultata za module

Proper-ties *Svojstva*	**Groups** *Skupine*	**By Equations** / *Prema jednadžbama*				**By Matrix** / *Prema matricama*			
		Mean *Srednja vrijednost*	**Std. Dev.** *Standardna devijacija*	**ANOVA**		**Mean** *Srednja vrijednost*	**Std. Dev.** *Standardna devijacija*	**ANOVA**	
				F.	**Sig.**			***F.***	**Sig.**
E_L, MPa	30°	5937 a*	497	26.075	0.000	4226 b [-28.8] ***	549	260.535	0.000
	45°	5676 b (-4.4)**	74			5179 a (22.6) [-8.8]	340		
	60°	5243 c (-11.7)	176			1930 c (-54.3) [-63.2]	475		
E_R, MPa	30°	494 b	54	119.452	0.000	315 b [-36.2]	66	10.159	0.000
	45°	516 b (4.5)	53			375 a (19.0) [-27.3]	48		
	60°	701 a (41.9)	29			291 b (-7.6) [-58.5]	67		
E_T, MPa	30°	600 b	32	186.100	0.000	494 b [-17.7]	29	842.181	0.000
	45°	697 a (16.2)	35			535 a (8.3) [-23.2]	32		
	60°	513 c (-14.5)	22			154 c (-68.8) [-70.0]	35		
G_{LR}, MPa	30°	583 c	8	610.461	0.000	590 c [1.2]	8	575.535	0.000
	45°	749 b (28.5)	26			749 b (26.9) [0.0]	26		
	60°	822 a (41.0)	27			822 a (39.3) [0.0]	27		
G_{LT}, MPa	30°	694 b	17	474.970	0.000	694 b [0.0]	17	476.918	0.000
	45°	740 a (6.6)	22			741 a (6.8) [0.1]	22		
	60°	530 c (-23.6)	28			530 c (-23.6) [0.0]	28		
G_{RT}, MPa	30°	129 b	4	133.815	0.000	130 b [0.8]	4	130.774	0.000
	45°	156 a (20.9)	3			156 a (20.0) [0.0]	3		
	60°	130 b (0.8)	9			131 b (0.8) [0.8]	9		

*Duncan homogeneity groups, **(%) difference from 30° group, and ***(%) difference between the calculation methods (equations and matrix)
**Duncanove grupe homogenosti, **razlika od skupine 30°* (%), ****razlika između metoda proračuna (jednadžbe i matrice)* (%)

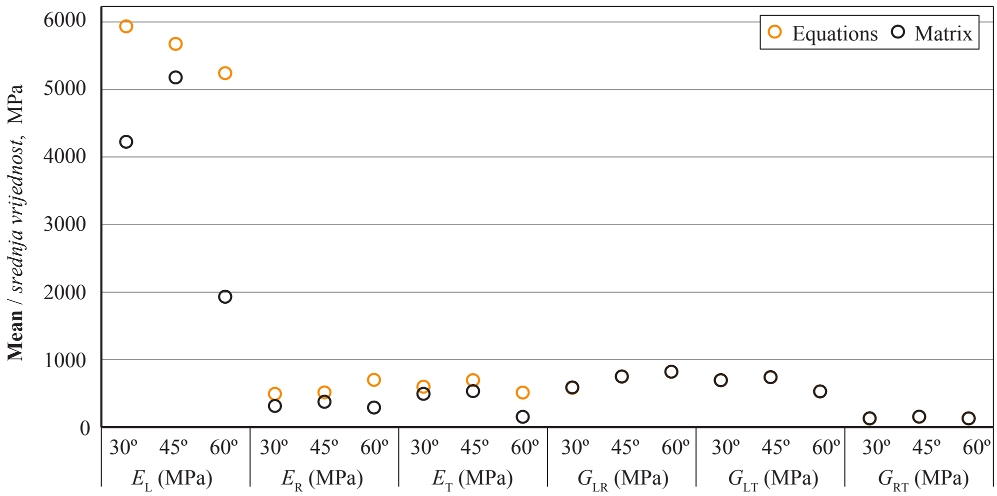

Figure 2 Differences in moduli caused by calculation methods
Slika 2. Razlike u modulima kao rezultat različitih metoda proračuna

tios are the fact for anisotropic elastic materials (Ting and Chen, 2005). Furthermore, for anisotropic or orthotropic 3D structures, Poisson's ratios significantly differ by the directions, and partial auxeticity (presents at least one but not all the directions) is the fact for some materials (Brańka *et al.*, 2011, 2012; Carneiro *et al.*, 2013; Narojczyk and Wojciechowski, 2010). Even though isotropic materials generally present a positive Poisson's ratio, it was highlighted that negative values can be seen for porous materials (Lakes, 1987). For example, Bucur and Najafi (2003) and Murata and Tanahashi (2010) reported NPRs. As seen in Table 4, partial auxeticity and higher than 1 Poisson's ratios were observed. Furthermore, the influence of ring inclination on all Poisson's ratios is statistically significant.

Poisson's ratio of wood can vary depending on factors such as the specific species, moisture content, and growth conditions. Furthermore, while it is challenging to provide precise values for all wood species, Poisson's ratio can also change with the direction of measurement within the wood sample. Extraordinary Poisson's ratios due to inclination (20° - 45°) were reported (Garab *et al.*, 2010; Liu, 2002; Murata and Tanahashi, 2010; Qing and Mishnaevsky, 2010; Reiterer and

Table 4 Descriptives and statistics for Poisson's ratios calculated by Matrix
Tablica 4. Statistička analiza rezultata za Poissonove omjere izračunane uz pomoć matrice

Properties *Svojstva*	**Groups** *Skupine*	**Mean** *Srednja vrijednost*	**Std. Dev.** *Standardna devijacija*	**ANOVA**	
				***F*.**	**Sig.**
μ_{RL}	30°	0.127 a*	0.0236	914.110	0.000
	45°	0.065 b	0.0321		
	60°	-0.264 c	0.0362		
μ_{TL}	30°	0.013 b	0.0325	376.768	0.000
	45°	-0.032 c	0.0384		
	60°	0.221 a	0.0194		
μ_{LR}	30°	1.773 a	0.5016	355.338	0.000
	45°	0.929 b	0.5073		
	60°	-1.744 c	0.2454		
μ_{TR}	30°	0.436 b	0.0862	20.370	0.000
	45°	0.561 a	0.0537		
	60°	0.548 a	0.0607		
μ_{LT}	30°	0.139 b	0.2476	650.469	0.000
	45°	-0.300 c	0.3849		
	60°	2.749 a	0.2029		
μ_{RT}	30°	0.276 c	0.0681	580.268	0.000
	45°	0.394 b	0.0636		
	60°	1.029 a	0.0908		

*Duncan homogeneity groups / *Duncanove grupe homogenosti*

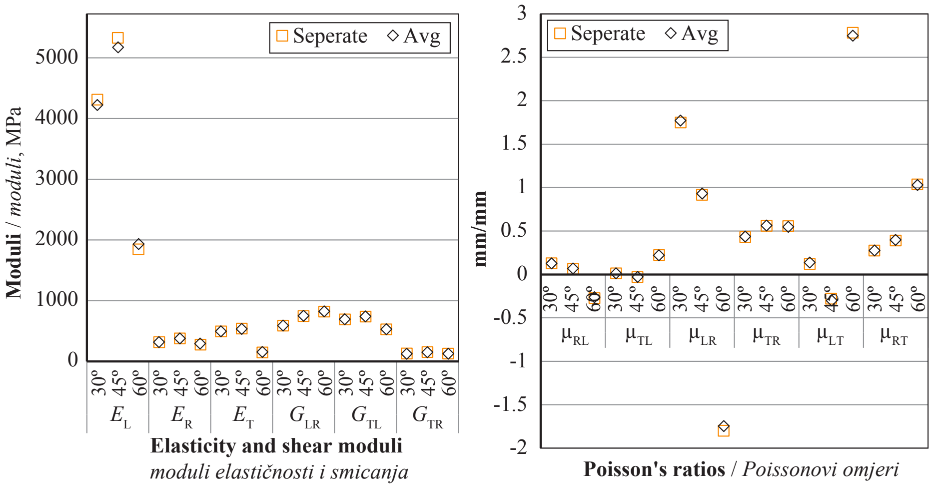

Figure 3 Diffraction illustrations of constants in terms of separate and averaged UWV utilization
Slika 3. Difrakcijske ilustracije konstanti u smislu zasebnoga i prosječnog iskorištenja brzine ultrazvučnih valova

Table 5 Elastic constant means calculated by averaged UWV using Matrix
Tablica 5. Srednje vrijednosti elastične konstante izračunane uz pomoć matrice i primjenom prosječne brzine ultrazvučnih valova

Groups *Skupine*	E_L	E_R	E_T	G_{TR}	G_{TL}	G_{LR}	μ_{RL}	μ_{TL}	μ_{LR}	μ_{TR}	μ_{LT}	μ_{RT}
30°	4313 (2.06)*	316 (0.32)	496 (0.40)	129 (-0.77)	694 (0)	590 (0)	0.128 (0.79)	0.014 (7.69)	1.751 (-1.24)	0.432 (-0.92)	0.122 (-12.23)	0.275 (-0.36)
45°	5331 (2.93)	380 (1.33)	543 (1.50)	156 (0)	740 (-0.13)	748 (-0.13)	0.065 (0)	-0.028 (12.50)	0.918 (-1.18)	0.561 (0)	-0.279 (7.00)	0.392 (-0.51)
60°	1848 (-4.25)	278 (-4.47)	149 (-3.25)	131 (0)	530 (0)	822 (0)	-0.271 (-2.65)	0.224 (1.36)	-1.800 (3.21)	0.556 (1.46)	2.785 (1.31)	1.039 (0.97)

* % difference from constants calculated separately by matrix and then averaged (Table 3)
* *%-tna razlika u odnosu prema konstantama koje su izračunane zasebno prema matrici i zatim uprosječene (tab. 3.)*

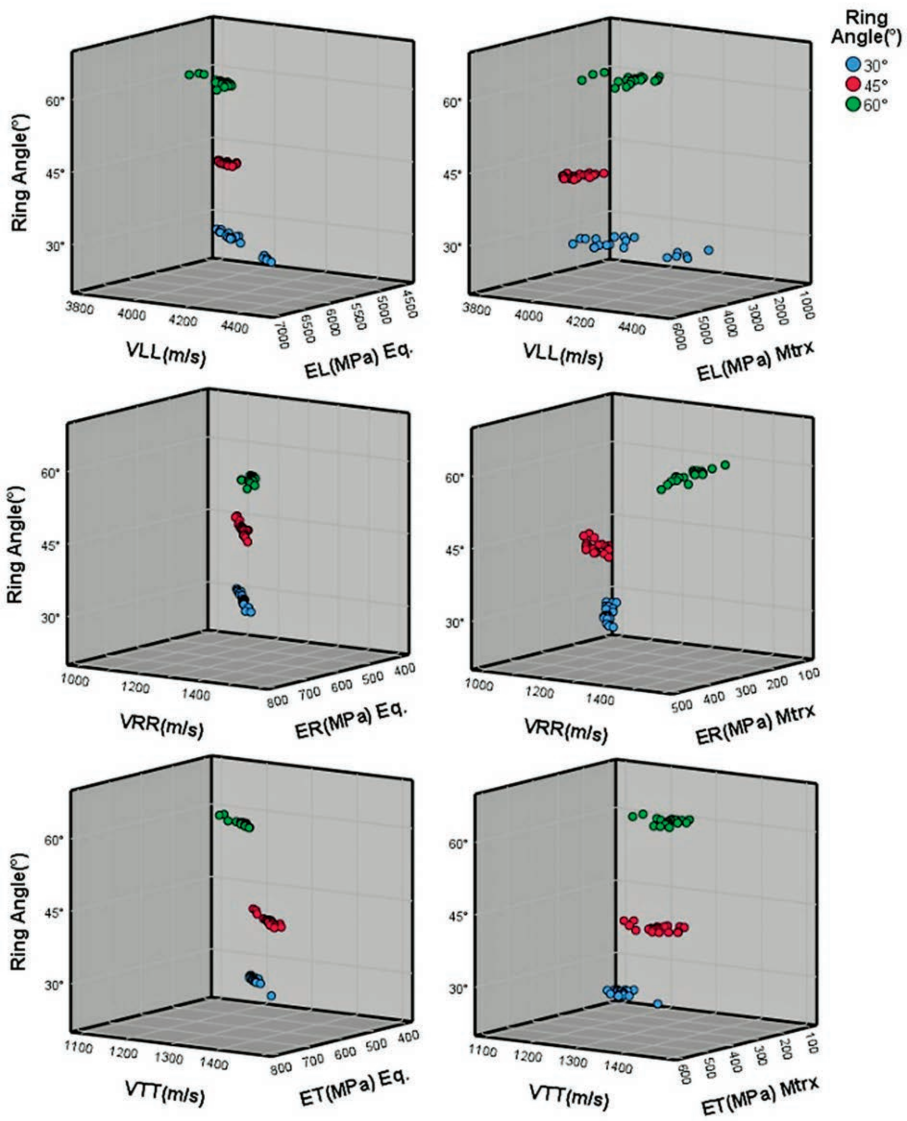

Figure 4 3D scatter of ring angle by longitudinal UWV by elasticity moduli
Slika 4. 3D dijagram raspršenosti kuta otklona goda prema uzdužnoj brzini ultrazvučnih valova i modulu elastičnosti

Stanzl-Tschegg, 2001). Kawahara *et al.* (2015) reported that Poisson's ratios of wood strike their extrema with grain inclination angle of approximately 30°, which was considered to be raised by the effect of shear forces in the L axes of wood. Furthermore, NPRs were observed in the LT plane when the inclination range was 15°-45°. Mascia and Nicolas (2013) determined Poisson's ratios of some Brazilian wood species and figured out the influence of fiber angles (0°, 20°, 45°, 70°, and 90°) on Poisson's ratios of LT, LR, and RT planes. However, no NPR was observed. As seen in Table 4, μLT is negative for 45° but, NPRs were not observed at 30°. Furthermore, LR and RL presented NPR in 60° inclination, and as illustrated in Figure 3, 30° inclination did not provide extrema Poisson's ratios, except for LR.

Numerical differences in the elastic constants due to individual and averaged UWV utilization in the matrix are presented in Table 5 and illustrated in Figure 3, respectively. As can be seen, moduli were slightly changed while diffractions in Poisson's ratios are more notable.

Bodig and Goodman (1973) stated that there is no reported clear interaction between Poisson's ratios and mechanical (moduli or strength) and physical (density) properties. Furthermore, according to Kawahara *et al.* (2015) variation of Poisson's ratios in wood in terms of direction or plane is barely figured out. In this study, the coefficients of determination (R^2) between density and Poisson's ratios are presented in Figure 6. Overall, structural hierarchy (Lakes, 1993), mechanical behavior of wood at the cellular level (Gibson, 2005), microporous structure of wood (Bertoldi *et al.,* 2010), and lots of interacting mechanical processes that occur at the microscopic grade (Ozyhar *et al.,* 2013) are attributed to NPR. Moreover, the anisotropic nature of wood exhibits viscoelastic behavior, and the time-dependent Poisson's impact is known as the viscoelastic Poisson's ratio.

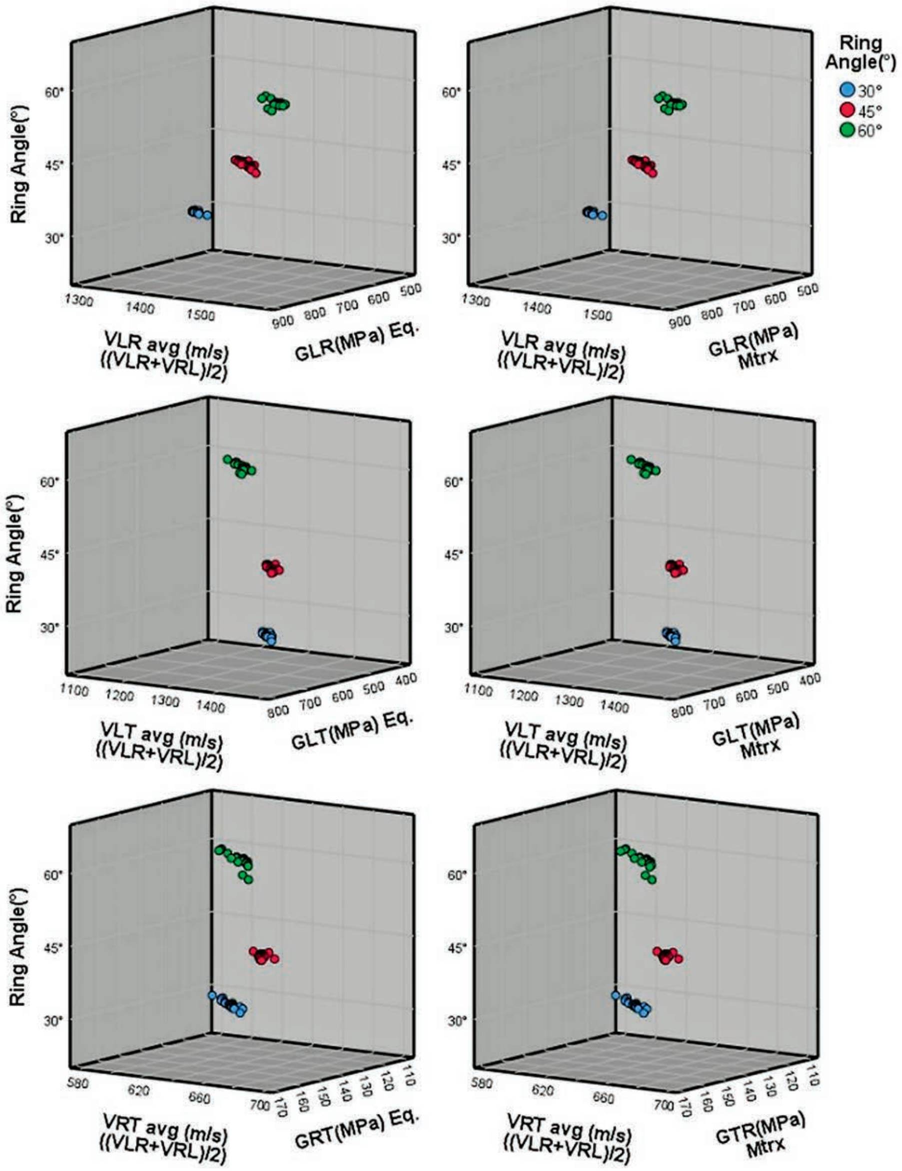

Figure 5 3D scatter of ring angle by averaged shear wave velocity by shear moduli
Slika 5. 3D dijagram raspršenosti kuta otklona goda prema prosječnoj brzini posmičnih valova i modulu smicanja

4 CONCLUSIONS
4. ZAKLJUČAK

Ultrasonic characterization provides valuable information about the structural properties, quality, and potential defects in wood, making it a useful tool for various applications, including wood grading, assessment of wood products, and research on wood properties.

Partial auxeticity was figured out for poplar wood in certain angles. However, a complete auxeticity is not a fact. However, it can be said that wood can be assumed as an auxetic material when the right cutting angles are ensured for obtaining NPRs.

Particularly for elasticity moduli, stiffness tensor provided remarkably lower values against simple formula calculation. Furthermore, the utilization of averaged density and UWV values in the tensor also caused some differences in elasticity and Poisson's ratios.

Almost no numerical differences were found for shear moduli in terms of calculation methods. Therefore, a simple formula can easily be used.

In general, the increase in inclination did not represent the stable behavior of UWV and elastic constants, but the impact is significant.

According to regression models, density was found to be unable to explain the Poisson's ratios.

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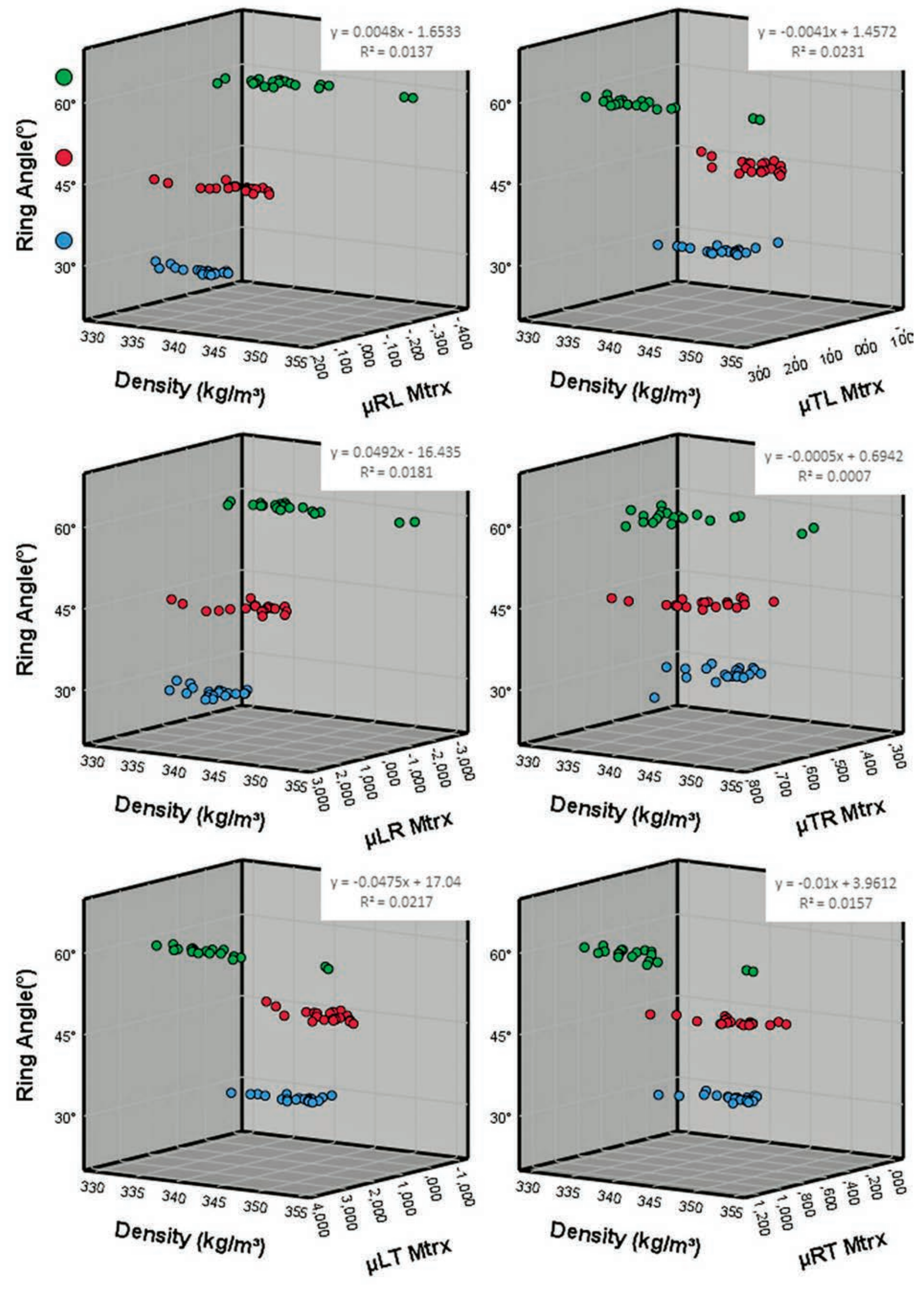

Figure 6 3D scatter of ring angle by density by Poisson's ratios
Slika 6. 3D dijagram raspršenosti kuta otklona goda prema gustoći i Poissonovim omjerima

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