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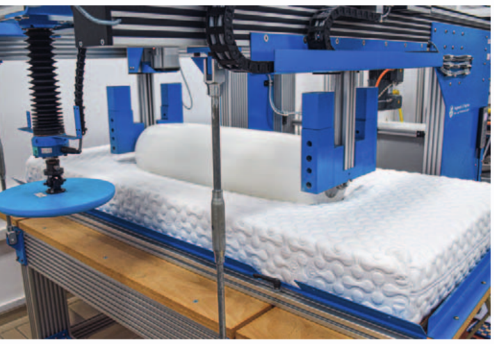

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Ibukun Oluseyi Oyeleye[1*], Jacob Mayowa Owoyemi[2],
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Resistance of Three Commonly Used Wood Species Treated with Selected Plant-Based Oil to Fungi Infestation

Otpornost na gljivice triju često upotrebljavanih vrsta drva zaštićenih odabranim biljnim uljem

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ABSTRACT • *Using wood as a construction material comes with the problem of degradation due to material resistance and exposure to favourable conditions conducive to fungal growth. This study investigated the resistance of treated commonly used wood species (Triplochiton scleroxylon, Gmelina arborea, and Terminalia superba) to fungal decay in construction in Nigeria. The selected wood species were treated with neem oil, moringa seed oil, and castor oil as preservatives. The treatability and physical properties of the treated wood samples were assessed, including moisture content, density, absorption, and retention of preservatives, to ascertain the suitability of oil preservatives. An accelerated fungi infestation test was carried out on the treated wood samples by inoculating them with Gilbertella persicaria for 7 weeks, and visual observation was done every week. The weight loss due to infestation was calculated after the 7th week of exposure to fungi. The wood species exhibited varying moisture content and density with Afara having (27.66 % and 508.61 kg/m^3), Gmelina wood (21.00 % and 528.07 kg/m^3), and Obeche (16.83 % and 531.75 kg/m^3), respectively. For the rate of absorption, Afara recorded (5.06 %, 4.18 %, and 6.58 %), Gmelina wood (9.35 %, 7.61 %, and 8.50 %) and Obeche (0.95 %, 4.22 %, and 8.15 %) when treated with neem oil, moringa seed oil, and castor oil, respectively. Treated wood samples demonstrated significantly lower volumetric swelling and weight loss compared to untreated samples. Castor oil treatment, especially on Gmelina wood, emerged as effective in minimizing dimensional changes and fungi infestation, making it a promising choice for applications requiring stability, leaching resistance, and protection against fungi infestation.*

KEYWORDS: *oil treatment; resistance; physical properties; fungal decay; plant based-oil*

SAŽETAK • *Pri upotrebi drva kao građevnog materijala veliki je problem propadanje drva zbog izloženosti uvjetima koji pogoduju rastu gljiva. U ovoj studiji istraživana je otpornost često upotrebljavanih vrsta drva u graditeljstvu Nigerije (Triplochiton scleroxylon, Gmelina arborea i Terminalia superba) koje su prethodno zaštićene od propadanja uzrokovanoga gljivama. Odabrane vrste drva premazane su uljem nima, uljem sjemenki moringe i ricinusovim uljem kao zaštitnim sredstvima. Procijenjena je mogućnost zaštitnog postupka i fizička svojstva zaštićenih uzoraka, uključujući sadržaj vode, gustoću drva te apsorpciju i retenciju zaštitnog sredstva kako bi se utvrdila prikladnost uljnih zaštitnih sredstava. Ubrzani test zaraze gljivama proveden je na tretiranim uzorcima*

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drva inokulacijom gljivom Gilbertella persicaria tijekom sedam tjedana, a uzorci su vizualno promatrani svaki tjedan. Nakon sedam tjedana izloženosti gljivama izračunan je gubitak mase. Vrste drva pokazale su različit sadržaj vode i gustoću, pri čemu je drvo limbe imalo (27,66 % sadržaj vode i gustoću 508,61 kg/m³), bijelog tika (21,00 % sadržaj vode i gustoću 528,07 kg/m³), a abahe (16,83 % sadržaj vode i gustoću 531,75 kg/m³). Brzina apsorpcije ulja nima, ulja sjemenki moringe i ricinusova ulja za uzorke drva limbe bila je 5,06 %, 4,18 % i 6,58 %, bijelog tika 9,35 %, 7,61 % i 8,50 %, a abahe 0,95 %, 4,22 % i 8,15 %. Tretirani uzorci drva pokazali su znatno niže volumno bubrenje i gubitak mase u usporedbi s netretiranim uzorcima. Tretman ricinusovim uljem, posebno na drvu bijelog tika, pokazao se učinkovitim u smanjenju dimenzijskih promjena i zaraze gljivama, što ga čini prikladnim izborom za primjene na drvu kad se zahtijevaju stabilnost, otpornost na ispiranje i zaštitu od zaraze gljivama.

KLJUČNE RIJEČI: *tretiranje uljem; otpornost; fizička svojstva; propadanje uzrokovano gljivama; prirodna ulja*

1 INTRODUCTION
1. UVOD

Wood, a fundamental resource intertwined with human civilization, serves diverse purposes, notably in construction, where over 80 % of Nigerian timber products are used for building, furniture, and various applications (Tolunay *et al.,* 2008; Ekundayo *et al.,* 2022). Its versatility and resilience make it invaluable, yet its variable nature necessitates the selective use of durable species due to concerns about long-term endurance (Oluwafemi and Adegbenga, 2007; Kayode, 2007). Wood deterioration caused by biological agents such as fungi, poses a significant issue in protecting the structural integrity and durability of wooden structures and furniture (Ligne *et al.,* 2022). This is especially noticeable when using wood species like *Triplochiton scleroxylon, Gmelina arborea,* and *Terminalia superba* due to their lightweight composition (Akanbi and Ashiru, 2002).

Fungal deterioration remains a challenge, leading to significant economic and social costs (Goktas *et al*., 2007). Decay fungi are multicellular filamentous microorganisms that feed on wood structural components by germinating on moist parts and disseminating their hyphae (mycelial filaments) throughout the wood. The resultant effect of this notable deterioration in wood is that its strength decreases as it varies depending on the kind of fungus, wood species, and lumber dimensions (Shupe *et al*., 2008). The use of chemical preservations to enhance wood resilience against bio-deteriorating agents is a traditional technique of wood preservation that has demonstrated limits in providing long-term solutions while also creating significant environmental problems (Khademibami and Bobadilha, 2022).

Addressing these challenges, eco-friendly wood preservatives, particularly plant-based oils, have gained attention (Woźniak *et al*., 2022; Kwon *et al.,* 2023). It has been demonstrated through various findings that the impregnation of wood with eco-friendly materials such as linseed oil, castor oil, basil oil, moringa oil, and other vegetable oil-based hydrophobic liquids significantly reduces cracking in load-bearing timber elements, and reduces water absorption, increasing durability and reducing costs and material consumption in timber structures (Shkarovskiy *et al.,* 2022; Sharaf *et al.,* 2022; Kachel *et al.,* 2023).

Neem oil, derived from the neem tree (*Azadirachta indica*), is known for its antifungal properties attributed to bioactive compounds such as azadirachtin, nimbin, and salannin, which inhibit fungal growth through various mechanisms, including disruption of fungal cell membranes and interference with enzyme activity (Zhang *et al.,* 2016; Brunner *et al.,* 2018). Similarly, Moringa seed oil, extracted from *Moringa oleifera*, shows promising antifungal effects, although its precise mode of action remains incompletely understood. Studies suggest that bioactive constituents like isothiocyanates, flavonoids, and phenolic compounds contribute to its antifungal properties (Deshmukh *et al.,* 2018). Castor oil, obtained from the seeds of the Ricinus communis plant, has been extensively researched for its diverse properties, including its potential as a treatment for fungal resistance in wood species (Kusch and Panstruga, 2017; Kwon *et al.,* 2023). Ricinoleic acid, found in castor oil, exhibits antifungal properties (Kusch and Panstruga, 2017). These oils offer potential avenues for enhancing wood species resistance against fungi, providing diverse mechanisms to combat fungal infestations in wood (Thirkell *et al.,* 2017).

Despite this, there is a research gap in understanding their efficacy in wood preservation, necessitating a push towards traditional organic techniques for environmental sustainability. Therefore, this study investigates the use of selected plant-based oil to enhance *Triplochiton scleroxylon, Gmelina arborea*, and *Terminalia superba* wood resistance against fungal deterioration.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The study was carried out at the Federal University of Technology Akure situated at Latitude 7.2629° N and Longitude 5.1924° E in Ondo State, Nigeria, in the Akure South Local Government Area. The three wood samples were collected from *Triplochiton scleroxylon, Gmelina arborea,* and *Terminalia superba* wood obtained from a reputable industrial sawmill in Akure, Ondo State, Nigeria. For the physical properties and durability test, wood samples (Plate 1) with dimensions of 20mm × 20mm × 60mm and 20mm × 20mm × 20mm were used, respectively. After that, they were oven-dried at about 100°C until constant weight. All samples were prepared and tested according to the modified test of the ASTM 2019 test method for solid woods.

2.1 Treatment of wood samples
2.1. Tretiranje uzoraka drva

The treatment of *Triplochiton scleroxylon, Gmelina arborea,* and *Terminalia superba* wood samples was performed using three plant-based oils: neem oil, moringa seed oil (MSO), and castor oil. Oven-dried wood samples were fully immersed in the oils at their original, undiluted concentrations for 24 hours. The oils were applied hot at approximately 60 °C to maximize flowability and penetration into the wood structure, ensuring adequate absorption. During the immersion, no pressure or vacuum was applied. Following this treatment, the wood samples were removed from the oils, allowed to drain excess oil, and subsequently dried in the oven at a temperature of (102±3) °C until constant weight was attained. The weight of each sample before and after immersion was recorded to estimate absorption efficiency. This procedure facilitated uniform distribution of the oils within the cellular structure of wood, preparing the samples for subsequent testing.

2.2 Fungi inoculation process
2.2. Postupak inokulacije gljivama

The *Gilbertella persicaria* (soft rot fungi) for the accelerated fungi infestation test was stored in the refrigerator at 4 ºC. Twelve sample plates were sterilized with ethanol to accommodate the infected samples. After being sterilized, the plates were placed in the oven for 25 minutes to dry, and 39 g of potato dextrose agar (PDA) was dissolved in 1000 ml of water and heated to dissolve the medium completely using an autoclave at 121 °C and pressure of 151 lbs for 15 minutes. An Amoxicillin capsule was also poured into the PDA to avoid bacteria contamination. After this, a 10 mm cork borer was used to inoculate the fungal isolate to the centre of the prepared PDA and incubate it under aseptic conditions.

Figure 1 Prepared wood samples of the three selected wood species
Slika 1. Pripremljeni uzorci triju odabranih vrsta drva

2.3 Determination of basic physical properties of the selected wood
2.3. Određivanje osnovnih fizičkih svojstava odabranog drva

The physical properties of the three wood species were determined on defect-free wood samples of dimensions of 20 mm × 20 mm × 60 mm for both treated and untreated samples according to the American Society for Testing Materials (2009).

2.3.1 Percentage moisture content
2.3.1. Postotak sadržaja vode

The moisture content of the wood samples was determined using the weight (Plate 3A) of the samples before drying and after drying in the oven to attain a constant weight.

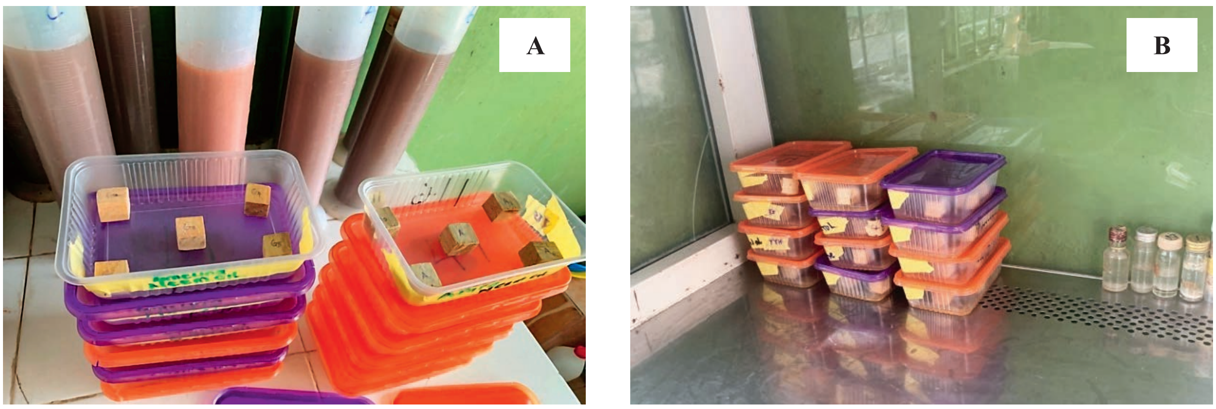

Figure 2 (A) Fungi Inoculation process; (B) Inoculated wood samples
Slika 2. (A) Postupak inokulacije gljivama; (B) inokulirani uzorci drva

$$Moisture\ content\ (\%) = \frac{W_g - W_o}{W_o} \cdot 100 \qquad (1)$$

Where: W_g – Weight of green samples (g); W_o – Weight of dried samples (g).

2.3.2 Density
2.3.2. Gustoća

The density of the wood samples after oven drying was determined using the mass and volume of the oven-dried wood samples. After oven drying, the density of the wood sample was calculated as follows:

$$Density\ (\rho) = \frac{Mass\ of\ oven\ dried\ sample}{Volume} \qquad (2)$$

2.3.3 Volumetric shrinkage (VS)
2.3.3. Volumno utezanje (*VS*)

The volumetric shrinkage of the samples was determined by recording the volume of the wood samples at the green stage and at the end of the drying period. The initial volume of the samples (L × B × H) was taken at the green stage using the vernier calliper, and at the end of the drying process. The final volume attained was measured. The volumetric shrinkage of the samples is estimated as follows:

$$VS\ (\%) = \frac{D_1 - D_2}{D_1} \cdot 100 \qquad (3)$$

Where: *VS* – volumetric shrinkage (%); D_1 – green dimension (mm); while D_2 – final dimensions after oven-drying (mm).

2.3.4 Volumetric swelling (VSW)
2.3.4. Volumno bubrenje (*VSW*)

The volumetric swelling of the three selected wood samples (Plate 3B) treated with oil was determined by taking the oven-dried dimensions of the wood, soaked in water for 24, 48, and 72 hours, respectively, and taking the final dimensions. The following formula was used:

$$VSW\ (\%) = \frac{D_2 - D_1}{D_1} \cdot 100 \qquad (4)$$

Where: *VSW* – volumetric swelling (%); D_1 – oven-dried dimensions (mm), while D_2 – final dimensions after soaking (mm).

2.3.5 Weight loss due to leaching after continuous soaking in water
2.3.5. Gubitak mase zbog ispiranja nakon kontinuiranog namakanja u vodi

After 72 (Plate 3C) hours of continuous soaking of both the treated and untreated samples in water, samples of each wood species were oven-dried till a constant weight was obtained. The weight loss due to leaching was calculated using the formula:

$$\%\ Weight\ loss = \frac{W_2 - W_3}{W_2} \cdot 100 \qquad (5)$$

Where: W_2 – weight before oven drying (g); W_3 – weight after oven drying (g).

2.4 Treatability of wood samples with oil preservatives
2.4. Obrada uzoraka drva uljnim zaštitnim sredstvima

2.4.1 Oil preservative absorption
2.4.1. Apsorpcija uljnih zaštitnih sredstava

This is the amount of preservation chemical the wood samples absorb. The percentage absorption was calculated by using the following formula:

$$\%\ Absorption = \frac{W_2 - W_1}{W_1} \cdot 100 \qquad (6)$$

Where: W_1 – Oven dry weight of the sample (g), W_2 – Initial weight after treatment (g), and W_3 – Final weight after treatment (g).

2.4.2 Oil preservative retention
2.4.2. Retencija uljnih zaštitnih sredstava

The amount of each preservative retained in the wood after the treatment period or cycle was calculated using the equation below:

Figure 3 Experimental procedures for physical properties test: A) weighing of wood samples B) extracted samples prepared for test C) soaking of samples in water
Slika 3. Eksperimentalni postupci ispitivanja fizičkih svojstava: A) vaganje uzoraka drva, B) izdvojeni uzorci pripremljeni za ispitivanje, C) namakanje uzoraka u vodi

Table 1 Assessment of mould growth
Tablica 1. Procjena rasta plijesni

Mould grade *Ocjena plijesni*	**Description** / *Opis*
0	No visible mould growth / *nema vidljivog rasta plijesni*
1	Small amount of mould growth: some doubt about mould *mala količina plijesni: postoji sumnja u postojanje plijesni*
2	Sparse mould growth without a doubt / *nesumnjivo vidljiva plijesan*
3	Moderate mould growth: most of the surfaces are not covered with mould *umjeren rast plijesni: većina površine nije prekrivena s plijesni*
4	Heavy mould growth: surfaces entirely covered with fluffy mycelia and spores *intenzivan rast plijesni: površine su potpuno prekrivene pahuljastim micelijem i sporama*
5	Sever mould growth: multicolour mould with black mould *vrlo izrazit rast plijesni: uz crnu plijesan pojavila se i višebojna plijesan*

$$Retention\ (kg/m^3) = \frac{G \cdot C}{V} \cdot 10 \qquad (7)$$

In Eq. 7, G is the amount of the oil preservatives absorbed by the wood samples at the initial and final weight of each sample in grams; C is the preservative solution in 100 g of the oil preservative; and V is the volume of the wood sample.

2.5 Resistance to fungi infestation test
2.5. Test otpornosti na gljive

2.5.1 Assessment of fungi mould growth
2.5.1. Procjena rasta gljiva i plijesni

The rate of fungi mould growth was calculated during the period of 7 weeks of exposing the wood samples to fungi infestation with visual observation every week using the parameters in Table 1 (Ahmed *et al.,* 2013).

2.5.2 Weight loss due to fungi infestation
2.5.2. Gubitak mase zbog zaraze gljivama

The weight of the wood samples after exposure to the fungi species was calculated using the following equaton:

$$Weight\ Loss\ (\%) = \frac{W_i - W_f}{W_i} \cdot 100 \qquad (8)$$

Where: W_i – oven-dried weight (g) after treatment; W_f – oven-dried weight (g) after exposure to fungi attack of samples treated.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Basic physical properties of the three selected wood species
3.1. Osnovna fizička svojstva triju odabranih vrsta drva

3.1.1 Moisture content and density
3.1.1. Sadržaj vode i gustoća drva

The result of the initial moisture content (*MC*, %) distribution presented in Table 2 showed that the *MC* among the three selected wood species differed significantly, with Afara having the highest moisture content at (27.66 ± 3.58) %, followed by Gmelina (21.00 ± 8.36) %, and Obeche with the lowest value of (16.83 ± 7.08) %. Also, Density distribution (Table 2) showed that Obeche had the highest density of (531.75 ± 49.70) kg/m³, followed by Gmelina (528.07 ± 20.27) kg/m³, while Afara recorded the lowest density of (508.61 ± 34.65) kg/m³. There was a significant difference in moisture content distribution and no significant difference in density among the species. A strong correlation was observed between density and moisture content, indicating that density increased as moisture content decreased. The variation in moisture content and density among the wood species may be attributed to inherent differences in their cellular structures according to Wodzicki (2001). Afara's higher moisture content might be due to its porous structure, influencing its density. There was an inverse relationship between moisture content and density – densities increased as moisture content decreased (Altuntaş and Yıldız, 2007).

3.1.2 Volumetric shrinkage
3.1.2. Volumno utezanje

The descriptive statistics illustrated in Table 2 revealed the distribution of percentage volumetric shrinkage (*VS*) among the three selected wood species, with Gmelina exhibiting the highest *VS* at (10.31 ± 2.61) %, followed by Obeche at (7.67 ± 3.59) %, and Afara recording the lowest value at (3.72 ± 1.79) %. Analysis of variance ($\alpha = 0.05$) for *VS* distributions revealed significant differences among the selected wood species (Table 2). Afara's lower shrinkage may indicate its suitability in applications where minimal dimensional changes are critical (Yildiz *et al*., 2006).

3.2 Treatability of the selected wood species with oil preservatives
3.2. Mogućnost tretiranja odabranih vrsta drva zaštitnim uljnim sredstvima

3.2.1 Treatment absorption
3.2.1. Apsorpcija zaštitnih sredstava

The absorption results (Figure 4) showed clear variation across wood species and treatment types. Afara ex-

Table 2 Descriptive statistics of the basic properties of the selected wood species
Tablica 2. Deskriptivna statistika osnovnih svojstava odabranih vrsta drva

Species *Vrsta drva*	Moisture content, % *Sadržaj vode, %*	Density, kg/m³ *Gustoća, kg/m³*	Volumetric shrinkage, % *Volumno utezanje, %*
Obeche / *abahi*	27.66 ± 3.58^a	508.61 ± 34.65^a	3.72 ± 1.79^c
Afara / *limba*	16.83 ± 7.08^b	531.75 ± 49.70^a	7.67 ± 3.59^b
Gmelina / *bijeli tik*	21.00 ± 8.36^b	528.06 ± 20.27^a	10.31 ± 2.61^a

Note: Alphabets with the same letter indicate no significant difference; alphabets with different letters indicate a significant difference.
Napomena: Vrijednosti s istim slovima nisu značajno različite, dok se vrijednosti s različitim slovima značajno razlikuju.

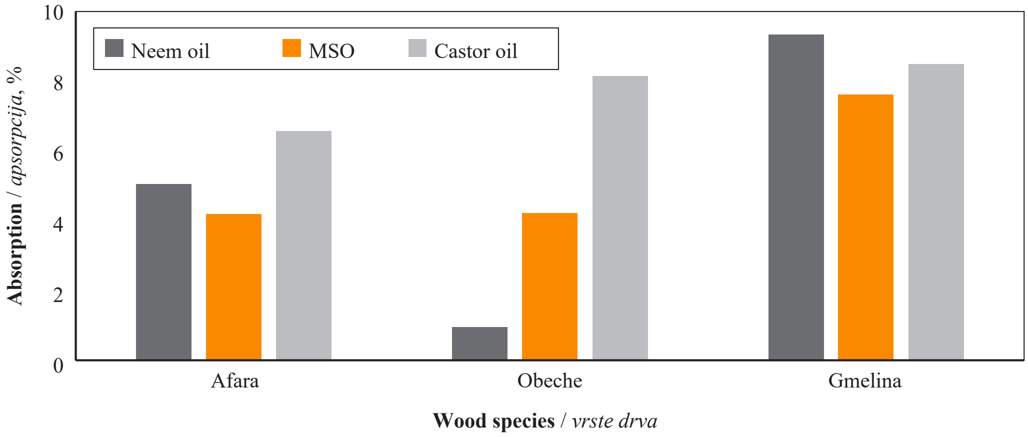

Figure 4 Absorption of varying treatments of the selected wood species
Slika 4. Apsorpcija različitih zaštitnih uljnih sredstava na odabranim vrstama drva

hibited absorption values of (5.06 ± 2.23) %, (4.18 ± 2.70) %, and (6.58 ± 2.51) % when treated with neem oil seed, moringa seed oil (MSO), and castor oil, respectively. Obeche recorded (0.95 ± 0.58) %, (4.22 ± 3.02) %, and (8.15 ± 1.48) % for the same treatments, while Gmelina showed the highest overall absorption, with values of (9.35 ± 3.20) %, (7.61 ± 2.36) %, and (8.50 ± 3.04) % in response to neem oil seed, MSO, and castor oil, respectively. These variations align with earlier findings by Adeduntan and Olusola (2008), who noted that preservative retention in cellulosic materials is strongly influenced by the anatomical structure of different wood species.

Duncan's Multiple Range Test for the treatment absorption (Table 3) also revealed that there are significant differences among both species and treatment types. Among the species, Gmelina (8.48 ± 2.77) % was assigned to group *a*, showing significantly higher absorption than Afara (5.28 ± 2.52) % and Obeche (4.44 ± 3.55) %, both placed in group *b*. This indicates that Afara and Obeche did not differ significantly from each other but absorbed significantly less than Gmelina. For the treatment types, castor oil (7.74 ± 2.41) % formed group *a* and produced significantly higher absorption than neem oil (5.12 ± 4.13) % and MSO (5.34 ± 5.01) %, which were grouped under *b* and showed no significant difference between them. The finding showed that Gmelina demonstrated superior absorption capacity across treatments, while castor oil proved to be the most effectively absorbed preservative.

3.2.2 Retention of oil preservative
3.2.2. Retencija zaštitnih uljnih sredstava

The oil retention results presented in Figure 5 for different treatments, demonstrated varied retention values across the wood species: Afara recorded values of (26.42 ± 10.07) kg/m³, (22.57 ± 14.03) kg/m³, and (33.24 ± 12.14) kg/m³; Obeche (5.50 ± 2.99) kg/m³, (21.95 ± 14.09) kg/m³, and (45.65 ± 8.17) kg/m³ and Gmelina recorded (54.70 ± 19.75) kg/m³, (40.79 ± 11.20) kg/m³, and (46.09 ± 16.32) kg/m³ when treated with Neem oil seed, Moringa seed oil, and Castor oil respectively. Duncan's Multiple Range Test (Table 4) revealed significant

Table 3 Duncan's multiple range tests for treatment absorption
Tablica 3. Duncanovi testovi višestrukog raspona za apsorpciju zaštirnog sredstva

Species *Vrsta drva*	Absorption, % *Apsorpcija, %*	Treatment *Zaštitno sredstvo*	Absorption, % *Apsorpcija, %*
Obeche / *abahi*	5.28 ± 2.52^b	Neem oil	5.12 ± 4.13^b
Afara / *limba*	4.44 ± 3.55^b	MSO	5.34 ± 5.01^b
Gmelina / *bijeli tik*	8.48 ± 2.77^a	Castor oil	7.74 ± 2.41^a

Note: Alphabets with the same letter indicate no significant difference; alphabets with different letters indicate a significant difference.
Napomena: Vrijednosti s istim slovima nisu značajno različite, dok se vrijednosti s različitim slovima značajno razlikuju.

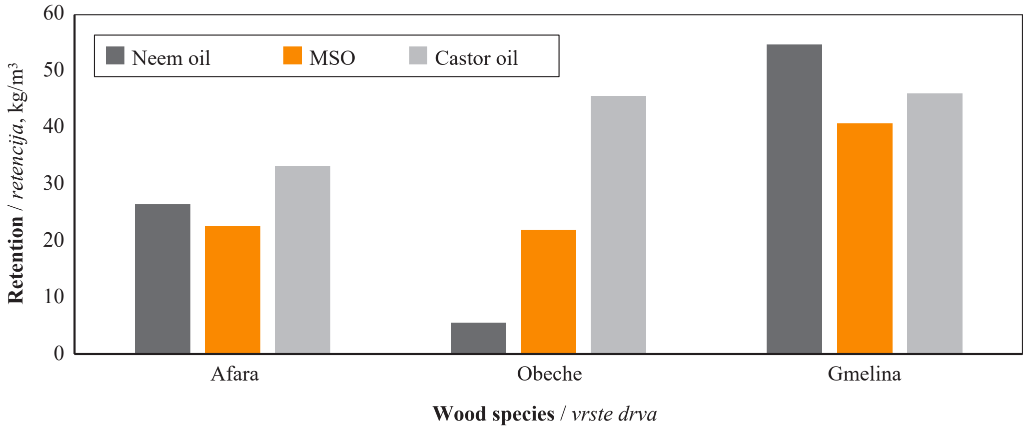

Figure 5 Retention of varying treatments of the selected wood species
Slika 5. Retencija različitih zaštitnih uljnih sredstava na odabranim vrstama drva

Table 4 Duncan's multiple range tests for retention
Tablica 4. Duncanovi testovi višestrukog raspona za retenciju

Species *Vrsta drva*	**Retention, kg/m³** *Retencija,* kg/m³	**Treatment** *Zaštitno sredstvo*	**Retention, kg/m³** *Retencija,* kg/m³
Obeche / *abahi*	24.37 ± 19.22[b]	MSO	28.44 ± 15.18[b]
Afara / *limba*	27.41 ± 12.14[b]	Neem oil	28.87 ± 24.05[b]
Gmelina / *bijeli tik*	47.19 ± 16.08[a]	Castor oil	41.66 ± 13.21[a]

Note: Alphabets with the same letter indicate no significant difference; alphabets with different letters indicate a significant difference.
Napomena: Vrijednosti s istim slovima nisu značajno različite, dok se vrijednosti s različitim slovima značajno razlikuju.

differences in retention among both the wood species and treatment types. Among the species, Gmelina recorded the highest mean retention value (47.19 ± 16.08) % and was assigned to group *a*, indicating that it retained significantly more preservative than the other species. Afara (27.41 ± 12.14) % and Obeche (24.37 ± 19.22) % were both placed in group *b*, showing no significant difference between them, but significantly lower retention compared to Gmelina. This trend suggests that the anatomical characteristics of Gmelina enhance its capacity to retain preservatives more effectively. Similarly, significant differences were observed among the treatment types. Castor oil (41.66 ± 13.21) % formed group *a*, demonstrating the highest and significantly greater retention compared to MSO (28.44 ± 15.18) % and neem oil (28.87 ± 24.05) %, both grouped under *b*. The similarity between MSO and neem oil indicates that these two treatments were absorbed and retained at comparable levels, but far less effectively than castor oil. However, Gmelina exhibited superior preservative retention among the three selected wood species, while castor oil proved to be the most efficient treatment in terms of retention capacity.

3.2.3 Volumetric swelling
3.2.3. Volumno bubrenje

Table 5 presents the descriptive statistics of the volumetric swelling of the three selected wood species

Table 5 Descriptive statistics of volumetric swelling of the selected wood species
Tablica 5. Deskriptivna statistika volumnog bubrenja odabranih vrsta drva

Treatment *Zaštitno sredstvo*	**Time** *Vrijeme*	**Afara** – *Limba* %	**Obeche** – *Abahi* %	**Gmelina** – *Bijeli tik* %
Neem oil / *ulje nima*	24 hours	7.76 ± 1.98	5.60 ± 1.96	7.53 ± 3.97
	48 hours	13.72 ± 4.36	12.05 ± 1.15	10.20 ± 3.52
	72 hours	16.05 ± 3.94	14.26 ± 1.81	14.40 ± 3.60
MSO / *ulje sjemenki moringe*	24 hours	7.48 ± 1.62	8.28 ± 2.97	7.37 ± 1.85
	48 hours	10.86 ± 1.50	12.18 ± 1.70	10.58 ± 1.87
	72 hours	14.71 ± 2.53	15.20 ± 2.54	12.53 ± 2.12
Castor oil *ricinusovo ulje*	24 hours	7.10 ± 2.91	11.13 ± 1.20	8.52 ± 6.84
	48 hours	8.72 ± 1.92	12.27 ± 1.02	11.31 ± 5.85
	72 hours	10.26 ± 3.23	15.71 ± 1.95	13.15 ± 5.89
Control *kontrolni uzorak*	24 hours	4.86 ± 3.07	7.67 ± 4.21	5.16 ± 1.50
	48 hours	8.77 ± 2.62	9.99 ± 3.07	6.51 ± 1.99
	72 hours	10.84 ± 3.10	11.35 ± 3.68	9.28 ± 1.74

Values are mean ± standard deviation. / *Vrijednosti su srednja vrijednost ± standardna devijacija.*

Table 6 Duncan's multiple range tests for volumetric swelling
Tablica 6. Duncanovi testovi višestrukog raspona za volumno bubrenje

Species *Vrsta drva*	**Volumetric swelling, %** *Volumno bubrenje, %*	**Treatment** *Zaštitno sredstvo*	**Volumetric swelling, %** *Volumno bubrenje, %*	**Time** *Vrijeme*	**Volumetric swelling, %** *Volumno bubrenje, %*
Gmelina *bijeli tik*	9.71 ± 3.66[b]	Control	8.27 ± 2.75[b]	24 hours	7.37 ± 2.80[c]
Afara *limba*	10.09 ± 2.90[b]	Castor oil	10.91 ± 3.23[a]	48 hours	10.60 ± 2.76[b]
Obeche *abahi*	11.31 ± 2.46[a]	MSO	11.02 ± 2.11[a]	72 hours	13.15 ± 3.56[a]
		Neem oil	11.28 ± 2.92[a]		

Note: Alphabets with the same letter indicate no significant difference; alphabets with different letters indicate a significant difference.
Napomena: Vrijednosti s istim slovima nisu značajno različite, dok se vrijednosti s različitim slovima značajno razlikuju.

(Afara, Obeche, and Gmelina) subjected to various oil treatments at different immersion durations. Table 4 shows that, on average, Afara, Obeche, and Gmelina recorded volumetric swelling values of (10.09 ± 2.90) %, (11.31 ± 2.46) %, and (9.71 ± 3.66) %, respectively. Table 6 showes that, based on the varying oil treatments, for Afara, samples treated with Neem oil (12.51 ± 3.41) % had the highest swelling, followed by Moringa seed oil (11.02 ± 2.11) %, Castor oil (8.60 ± 2.69) %, and the control (8.61 ± 2.62) %. Similarly, for Obeche, samples treated with Castor oil (13.04 ± 1.39) % showed the highest swelling, followed by Moringa seed oil (11.89 ± 2.04) %, Neem seed oil (10.64 ± 1.64) %, and the control (9.67 ± 3.00) %. For Gmelina, samples treated with Castor oil (11.00 ± 5.54) % recorded the highest swelling, followed by Neem seed oil (10.71 ± 3.70) %, Moringa seed oil (10.16 ± 1.95) %, and the control (6.99 ± 1.74) %. The results indicate that the oil treatments did not bring about a statistically significant improvement in the dimensional stability of the wood species. Nevertheless, the swelling values were closely related across treatments, suggesting that oil impregnation maintained a comparable performance to untreated samples. This observation showed that after 72 hours of water soaking, the volumetric swelling did not differ significantly between the treated and untreated specimens, indicating that the treatments contributed to modest stabilization without detrimental effects on wood structure.

3.2.4 Weight loss due to leaching after soaking in water
3.2.4. Gubitak mase zbog ispiranja tijekom namakanja u vodi

The weight loss due to leaching of the three selected wood treated with varying oil treatments, presented in Figure 6, showed that Afara, Obeche, and Gmelina had (10.43 ± 3.68) %, (15.61 ± 5.22) %, and (7.07 ± 2.14) %, respectively. Based on treatment, for Afara, the untreated samples recorded the highest value of (11.51 ± 5.94) %, followed by Moringa seed oil (11.38 ± 4.50) %, Neem seed oil (10.05 ± 0.42) %, and castor oil (8.79 ± 1.57) %. Likewise, for Obeche, the samples treated with Neem oil recorded the highest value of (19.84 ± 1.49) %, followed by castor oil (16.55 ± 1.49) %, followed by moringa seed oil with (15.66 ± 5.49) % and the control had the lowest value of (10.37 ± 6.09) %, while, for Gmelina the untreated samples recorded the highest value of (9.43 ± 1.97) %, followed by moringa seed oil (7.19 ± 1.91) %, followed by castor oil with (5.88 ± 1.28) % and the wood treated with neem. There is no significant difference in the varying treatments, but the three wood samples are significantly different in terms of weight loss, as samples obtained from Gmelina per-

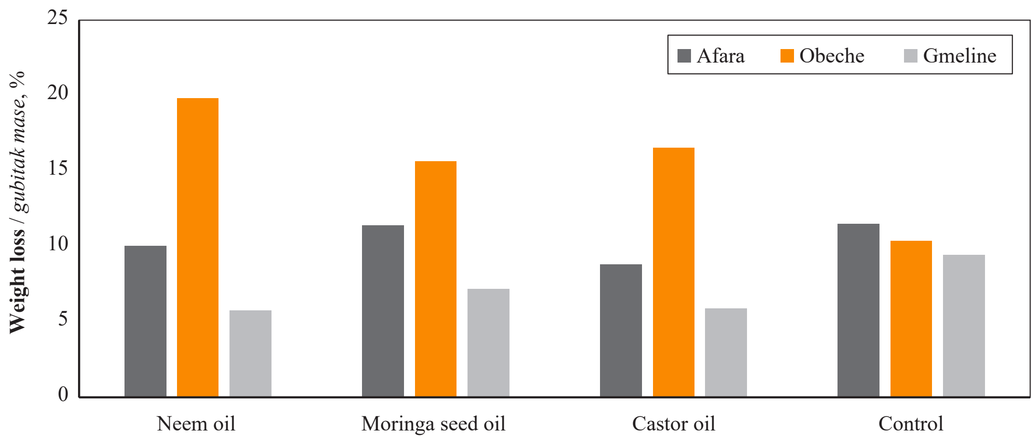

Figure 6 Descriptive statistics of weight loss due to leaching of the selected wood species
Slika 6. Deskriptivna statistika gubitka mase odabranih vrsta drva zbog ispiranja

Table 7 Duncan's multiple range tests for weight loss
Tablica 7. Duncanovi testovi višestrukog raspona za gubitak mase

Species *Vrsta drva*	**Weight loss, %** *Gubitak mase, %*	**Treatment** *Zaštitno sredstvo*	**Weight loss, %** *Gubitak mase, %*
Gmelina / *bijeli tik*	7.07 ± 2.14[a]	Castor oil	10.41 ± 4.85[a]
Afara / *limba*	10.44 ± 3.68[b]	Control	10.44 ± 4.75[a]
Obeche / *abahi*	15.61 ± 5.22[c]	MSO	11.41 ± 5.32[a]
		Neem oil	11.88 ± 6.19[a]

Note: Alphabets with the same letter indicate no significant difference; alphabets with different letters indicate a significant difference.
Napomena: Vrijednosti s istim slovima nisu značajno različite, dok se vrijednosti s različitim slovima značajno razlikuju.

formed best, which was significantly different from samples obtained from Afara and Obeche.

Duncan's Multiple Range Test (Table 7) revealed significant differences in weight loss among the wood species but not among the treatment types. Among the species, *Gmelina* recorded the lowest weight loss (7.07 ± 2.14) % and was placed in group *a*, indicating significantly greater resistance to deterioration. Afara (10.44 ± 3.68) % was assigned to group *b*, showing moderate weight loss, while Obeche (15.61 ± 5.22) % exhibited the highest weight loss and was assigned to group *c*, indicating significantly lower durability compared to both Gmelina and Afara. This pattern suggests that Gmelina possesses inherently superior natural resistance to degradation, while *Obeche* is the most susceptible to weight loss. In contrast, the treatment types showed no significant differences in weight loss. Castor oil (10.41 ± 4.85) %, the control (10.44 ± 4.75) %, MSO (11.41 ±

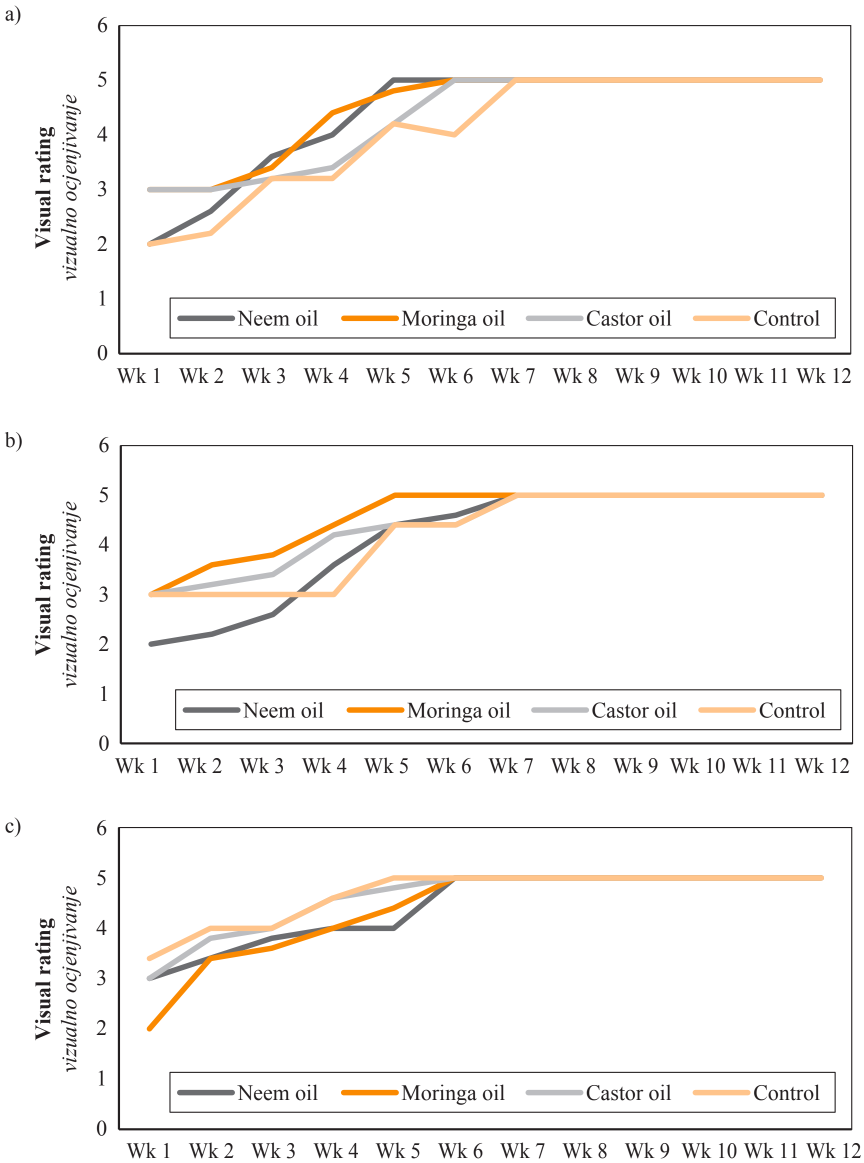

Figure 7 Resistance of treated wood against fungi infestation; a) Afara, b) Gmelina, c) Obeche
Slika 7. Otpornost tretiranog drva na zarazu gljivama: a) drvo limba, b) drvo bijelog tika, c) drvo abahija

5.32) %, and neem oil (11.88 ± 6.19) % all belonged to the same statistical group, indicating that none of the treatments provided a significantly different level of protection under the conditions of this study. This suggests that treatment type had little influence on weight loss compared to inherent species characteristics.

3.3 Resistance of wood treated against fungi infestation
3.3. Otpornost tretiranog drva na zarazu gljivama

3.3.1 Fungi mold growth
3.3.1. Rast plijesni

Figure 7a shows the resistance of Afara wood treated with varying oil treatments against fungi infestation. It showes that the untreated samples of Afara and samples treated with Neem oil recorded moderate infestation after exposure to fungi from week 1 to week 3 and complete infestation at week 8 and week 5, respectively, owning that the untreated Afara wood tended to sustain more resistance against fungi, while Afara wood treated with moringa oil and castor oil showed heavy infestation from week 1 of exposure and complete infestation from week 5 and 6, respectively. Also, Figure 7b shows that the Gmelina wood treated with neem seed oil recorded the best resistance against fungi infestation after showing slight infestation from week 1 to week 4 of exposure to fungi infestation. In contrast, untreated wood samples and those treated with moringa oil and castor oil showed moderate infestation from week 1 of exposure and were completely infested from week 5 of exposure. Likewise, Figure 7c shows that the Obeche wood treated with moringa oil recorded the best resistance against fungi infestation after showing slight infestation from week 1 to week 2 of exposure to fungi infestation. In contrast, wood samples treated with neem seed oil and castor oil showed moderate infestation from week 1 of exposure, and were completely infested from week 6 of exposure, while the untreated Obeche, which showed the least performance, was heavily infested from week 1 and showed complete infestation at week 5 of exposure to fungi.

3.3.2 Weight loss due to fungi infestation
3.3.2. Gubitak mase zbog zaraženosti gljivama

Weight loss of oil-treated wood species due to fungal infestation (Figure 8) varied across species and treatments. Among the wood species, Gmelina exhibited the lowest overall weight loss (4.29 ± 2.46) %, followed by Afara (7.56 ± 3.84) % and Obeche (9.02 ± 6.80) %, indicating differences in inherent resistance to biodeterioration. Within species, weight loss also varied depending on the treatment. For Afara, neem oil-treated samples showed the highest weight loss (8.97 ± 4.69) %, followed by untreated samples (7.51 ± 1.60) %, moringa seed oil (MSO) (7.43 ± 4.58) %, and castor oil (6.31 ± 4.48) %. In Obeche, untreated samples exhibited the greatest weight loss (15.99 ± 8.85) %, followed by neem oil (8.79 ± 6.85) %, castor oil (6.17 ± 1.83) %, and MSO (5.13 ± 1.08) %. For Gmelina, the highest weight loss was recorded in neem oil-treated samples (6.80 ± 3.28) %, followed by the control (4.14 ± 1.87) %, MSO (3.55 ± 1.26) %, and castor oil (2.67 ± 1.06) %. Overall, preservative-treated wood experienced less heavy infestation, while Afara wood showed moderate damage even in oil-treated samples from the first week of exposure.

Duncan's Multiple Range Test (Table 8) confirmed these observations, revealing significant differences in weight loss among wood species. Gmelina (4.29 ± 2.46) % was placed in group *a*, demonstrating significantly greater resistance compared to Afara (7.56 ± 3.84) % and Obeche (9.02 ± 6.80) %, both in group *b*, which did not differ significantly from each other. This highlights the inherently superior durability of Gmelina. Significant differences were also observed among the treatments. Castor oil (5.05 ± 3.17) % and MSO (5.37 ± 3.08) % formed group *a*, representing the

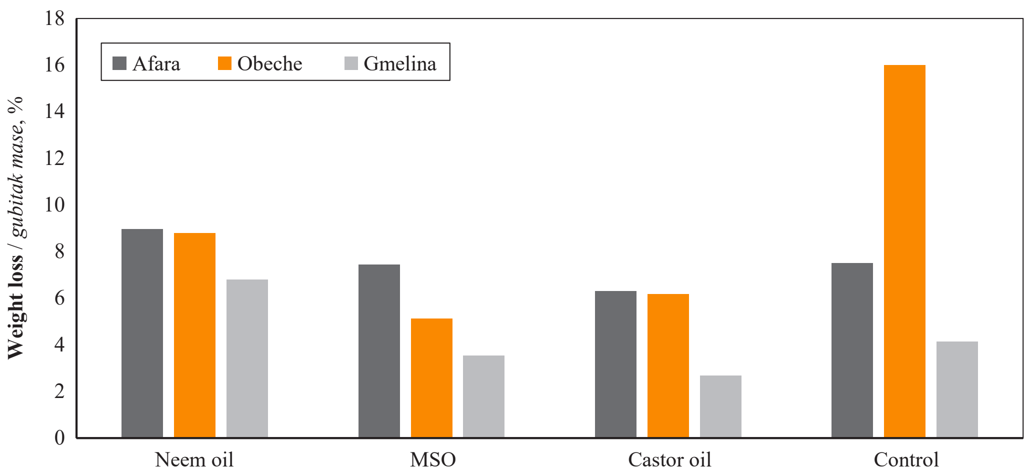

Figure 8 Percentage weight loss of wood species to fungal infestation
Slika 8. Postotni gubitak mase drva zbog zaraženosti gljivama

Table 8 Duncan's multiple range tests for weight loss
Tablica 8. Duncanovi testovi višestrukog raspona za gubitak mase

Species *Vrsta drva*	**Weight loss, %** *Gubitak mase, %*	**Treatment** *Zaštitno sredstvo*	**Weight loss, %** *Gubitak mase, %*
Gmelina / *bijeli tik*	4.29 ± 2.46[a]	Castor oil	5.05 ± 3.17[a]
		MSO	5.37 ± 3.08[a]
Afara / *limba*	7.56 ± 3.84[b]	Neem oil	8.18 ± 4.88[b]
Obeche / *abahi*	9.02 ± 6.80[b]	Control	9.21 ± 7.13[b]

Note: Alphabets with the same letter indicate no significant difference; alphabets with different letters indicate a significant difference.
Napomena: Vrijednosti s istim slovima nisu značajno različite, dok se vrijednosti s različitim slovima značajno razlikuju.

most effective treatments for minimizing weight loss, while neem oil (8.18 ± 4.88) % and the untreated control (9.21 ± 7.13) % were grouped in *b*, indicating lower protective efficacy. Although neem oil reduced weight loss slightly relative to the control, it was not significantly more effective under the conditions tested. These findings are consistent with previous studies demonstrating that untreated wood is more susceptible to fungal attack (Schmidt, 2006; Owoyemi *et al*., 2020; Salami *et al*., 2020) and that plant oil treatments can enhance the biological resistance of wood (Akhtar and Ahmad, 2011). The results also align with Carlquist (2012) report that variation in preservative efficacy and wood resistance depends on species and inherent anatomical characteristics. Gmelina exhibited the highest resistance to fungal degradation, while castor oil and MSO proved to be the most effective preservatives across the tested wood species.

As previously noted, neem oil contains bioactive compounds such as azadirachtin, nimbin, and salannin, which are known to disrupt fungal cell membranes and interfere with enzyme activity (Zhang *et al.,* 2016; Brunner *et al.,* 2018). Moringa seed oil similarly contains isothiocyanates, flavonoids, phenolics, and chitin-binding proteins that may inhibit fungal growth through membrane destabilization, oxidative stress induction, and interference with vital metabolic pathways (Deshmukh *et al*., 2018; Batista *et al*., 2014). Castor oil, rich in ricinoleic acid, has been documented to impair fungal cell membrane structure and function, leading to reduced nutrient uptake and suppressed growth (Kusch and Panstruga, 2017; Kwon *et al*., 2023). These mechanisms collectively provide a biological basis for the partial protection observed in treated wood samples.

The results obtained in this study demonstrate that neem, moringa, and castor oils enhance wood resistance primarily by delaying fungal colonization and reducing the rate of degradation, rather than by achieving complete protection. This is supported by two observations: (a) treated samples exhibited lower weight loss and slower onset of visible decay compared to untreated controls, and (b) most samples were eventually colonized under prolonged exposure. Thus, the oils behaved mainly as fungistatic agents, suppressing fungal activity without fully preventing growth.

The mechanistic properties reported in the literature also align with this pattern. For instance, neem limonoids and flavonoids have been shown to reduce mycelial growth and inhibit fungal enzymes, often resulting in slowed but not entirely halted fungal development (Wylie and Merrell, 2022). Similarly, moringa-derived proteins such as Mo-CBP3 can block spore germination and disrupt plasma-membrane organization, but their action becomes fully fungicidal only at higher concentrations than those typically achieved in wood impregnation (Batista *et al.,* 2014). Castor oil's ricinoleic acid disrupts fungal membranes but generally provides growth inhibition rather than total eradication at low application rates (Nitbani, 2022; Suurbaar *et al.,* 2017). These mechanistic insights explain why treated samples in this study exhibited slowed decay yet were still susceptible under extended exposure.

When compared with conventional preservatives such as copper-based systems or borates, the plant oils tested here do not provide the same level of long-term or systemic protection. Chemical preservatives form stable, leach-resistant deposits within the wood matrix, making them more effective at completely preventing colonization over long periods, particularly under high-moisture conditions (Rahman *et al*., 2019). By contrast, plant oils tend to remain within surface layers and lumina, where they act by creating temporary chemical and physical barriers to fungal establishment. However, their advantages, including low toxicity, biodegradability, and reduced environmental impact, support their value as eco-friendly alternatives for low-risk applications or as supplementary treatments within integrated protection systems.

The scatter plot in Figure 9 illustrates the relationship between the rate of fungal infestation and treatment absorption. The data points are widely dispersed with no clear upward or downward trend, indicating that there is little to no meaningful correlation between the two variables. Treatment absorption varies substantially across all levels of infestation, suggesting that factors other than infestation rate likely play a stronger role in determining absorption levels. The dotted horizontal line represents the average treatment absorption, which appears to be around seven units, and the distribution of points above and below this line fur-

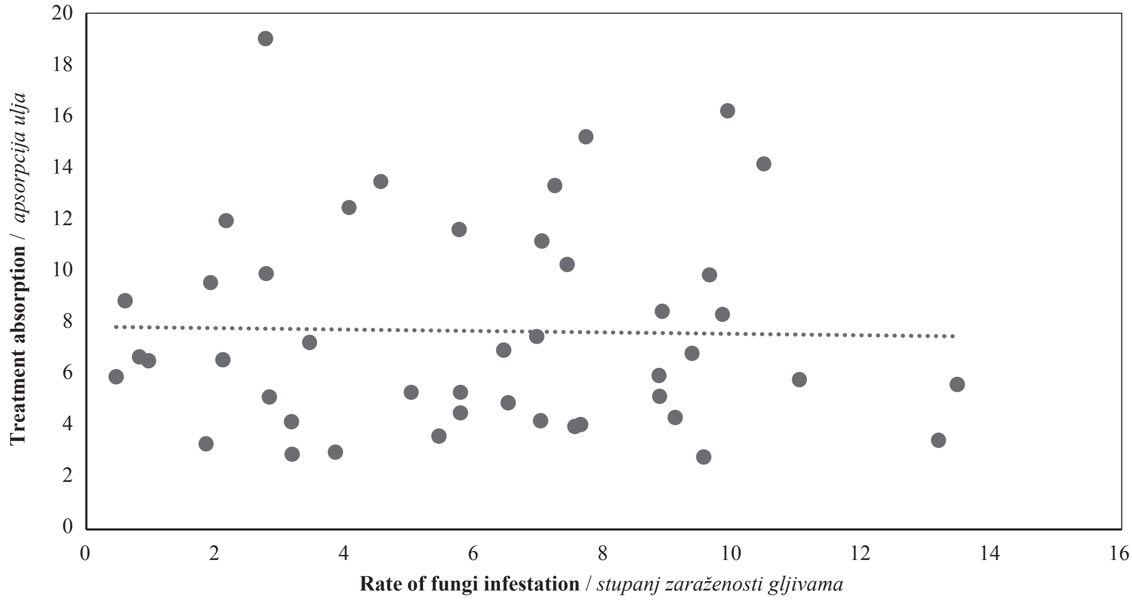

Figure 9 Correlation between oil absorption and resistance against fungal attack
Slika 9. Korelacija između apsorpcije ulja i otpornosti na gljivične napade

ther highlights the high variability in the data. Overall, the figure suggests that the rate of fungal infestation is not a reliable predictor of treatment absorption.

4 CONCLUSIONS
4. ZAKLJUČAK

The study confirms that untreated wood is highly vulnerable to infestation and deterioration, particularly evident in Afara, Gmelina, and Obeche wood species. Density influences absorption levels and resistance to infestation, with denser woods exhibiting lower absorption and greater resistance. Wood treated with castor oil shows reduced swelling and weight loss, highlighting its effectiveness in mitigating fungi infestation. The need for understanding the differences in wood properties is crucial for informed selection and application. Gmelina, especially with castor oil treatment, emerges as a promising option for applications requiring dimensional stability and protection against infestation.

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5 REFERENCES
5. LITERATURA

1. Adeduntan, H.; Olusola, O., 2008: Comparative study of the retention and leaching characteristics of some Nigerian hardwoods treated with neem (*Azadirachta indica*) and opepe (*Nauclea diderrichii*) seed oils. Bioresource Technology, 99 (1): 237-242.
2. Adetogun, A.; Dauda, T.; Oluwadare, A., 2009: Utilization of neem seed (*Azadirachta indica*) oil for the preservation of wood against fungal attack. Journal of Applied Sciences Research, 5 (11): 2039-2042.
3. Adeyanju, A., 2001: Effects of moisture content on fungal decay of wood by Fomes lignosus. Bioresource Technology, 76 (1): 89-91.
4. Ahmed, S. A.; Sehlstedt-Persson, M.; Morén, T., 2013: Development of a new rapid method for mould testing in a climate chamber: preliminary tests. European Journal of Wood and Wood Products, 71 (4): 451-461. https://doi.org/10.1007/s00107-013-0697-0
5. Akanbi, C. T.; Ashiru, O. A., 2002: Timber Utilization and Constraints in Nigeria: A Review. International Journal of Natural and Applied Sciences, 1 (1): 26-32.
6. Akhtar, M.; Ahmad, S., 2011: Plant products as green substitutes for synthetic wood preservatives: A review. Forest Products Journal, 61 (4): 301-313.
7. Altuntaş, E.; Yıldız, M., 2007: Effect of moisture content on some physical and mechanical properties of faba bean (*Vicia faba* L.) grains. Journal of Food Engineering, 78, 174-183.
8. Batista, A. B.; Oliveira, J. T. A.; Gifoni, J. M.; Pereira, M. L.; Almeida, M. G. G.; Gomes, V. M.; Da Cunha, M.; Ribeiro, S. F. F.; Dias, G. B.; Beltramini, L. M.; Lopes, J. L. S.; Grangeiro, T. B.; Vasconcelos, I. M., 2014: New insights into the structure and mode of action of Mo-CBP3, an antifungal chitin-binding protein of *Moringa*

oleifera seeds. *PLoS ONE, 9* (10): e111427. https://doi.org/10.1371/journal.pone.0111427
9. Brunner, I.; Fischer, M.; Rüthi, J.; Stierli, B.; Frey, B., 2018: Ability of fungi isolated from plastic debris floating in the shoreline of a lake to degrade plastics. *PLoS ONE, 13* (8): e0202047. https://doi.org/10.1371/journal.pone.0202047
10. Deshmukh, S.; Gupta, M.; Prakash, V.; Saxena, S., 2018: Endophytic Fungi: A Source of Potential Antifungal Compounds. Journal of Fungi, 4 (3): 77. https://doi.org/10.3390/jof4030077
11. Ekundayo, O.; Arum, C.; Owoyemi, J., 2022: Evaluation of Physical and Mechanical Properties of Selected Wood Species obtained from Saw Mills in Akure, Nigeria. Journal of Applied Sciences and Environmental Management. 26 (2): 999-1005.
12. Goktas, O.; Dundar, T.; Guler, C., 2007: Wood preservation by propolis. Bioresource Technology, 98 (3): 491-495.
13. Kachel, M.; Krawczuk, A.; Krajewska, M.; Parafiniuk, S.; Guz, T.; Rząd, K.; Matwijczuk, A., 2023: Comparative Analysis of Vegetable and Mineral Oil-Based Anti-adhesive/Hydrophobic Liquids and Their Impact on Wood Properties. Materials, 2023; 16 (14): 4975. https://doi.org/10.3390/ma16144975
14. Kayode, J., 2007: Effect of anatomical and chemical properties on wood shrinkage and mechanical properties of six Nigerian timber species. The Pacific Journal of Science and Technology, 8 (2): 182-187.
15. Khademibami, L.; Bobadilha, G. S., 2022: Recent Developments Studies on Wood Protection Research in Academia: A Review. Frontiers in Forests and Global Change, 5, 793177. https://doi.org/10.3389/ffgc.2022.793177
16. Kusch, S.; Panstruga, R., 2017: mlo-based resistance: an apparently universal "weapon" to defeat powdery mildew disease. Molecular Plant-Microbe Interactions, 30 (3): 179-189.
https://doi.org/10.1094/MPMI-12-16-0255-CR
17. Kwon, O.; Choi, Y.; Choi, W.; Lee, Y.; Choi, J.; Choi, J.; Yang, I., 2023. Decay resistance and dimensional stability of wood impregnated with castor oil using a pressure treatment. Holzforschung, 77: 879-888. https://doi.org/10.1515/hf-2023-0050
18. Ligne, L.; Muynck, A.; Caes, J.; Baetens, J.; Baets, B.; Hoorebeke, L.; Acker, J; Bulcke, J., 2022. Studying the spatio-temporal dynamics of wood decay with X-ray CT scanning. Holzforschung, 76: 408-420. https://doi.org/10.1515/hf-2021-0167
19. Nitbani, F. O., 2022. Preparation of ricinoleic acid from castor oil: A review. *Journal of Oleo Science, 71 (6): 781-793.* https://doi.org/10.5650/jos.ess21226
20. Oluwafemi, A.; Adegbenga, A., 2007: The durability of rubber wood treated with chromated copper arsenate. The Pacific Journal of Science and Technology, 8 (2): 188-195.
21. Owoyemi, O.; Odunsi, M.; Oluyege, J., 2020: Fungi associated with the deterioration of three wood species commonly used in Nigeria. Cogent Food & Agriculture, 6 (1): 1840342.
22. Rahman, M. A., 2019. Development of eco-friendly wood preservative: efficacy of neem leaves extract against wood-destroying microbes (report). CAB Digital Library.
23. Salami, A.; Owoyemi, O.; Ayoola, A., 2020: Fungal deterioration of some tropical wood species used for furniture and other domestic purposes. Journal of Biological Sciences and Bioconservation, 12 (1): 23-30.
24. Schmidt, O., 2006: Wood and tree fungi: Biology, damage, protection and use. Springer Berlin, Heidelberg. https://doi.org/10.1007/3-540-32139-X
25. Sharaf, L.; Hadidi, N.; Saber, W., 2022: Preliminary study for the evaluation of basil essential oil in the preservation of Ficus sycomorus wood. Advanced Research in Conservation Science, 3 (1): 1-12. https://doi.org/10.21608/arcs.2022.131062.1022
26. Shkarovskiy, A.; Mironova, S.; Mamedov, S.; Danilov, E., 2022: Use of Eco-friendly Protective Compounds to Increase Crack Resistance of Timber Structures. Rocznik Ochrona Środowiska, 24: 74-82. https://doi.org/10.54740/ros.2022.006
27. Shupe, T.; Lebow, S.; Ring, D., 2008: Causes and Control of Wood Decay, Degradation and Stain (Pub. 2703). Baton Rouge, LA: Louisiana Cooperative Extension Service.
28. Suurbaar, J.; Mosobil, R.; Donkor, A. M., 2017. Antibacterial and antifungal activities and phytochemical profile of *Ricinus communis* leaf extracts. *BMC Research Notes, 10,* 660. https://doi.org/10.1186/s13104-017-3001-2
29. Thirkell, T. J.; Charters, M. D.; Elliott, A. J.; Sait, S. M.; Field, K. J., 2017: Are mycorrhizal fungi our sustainable saviours? Considerations for achieving food security. Journal of Ecology, 105 (4): 921-929. https://doi.org/10.1111/1365-2745.12788
30. Tolunay, D.; Moya, L.; Shupe, T., França, F., 2008: Wood: A Human History. Journal of Natural Resources Policy Research, 1 (1): 3-11.
31. Wodzicki, T., 2001: Natural factors affecting wood structure. Wood Science and Technology, 35: 5-26. https://doi.org/10.1007/s002260100085
32. Woźniak, M.; Łagan, J.; Rój, E., 2022: Chitosan-caffeine formulation as an ecological preservative in wood protection. Journal of Cleaner Production, 334: 130015. https://doi.org/10.1007/s00226-022-01426-6
33. Wylie, M. R.; Merrell, D. S., 2022. The antimicrobial potential of the neem tree *Azadirachta indica*. *Frontiers in Pharmacology, 13:* 891535. https://doi.org/10.3389/fphar.2022.891535
34. Yildiz, S.; Gezer, E. D.; Yildiz, U. C., 2006: Mechanical and chemical behavior of spruce wood modified by heat. Building and Environment, 41 (12): 1762-1766. https://doi.org/10.1016/j.buildenv.2005.07.017
35. ***American Society for Testing Materials, 2009: Annual book of ASTM standards. ASTM International.

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Comparative Experimental Investigation of Two Different Levels of Heat-Treated Wood Properties

Eksperimentalno istraživanje svojstava drva toplinski obrađenoga pri dvjema temperaturama

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ABSTRACT • *This study examines the effects of heat treatment on the mechanical properties of four wood species: oak (Quercus petraea L), Scotch pine (Pinus sylvestris), chestnut (Castanea sativa) and cedar (Cedrus libani). Samples were subjected to heat treatment at 175 °C and 205 °C, and their bending strength, modulus of elasticity, compression strength, dynamic bending (shock) strength, column strength, and hardness were compared with untreated controls. Results revealed that wood species, treatment temperature and their interaction significantly influenced all mechanical properties. Oak consistently showed the highest performance, while cedar exhibited the lowest values. Heat treatment caused notable reductions in mechanical properties, with losses ranging from 0.2 % to 52.2 % at 175 °C and increasing further at 205 °C. The reduction is attributed to the thermal degradation of wood components such as cellulose, hemicellulose and lignin, leading to weakened cell walls and increased brittleness. Lower temperatures primarily produced a pre-treatment and drying effect, while higher temperatures intensified chemical degradation. Among the properties tested, bending strength, modulus of elasticity and hardness were most affected. The findings demonstrate that heat treatment significantly alters the mechanical performance of wood, and these changes must be considered in structural and engineering applications where strength and durability are critical factors. It has been determined that the mechanical property changes of needle-leaved and broad-leaved wood samples subjected to thermal treatment at both 175 °C and 205 °C in the same chamber are similar. It has been suggested that thermal treatment of both wood types could be carried out at a slightly higher chamber temperature (above 175 °C), thereby achieving a much closer thermal treatment effect for both wood types and potentially achieving significant energy savings.*

KEYWORDS: *heat treatment; wood type; mechanical properties; bending strength; modulus of elasticity; compressive strength; hardness*

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SAŽETAK • *U studiji je istražen utjecaj toplinske obrade na mehanička svojstva četiriju vrsta drva: hrasta (Quercus petraea L.), običnog bora (Pinus sylvestris), kestena (Castanea sativa) i cedra (Cedrus libani). Uzorci su podvrgnuti toplinskoj obradi pri 175 i 205 °C, a njihova čvrstoća na savijanje, modul elastičnosti, čvrstoća na tlak, čvrstoća na udar, čvrstoća izvijanja i tvrdoća uspoređeni su s istim svojstvima netretiranih kontrolnih uzoraka. Rezultati su pokazali da vrsta drva, temperatura obrade i njihova interakcija znatno utječu na sva mehanička svojstva. Hrastovina je dosljedno pokazala najbolja svojstva, dok su za cedrovinu zabilježena najlošija svojstva. Toplinska obrada prouzročila je znatno slabljenje mehaničkih svojstava s gubitcima u rasponu od 0,2 do 52,2 % za drvo obrađeno pri 175 °C, uz dodatno povećanje gubitaka na 205 °C. Slabljenje svojstava pripisuje se toplinskoj razgradnji drvnih komponenata poput celuloze, hemiceluloze i lignina, što dovodi do slabljenja staničnih stijenki i povećanja krhkosti drva. Niže temperature ponajprije su prouzročile efekt predobrade i sušenja, dok su više temperature pojačale kemijsku razgradnju. Među promatranim svojstvima najviše su oslabljeni čvrstoća na savijanje, modul elastičnosti i tvrdoća. Rezultati su pokazali da toplinska obrada znatno mijenja mehanička svojstva drva i te se promjene moraju uzeti u obzir u konstrukcijskim i građevinskim primjenama, u kojima su čvrstoća i trajnost ključni zahtjevi. Utvrđeno je da su promjene mehaničkih svojstava uzoraka crnogoričnoga i listopadnog drva podvrgnutih toplinskoj obradi pri 175 i 205 °C u istoj komori slične. Predloženo je da se toplinska obrada obiju vrsta drva provede na nešto višoj temperaturi komore (višoj od 175 °C), čime se postiže sličniji učinak toplinske obrade za obje vrste drva i ostvaruju se potencijalno veće uštede energije.*

KLJUČNE RIJEČI: *toplinska obrada; vrsta drva; mehanička svojstva; modul elastičnosti; čvrstoća na tlak; tvrdoća*

1 INTRODUCTION
1. UVOD

Current studies have generally shown that heat treatment at different temperatures and durations reduces bending strength, elastic modulus, compressive strength, and impact resistance. However, studies comparing the responses of both coniferous and broadleaf species to different temperature levels under the same conditions are quite limited. This study experimentally compares the effects of heat treatment at two different temperature levels (175 °C and 205 °C) on the mechanical properties of four different tree species – Scotch pine (*Pinus sylvestris*), Taurus cedar (*Cedrus libani*), oak (*Quercus petraea* L.), and chestnut (*Castanea sativa*) – in order to fill this gap. The novelty of the study lies in the simultaneous evaluation of both coniferous and broadleaf species under the same treatment conditions and the systematic presentation of changes in mechanical properties.

In this study, it was aimed to determine whether the heat treatment effect occurred in oak and Anatolian chestnut while the normal heat change occurred in the chemical structure of Scotch pine and cedar at 175 °C process at both temperature levels and heat treatment applications, and to determine what kind of a change occurred in Scotch pine and cedar exposed to heat treatment at higher temperatures while the normal heat change occurred in the chemical structure of oak and Anatolian chestnut at 205 °C. The hypothesis that temperature has an effect on both needle-leaved and broad-leaved tree species was used as a starting point.

It is shown that the shore D hardness values and density values of rowan, chestnut, maple, common alder, Uludağ fir, willow, common hornbeam, Strandja oak and ash woods are reduced by heat treatment at 212 °C for 1 and 2 hours according to the ThermoWood method. (Türk *et al*., 2021).

In heat treatment methods, strength values decreased with increasing temperature. Compared to control samples, bending strength decreased by 35 % and 38 % in pine and beech samples heat-treated at 210°C using the hot air method, respectively. (Bayraktar *et al*., 2022).

Heat treatment significantly alters physical, chemical and mechanical properties of wood. Lower temperatures and duration of exposures resulted in some improvements in elastic constants probably due to lower EMC (Gültekin, 2024).

Changes in chemical composition due to the heat treatment included reducing carbohydrate content (particularly hemicelluloses) and decreasing the number of hydroxyls. The alterations were more pronounced for mature wood, making it more similar to juvenile control treated wood than to control mature wood. Also, more distinct alterations in the mechanical parameters measured in compression were observed (Broda *et al*., 2024).

The smallest effect of the heat treatment was determined at 130 °C for 2 h. Treatment temperature is highly correlated with all physical, mechanical and chemical properties of chestnut wood. In this case it can be said that temperature has greater influence on strength properties than time. For heat treatment process, 130 °C for 2 h should be applied where mechanical properties are important. However, 230 °C for 2 h should be used where physical properties are more important. Heat treated woods can be utilised using proper heat treatment time and temperature without any losses in strength values and chemical characteristics in areas where stability is important. Also, heat treatment can be considered as an environmentally friendly technique because no chemicals are involved during the process (Ates *et al*., 2010).

Thermal modification is an environmentally friendly technique that does not involve the use of toxic chemicals or generate harmful emissions. The increased durability of thermally modified wood can also contribute to the sustainable management of forest resources by reducing the demand for raw wood materials and promoting the use of fast growing and low-value wood species (Hasanagic *et al*., 2023).

Prior to a treatment temperature of 150 °C, the wood undergoes dehydration reactions. Elevated temperatures cause gradual water evaporation, reducing wood moisture content. Reduced moisture enhances the compactness and hardness of the wood, strengthening its mechanical properties compared to room temperature. Beyond 150 °C, continued dehydration leads to the gradual decomposition of hemicellulose in the cell wall, reducing its mechanical performance. The ultimate bearing capacity results of the compression test and bending test show that the ultimate bearing capacity of beech and maple is close to each other, while that of sylvestris Pine is poor. This is because sylvestris Pine is different from the other two kinds of softwood, and softwood is generally less dense and less hard (Zhou *et al*., 2024).

If overall changes in surface roughness were evaluated, the roughness of the sanded surface would increase after thermal modification in the case of pine and chestnut wood. In the case of the examined oak wood, there were no statistically significant changes in surface roughness after Thermo-Vacuum modification, despite a significant reduction in density and hardness. This was mainly due to the deep vessels present, which had a greater impact on surface roughness than microscopic grooves after sanding. Cedar wood showed no statistical differences in surface roughness before and after thermal modification (Adamcik *et al*., 2025).

Chemical transformations improve dimensional stability and resistance to biological agents such as fungi and insects, but at the same time, may lead to a weakening of some mechanical properties of wood, such as elasticity. Research from 2025 emphasises the importance of optimizing process parameters such as temperature, time, and treatment atmosphere to achieve a balanced improvement in properties while minimizing negative effects on the wood structure. Ongoing research aimed at a detailed understanding of chemical changes and their impact on the mechanical and physical properties of wood will help further improve the technology (Jancikova *et al*., 2025)

The release level of volatile organic compounds during high temperature heat treatment is much higher than that of conventional drying. Along with the heat treatment modification, the exhaust gas pollution purification treatment and absorption device is equipped to prevent the release of organic volatile compounds to pollute the air and harm human health (Cao *et al*., 2022).

Three wood species, Scotch pine, oak and chestnut samples were heat treated at four different conditions (150 °C / 5 h, 170 °C / 4 h, 190 °C / 3 h, 210 °C / 2 h) and these samples were tested in three different climatic conditions (20 °C / 65 %, 40 °C / 35 %, 10 °C / 50 %), respectively. According to the results of the study, it was determined that the highest values of bending strength and modulus of elasticity were obtained at the lowest temperature heat treatment (150 °C / 5 h) and 40 °C / 35 % climate condition. It was determined that the resistance values decreased as the heat treatment temperature increased (Altunok *et al*., 2023).

The effect of heat treatment temperature on the modulus of elasticity in bending of Scotch pine wood test samples was found to be significant. The highest modulus of elasticity value was determined in samples heat treated at 170 °C, while the lowest was determined in samples heat treated at 210 °C. These decreases in modulus of elasticity may have occurred due to structural damages (thermal decomposition) in wood material components as a result of high heat treatment temperature, as well as mass decrease and density losses (Bayraktar, 2023).

Heat-treated wood has a more aesthetic appearance and is an environmentally friendly, renewable material. One of the negative properties of heat-treated wood is its low mechanical strength. In the literature, it has been reported that impregnation of wood material with some chemicals before heat treatment reduces its thermal degradation (Perçin *et al*., 2023).

Aydemir *et al.* (2009), reported that heat treatment should be considered as an alternative method of wood preservation and wood modification. It was recommended that the heat treatment temperature should be above 200 °C when better protection against the external environment or decay is desired, and below 200 °C for indoor use.

According to the results obtained from the physical, mechanical, morphological and thermal properties of Beech and Oak woods after heat treatment in Bürüç *et al*. (2019), it was found that all mechanical properties and density, as well as water absorption values decreased with heat treatment.

Doruk and Perçin (2010) determined that the losses in the mechanical properties of the wood material modified at low temperatures were less. In the samples exposed to heat treatment at 130 °C, 165 °C and 200 °C for 2, 6 and 10 hours, the least decrease in mechanical properties was found in the samples treated at 130°C for 2 hours and it was determined that the mechanical resistance decreased as the time of heat treatment increased.

Kaymakci and Bayram (2021) found in their study that heat treatment applications above 150 °C or 4 hours are not recommended for structural uses as they cause a decrease in mechanical properties.

Perçin *et al*. (2017) reported that bending strength and compressive strength parallel to the fibres increased at low temperatures due to some drying, while these resistances decreased at high oven temperatures.

Xu *et al*. (2019) performed thermal modification on test samples obtained from white oak (*Quercus alba* L.) wood by heat treatment at 160 °C, 180 °C and 200 °C for 3, 6 and 9 hours. It was observed that *MOR* values started to decrease as the temperature increased. While the *MOR* value was 203.85 MPa in the control samples, the minimum decrease was 202.36 MPa in the samples treated at 160°C for 3 hours and the maximum decrease was 169.28 MPa in the samples treated at 200 °C for 9 hours.

Gündüz *et al*. (2011) applied 180 °C and 2 hours heat treatment to tannin and tannin-free samples prepared from chestnut wood. The highest bending strength was obtained in tannin-control samples and the lowest in tannin-free-heat-treated samples. The compressive strength was 51.2 N/mm^2 in control samples, the highest 58.22 N/mm^2 in tannin-control samples and 55.12 N/mm^2 in tannin-treated samples. It was found that the bending and compressive strengths decreased in the heat-treated samples and tannin reduced this decrease.

As the weight loss increases, hardness values decrease on the tangential and radial surfaces and increase slightly on the cross-sectional surface. In the group treated at 220 °C, there was a decrease of approximately 18 % in hardness values on the tangential and radial surfaces. According to these data, considering the expansion percentages and hardness value data, the temperature range between 200 °C and 220 °C can be recommended as the appropriate treatment range for yellow pine timber (Bal *et al*., 2016).

Heat treatment causes the loss of strength of wood. Therefore, heat-treated wood should not be used where strength is a dominant factor (Toker *et al*., 2016).

Korkut (2016) showed that all mechanical properties of the heat-treated sessile oak samples tested in his study were slightly reduced compared to the control samples. Heat treatment temperature is not the only parameter contributing to the reduction of mechanical properties; weight loss is directly linked to the treatment time. As the mechanical properties of sessile oak are reduced as a result of heat treatment, it is recommended that such units should not be used in construction applications.

An increase in the modulus of elasticity was recognised after heat treatment during the bending strength test. Changes and/or modifications in the main wood components influence the mechanical properties of the heat treatment. However, heat-treated timber shows potential for use in construction. Since *MOE* is usually the most critical parameter for a construction, with higher stiffness resulting in lower deflection for a given load, heat treatment does not seem to reduce the potential for construction applications. However, it is important to carefully evaluate the stresses and some practical consequences in a construction when using heat-treated timber, because the effect of heat treatment on different strength properties is not proportional. Furthermore, further test work is required to study the effect of heat treatment in long-term and repeated loadings for internal and external conditions (Michiel *et al*., 2007).

Another phenomenon that may affect the strength properties of wood after heat treatment is the thermoplastic property of wood. Above a certain temperature the physical properties of haemicelluloses (127-235 °C), lignin (167-217 °C) and cellulose (231-253 °C) change to a rubber or plastic state. Thermal softening of wood as a whole occurs at temperatures above 200 °C, but steaming lowers the softening point (180 °C) due to water acting as a plasticiser. The thermal behaviour of lignin and hemicelluloses appears to be constrained by interactions due to secondary intermolecular bonding with cellulose. The degradation of hemicelluloses during the hydro-thermolysis phase affects this secondary bonding, which allows the remaining hemicelluloses and lignin to be plasticised. During the cooling phase, these components harden again, and the molecular polymer structure may change. This probably influences the interaction between the main components of the wood, affecting its strength properties (Michiel *et al*., 2007).

It can be said that both *MOR* and *MOE* values decrease with the increase of the temperature and time of heat treatment. The maximum decreases to all parameters were recorded with the treatment at 160 °C for 9 h. The lowest modulus of rupture value was obtained from samples treated at the 205 °C for 12 h (43.10 N/mm^2). The lowest modulus of elasticity value was obtained from the same heat treatment conditions. Heat treatment decreases mechanical properties of wood, but it increases the properties of dimensional stability and the biological durability of wood (Yapıcı *et al*., 2012).

In this study, the wood species were heat treated for 3 hours at low temperatures determined at both levels. At 175 °C, it was aimed to determine whether a normal thermal change occurred in the chemical structure of Scotch pine and cedar wood, while a heat treatment effect occurred in oak and chestnut, and at 205 °C, while a normal thermal change occurred in the chemical structure of oak and chestnut, it was aimed to determine what kind of extra change occurred in Scotch pine and cedar exposed to heat treatment at higher temperature.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

In this study, first class sessile oak (*Quercus petrea* L), chestnut (*Castenea sativa*), taurus cedar (*Cedrus libani*), Scotch pine (*Pinus sylvestris*) timbers, which are widely used in the woodworking industry and are locally produced, were randomly obtained from Ankara Keresteciler Sitesi.

2.1 Preparation of test samples
2.1. Priprema ispitnih uzoraka

Four different types of wooden slats of draft sizes obtained randomly from the market were heat treated at 175 °C and 205 °C in the same process, and test and measurement samples were prepared by cutting the test and measurement samples from these materials in the sizes stipulated by the standards in the size and number given in Table 1.

2.2 Heat treatment
2.2. Toplinska obrada

In the first stage, draft pieces from each of the four wood species sufficient for the samples in Table 1 were placed in the heat treatment furnace with laths between them (Figure 1), and heat treatment was applied at 175 °C.

In the second step, draft pieces from each of the four wood species sufficient for the samples in Table 1 were placed in the heat treatment furnace with laths

Table 1 Type of wood to be heat treated and research test/measurement pattern, standards.
Tablica 1. Vrste drva koje su toplinski obrađene i postupak ispitivanja/mjerenja u istraživanju te standardi

<table>
<tr><th></th><th colspan="4">Properties, dimensions and number of wooden specimens
Svojstva, dimenzije i broj uzoraka drva</th><th colspan="3">Treatment of samples
Vrsta obrade</th></tr>
<tr><th>Wood type
Vrsta drva</th><th>Test / measurement
Ispitivanje/mjerenje</th><th>Standards
Standardi</th><th>Dimensions, mm
Dimenzije, mm</th><th>Total sample
Ukupno uzoraka</th><th>Control
Kontrolni uzorci</th><th>175 °C</th><th>205 °C</th></tr>
<tr><td rowspan="7">Cedar
Skotch pine
Oak
Chestnut
cedrovina
borovina
hrastovina
kestenovina</td><td>Bending strength
čvrstoća na savijanje</td><td>TS ISO 13061-3, 2021
TS 13061-4 , 2014</td><td>30×60×960</td><td>15</td><td>5</td><td>5</td><td>5</td></tr>
<tr><td>Elastical modulus
modul elastičnosti</td><td>TS ISO 13061-3, 2021
TS 13061-4 , 2014</td><td>30×60×960</td><td>15</td><td>5</td><td>5</td><td>5</td></tr>
<tr><td>Compression strength
čvrstoća na tlak</td><td>TS EN 408 + A1, 2014</td><td>20×20×30</td><td>15</td><td>5</td><td>5</td><td>5</td></tr>
<tr><td>Hardness
tvrdoća</td><td>TS ISO 13061-12 [96] , 2021</td><td>20×50×50</td><td>15</td><td>5</td><td>5</td><td>5</td></tr>
<tr><td>Column strength
čvrstoća na izvijanje</td><td>TS EN 408 + A1 , 2014</td><td>30×60×600</td><td>15</td><td>5</td><td>5</td><td>5</td></tr>
<tr><td>Shock strength
čvrstoća na udarac</td><td>TS ISO 13061-10 , 2021</td><td>20×20×350</td><td>15</td><td>5</td><td>5</td><td>5</td></tr>
<tr><td colspan="3">Total / *Ukupno*</td><td>90</td><td>30</td><td>30</td><td>30</td></tr>
</table>

Note: The number of samples given above is valid only for one wood species, the same number of samples were prepared for 4 wood species (90 × 4 = 360 pieces).
Napomena: Navedeni broj uzoraka vrijedi samo za jednu vrstu drva. Za sve četiri vrste drva pripremljen je jednak broj uzoraka (90 × 4 = 360 komada).

Figure 1 Stacking in heat treatment furnace
Slika 1. Slaganje uzoraka u komoru za toplinsku obradu

between them, and heat treatment was applied at 205 °C. The heat treatment in both steps was carried out in the process shown in Figure 2 below.

Drying of wood: By gradually increasing the temperature up to 130 °C, the wood material is dried for a long time.

Heat treatment application: First, pre-heat treatment at an increasing temperature and then heat treatment at constant temperature of 175 °C and 205 °C. In this process, water vapour is sprayed into the furnace for 15 seconds per minute, preventing the wood from catching fire and reducing the internal stress (Figure 3).

Cooling: Cooled by spraying water until the temperature drops to 30 °C.

2.3 Statistical analysis
2.3. Statistička analiza

Under the same chamber conditions, the effect of heat treatment on specific mechanical properties of coniferous tree species (Scots pine and cedar) and broadleaf tree species (oak and chestnut) was determined at two different temperatures (175 °C and 205 °C). When the effect of tree species and treatment type on mechanical properties was significant, a homogeneity test was performed at a significance level of $p \leq 0.05$ using a t-test. When the effect of tree species and processing types on mechanical properties was found to be significant, Duncan's test was applied to determine the homogeneity groups.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Some of the mechanical property changes experimentally obtained from the control and heat-treated samples at the end of heat treatment of four wood species at two different temperature levels (175 °C – 205 °C) are given below.

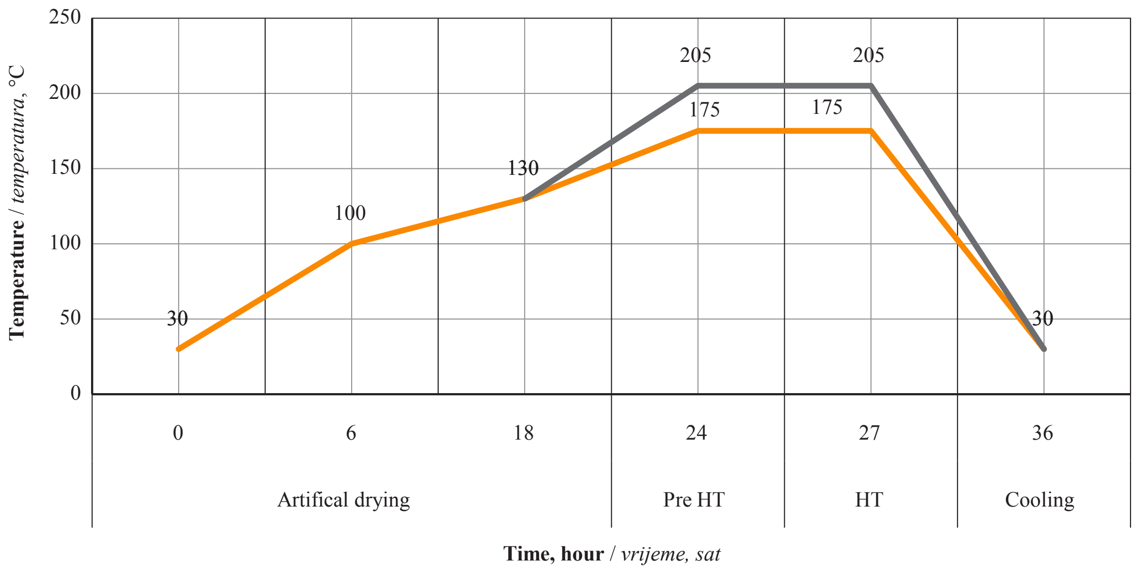

Figure 2 Heat treatment graph
Slika 2. Grafikon procesa toplinske obrade

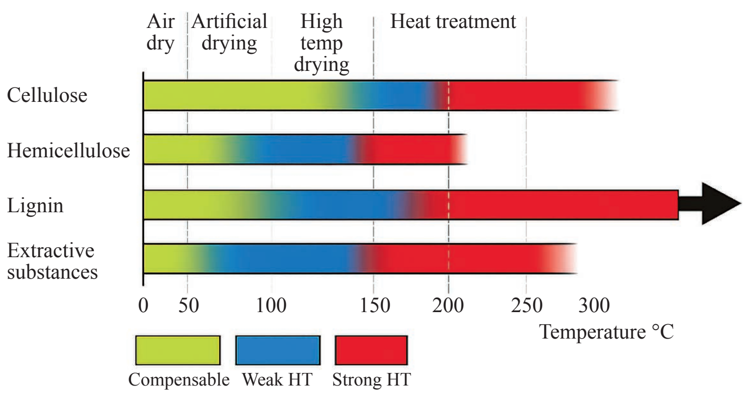

Figure 3 Behaviour of wood basic components in the heat treatment process (Sundqvist *et al.*, 2004)
Slika 3. Ponašanje osnovnih komponenata drva u procesu toplinske obrade (Sundqvist i sur., 2004.)

3.1 Bending strength change
3.1. Promjena čvrstoće na savijanje

To determine the variables causing variation in the bending strength values of heat treatment at two different temperature levels and four wood species, multiple variance analysis was applied, and the results are presented in Table 2.

The analysis of variance in Table 2 shows that the effects of wood type, treatment type and their binary interactions on bending strength are significant. It was found that the heat treatment process contributed the highest to the change in bending strength, then the wood and the lowest to the binary interaction.

The averages of the bending strength values of the samples of four wood species after control and heat treatment, the averages of the interaction of bending strength with wood and heat treatment and the homogeneity groups of these averages are given in Table 3.

In Table 3, in terms of wood species, the highest bending strength was found in oak, followed by Scotch pine, chestnut and cedar, respectively. In terms of treatment, the highest bending strength was found in control, then in samples heat treated at 175 °C and 205 °C, respectively. Compared to the bending strength of the control samples, the bending strength of each wood species decreased in the heat-treated samples, and the bending strength decreased further as the heat treatment temperature increased. It can be said that the decrease in bending strength is due to the degradation of wood cell components (cellulose, lignin and hemicellulose) depending on the process temperature of the heat treatment. At the same time, in the dual interaction of these two factors, the highest bending bending strength was found in the control group of oak samples, then in the control group of Scotch pine and heat treated oak samples -175 °C and Skotch pine – 175 °C. The lowest bending bending strength was obtained in Cedar – 175 samples. In the wood-treatment interaction, it can be said that the reason for the highest bending bending strength in oak – 175 °C samples is that the cabin temperature of 175 °C is low for broadleaf oak. It creates an effect at the level of pre-heat treatment, and the heat treatment effect at this temperature is not sufficient for cellular degradation. In the 205 °C heat treatment processes, it is seen that Scotch pine and cedar lost more bending strength and it can be said that this is due to the fact that coniferous samples undergo more degradation at high temperature causing more disintegration and collapse of cell walls. This result is also supported by the research results of Xu *et al*. (2019); Michiel *et al*. (2007).

Table 2 Multiple variance analysis for bending strength
Tablica 2. Višestruka analiza varijance za čvrstoću na savijanje

K value *K-vrijednost*	Source *Izvor*	Degrees of freedom *Stupanj slobode*	Sum of squares *Zbroj kvadrata*	Mean square *Srednji kvadrat*	F value *F-vrijednost*	P <0.05
2	A (Wood)	3	4702.225	1567.408	183.5499	0.0000
4	B (Process)	2	9211.451	4605.726	539.3492	0.0000
6	AB	6	3391.412	565.235	66.1914	0.0000
-7	Error	48	409.892	8.539		
	Total	59	17714.980			

Table 3 Bending strength (N/mm^2) comparisons and homogeneity groups in terms of wood species and heat treatment
Tablica 3. Usporedbe čvrstoće na savijanje (N/mm^2) i skupine homogenosti s obzirom na vrstu drva i toplinsku obradu

Wood type *Vrsta drva*	Averages, N/mm^2 *Srednja vrijednost,* N/mm^2	HG.
Oak (O)	64.79	A
Scotch pine (Sp)	58.08	B
Chestnut (Ch)	47.88	C
Cedar (C)	41.93	D
LSD = 2.135, α = 0.050		

Process *Obrada*	Averages, N/mm^2 *Srednja vrijednost,* N/mm^2	HG.
Control	69.82	A
175 °C heat treated	49.59	B
205 °C heat treated	40.10	C
LSD = 1.849, α = 0.050		

Wood type + process interaction *Interakcija vrste drva i obrade*	Averages, N/mm^2 *Srednja vrijednost,* N/mm^2	HG.
O+Control	86.186	A
Sp+Control	68.472	B
O+175 °C	66.086	BC
Sp+175 °C	65.892	BC
C+Control	62.836	CD
Ch+Control	61.768	D
O+205 °C	42.096	E
Ch+175 °C	41.950	E
Ch+205 °C	39.930	E
Sp+205 °C	39.884	E
C+205 °C	38.510	E
C+175 °C	24.438	F
LSD = 3.698, α = 0.050		

3.2 Elastic modulus change in bending
3.2. Promjena modula elastičnosti pri savijanju

To determine the variables causing variation in the bending strength values of four wood species and two different heat treatment temperatures, multiple variance analysis was applied, and the results are presented in Table 4.

The analysis of variance in Table 4 shows that the effects of wood type, treatment type and their binary interactions on the elastical modulus are significant. It was found that the heat treatment process contributed the highest to the change in the elastical modulus, then the wood and the lowest to the binary interaction.

The averages of the changes in the elastical modulus values of the samples of four wood species after control and two heat treatments, the averages of the interaction of wood and heat treatment in terms of the effect on the elastical modulus and the homogeneity groups of these averages are given in Table 5.

In Table 5, in terms of wood species, the highest elastical modulus was found in oak and Scotch pine, followed by chestnut and cedar, respectively. In terms of heat treatment, the highest elastical modulus was found in the control, followed by 175 °C and 205 °C samples, respectively. Compared to the elastical modulus in the control samples, the elastical modulus of each wood species decreased in the heat-treated samples, and the elastical modulus decreased further as the heat treatment temperature increased. It can be said that the decrease in the elastical modulus is due to the degradation of wood cell components (cellulose, lignin and hemicellulose) depending on the process temperature of the heat treatment. At the same time, in the dual interaction of these two factors, the highest elastical modulus was found in oak-control samples, followed by oak – 175 °C. The lowest elastical modulus was obtained in cedar – 205 °C samples. In the wood-treatment interaction, it can be said that the reason for the highest elastical modulus in oak-175 °C samples is that the cabin temperature of 175 °C is low for broadleaf oak. It creates an effect at the level of pre-heat treatment and the heat treatment effect at this temperature is not sufficient for cellular degradation. In the 205 °C heat treatment processes, Scotch pine and cedar lost more elasticity (became brittle), and it can be said that this is due to the fact that coniferous samples undergo more degradation at high temperature causing more collapse in the cell walls. This result is also supported by the research results of Xu *et al*. (2019); Michiel *et al*. (2007); Gültekin (2024); Jancikova *et al*. (2025).

Table 4 Multiple variance analysis for elastical modulus
Tablica 4. Višestruka analiza varijance za modul elastičnosti

K value *K-vrijednost*	Source *Izvor*	Degrees of freedom *Stupanj slobode*	Sum of squares *Zbroj kvadrata*	Mean square *Srednji kvadrat*	F value *F-vrijednost*	P <0.05
2	A (Wood)	3	813505335.784	271168445.261	109.2641	0.0000
4	B (Process)	2	670911421.878	335455710.939	135.1679	0.0000
6	AB	6	863073230.740	143845538.457	57.9608	0.0000
-7	Error	48	119125015.034	2481771.147		
	Total	59	2466615003.436			

Table 5 Elastical modulus (N/mm²) comparisons and homogeneity groups in terms of wood species and heat treatment
Tablica 5. Usporedbe modula elastičnosti (N/mm²) i skupine homogenosti s obzirom na vrstu drva i toplinsku obradu

Wood type *Vrsta drva*	Averages, N/mm² *Srednja vrijednost,* N/mm²	HG.
Oak (O)	21510	A
Scotch pine (Sp)	21190	A
Chestnut (Ch)	14780	B
Cedar (C)	13340	C
LSD = 1151, α = 0.050		

Process *Obrada*	Averages, N/mm² *Srednja vrijednost,* N/mm²	HG.
Control	22040	A
175 °C heat treated	17170	B
205 °C heat treated	13900	C
LSD = 996.8, α = 0.050		

Wood type + process interaction *Interakcija vrste drva i obrade*	Averages, N/mm² *Srednja vrijednost,* N/mm²	HG.
O+Control	34130	A
O+175 °C	25110	B
Sp+Control	22760	C
O+205 °C	16650	D
Sp+175 °C	16420	D
C+Control	16050	DE
Ch+Control	15210	DE
Ch+175 °C	14890	DEF
Ch+205 °C	14230	EFG
Sp+205 °C	13020	FGH
C+175 °C	12270	GH
C+205 °C	11700	H
LSD = 1994, α = 0.050		

3.3 Compression strength change
3.3. Promjena čvrstoće na tlak

To determine the variables causing variation in the compression strength values of four wood species and two different heat treatment temperatures, multiple variance analysis was applied, and the results are presented in Table 6.

The analysis of variance in Table 6 shows that the effects of wood species, treatment type and their binary interactions on compression strength are significant. It was determined that the highest contribution to the change in compression strength was made by the wood species, then by the heat treatment and the lowest by the binary interaction.

The averages of the changes in the compression strength values of the samples of four wood species after control and two heat treatments, the averages of the interaction of wood and heat treatment in terms of the effect on compression strength and the homogeneity groups of these averages are given in Table 7.

In Table 7, in terms of wood species, the highest compression strength was found in oak, followed by chestnut cedar and Scotch pine samples, respectively. Compared to the compression strength in the control samples, the compression strength of each wood species decreased in the heat-treated samples and the compression strength decreased further as the heat treatment temperature increased. It can be said that the decrease in compression strength is due to the degradation of wood cell components (cellulose, lignin and hemicellulose) depending on the process temperature of the heat treatment.

At the same time, in the dual interaction of these two factors, the highest compression strength was found in oak control and heat-treated oak samples. The lowest compression strength was found in Scotch pine – 205 °C samples. In the wood-treatment interaction, it can be said that the reason for the highest compression strength in oak samples is that the cabin temperature of 175 °C is low for broadleaf oak, and the heat treatment effect at this temperature is not sufficient for cellular degradation. The low temperature (175 °C) caused pre-heat treatment with a drying effect. These results are supported by the results of Gündüz *et al*. (2011), Michiel *et al*. (2007) and Broda *et al*. (2024).

In the 205 °C heat treatment processes, it is seen that Scotch pine and cedar lost more resistance, and it can be said that this is due to the fact that coniferous samples undergo more degradation at high temperature causing more collapse in the cell walls.

Table 6 Multiple variance analysis compression strength
Tablica 6. Višestruka analiza varijance za čvrstoću na tlak

K value *K-vrijednost*	Source *Izvor*	Degrees of freedom *Stupanj slobode*	Sum of squares *Zbroj kvadrata*	Mean square *Srednji kvadrat*	F value *F-vrijednost*	P <0.05
2	A (Wood)	3	4286.472	1428.824	352.8743	0.0000
4	B (Process)	2	158.385	79.192	19.5580	0.0000
6	AB	6	58.698	9.783	2.4161	0.0403
-7	Error	48	194.357	4.049		
	Total	59	4697.912			

Table 7 Compression strength (N/mm^2) comparisons and homogeneity groups in terms of wood species and heat treatment
Tablica 7. Usporedbe čvrstoće na tlak (N/mm^2) i skupine homogenosti s obzirom na vrstu drva i toplinsku obradu

Wood type *Vrsta drva*	Averages, N/mm^2 *Srednja vrijednost,* N/mm^2	HG.
Oak (O)	63.37	A
Chestnut (Ch)	45.62	B
Cedar (C)	44.98	B
Scotch pine (Sp)	41.81	C
LSD = 1.470, α = 0.050		

Process *Obrada*	Averages, N/mm^2 *Srednja vrijednost,* N/mm^2	HG.
Control	51.07	A
175 °C heat treated	48.64	B
205 °C heat treated	47.12	C
LSD = 1.273, α = 0.050		

Wood type + process interaction *Interakcija vrste drva i obrade*	Averages, N/mm^2 *Srednja vrijednost,* N/mm^2	HG.
O+Control	63.00	A
O+175 °C	62.86	A
O+205 °C	62.86	A
Ch+175 °C	49.42	B
C+175 °C	46.58	C
Ch+205 °C	45.63	CD
C+205 °C	44.22	CDE
C+Control	44.14	CDE
Sp+Control	44.03	DE
Ch+Control	41.81	EF
Sp+175 °C	41.72	EF
Sp+205 °C	39.68	F
LSD = 2.547, α = 0.050		

3.4 Dynamic bending (shock) strength change
3.4. Promjena čvrstoće na udarac

To determine the variables causing variation in the shock strength values of four wood species and two different heat treatment temperatures, multiple variance analysis was applied, and the results are presented in Table 8.

The analysis of variance in Table 8 shows significant effects of wood species, treatment type and their binary interactions on shock strength. It was found that the highest contribution to the change in shock strength was made by wood type and heat treatment in equal proportions and the lowest by their interaction.

The averages of the changes in the shock strength values of the samples of four wood species after control and two heat treatments, the averages of the wood and heat treatment interaction in terms of the effect on shock strength and the homogeneity groups of these averages are given in Table 9.

In Table 9, in terms of wood species, the highest shock strength was found in oak, followed by chestnut, Scotch pine and cedar samples, respectively. Compared to the shock strength in the control samples, the shock strength of each wood species was found to decrease in the heat treated samples and the shock strength decreased further as the heat treatment temperature increased. It can be said that the decrease in shock strength is due to the degradation of wood cell components (cellulose, lignin and hemicellulose) depending on the process temperature of the heat treatment. These results are supported by the results of Gündüz *et al.* (2011) and Michiel *et al.* (2007). At the same time, in the dual interaction of these two factors, the highest shock strength was found in oak control and oak – 175 °C samples. The lowest shock strength was obtained in cedar samples. In the wood-treatment interaction, it can be said that the reason for the highest shock strength in oak samples is that the cabin temperature of 175 °C is low for broadleaf oak and the heat treatment effect at this temperature is not sufficient for cellular degradation (cellulose and lignin). The low temperature (175 °C) created a pre-heat treatment with a drying effect. In the 205 °C heat treatment processes, it is seen that Scotch pine and cedar lost more strength and it can be said that this is due to the fact that coniferous samples undergo more degradation at high temperature and causing collapse in the cell walls.

3.5 Column strength change
3.5. Promjena čvrstoće na izvijanje

To determine the variables causing variation in the column strength values of four wood species and two different heat treatment temperatures, multiple variance analysis was applied, and the results are presented in Table 10.

Table 8 Multiple variance analysis for dynamic bending (shock) strength
Tablica 8. Višestruka analiza varijance za čvrstoću na udar

K value *K-vrijednost*	**Source** *Izvor*	**Degrees of freedom** *Stupanj slobode*	**Sum of squares** *Zbroj kvadrata*	**Mean square** *Srednji kvadrat*	**F value** *F-vrijednost*	**P <0.05**
2	A (Wood)	3	4809.807	1603.269	123.8336	0.0000
4	B (Process)	2	2380.756	1190.378	123.8336	0.0000
6	AB	6	1000.389	166.732	12.8780	0.0000
-7	Error	48	621.454	12.947		
	Total	59	8812.406			

Table 9 Dynamic bending (shock) strength averages and Duncan test homogeneity groups
Tablica 9. Prosjeci čvrstoće na udarac i skupine homogenosti Duncanova testa

Wood type *Vrsta drva*	**Averages, kJ/m²** *Srednja vrijednost,* kJ/m²	**HG.**
Oak (O)	44.85	A
Chestnut (Ch)	39.82	B
Scotch pine (Sp)	36.50	C
Cedar (C)	20.89	D
LSD = 2.629, α = 0.050		

Process *Obrada*	**Averages, kJ/m²** *Srednja vrijednost,* kJ/m²	**HG.**
Control	43.74	A
175 °C heat treated	34.37	B
205 °C heat treated	28.43	C
LSD = 2.277, α = 0.050		

Wood type + process interaction *Interakcija vrste drva i obrade*	**Averages, kJ/m²** *Srednja vrijednost,* kJ/m²	**HG.**
O+Control	61.06	A
O+175 °C	44.78	B
Ch+Control	44.41	B
Sp+Control	42.87	BC
Ch+175 °C	38.78	CD
Ch+205 °C	36.28	D
Sp+175 °C	35.16	DE
Sp+205 °C	31.47	EF
O+205 °C	28.70	FG
C+Control	26.59	G
C+175 °C	18.77	H
C+205 °C		H
LSD = 4.554, α = 0.050		

Table 10 Column strength multiple variance analysis
Tablica 10. Višestruka analiza varijance za čvrstoću na izvijanje

K value *K-vrijednost*	**Source** *Izvor*	**Degrees of freedom** *Stupanj slobode*	**Sum of squares** *Zbroj kvadrata*	**Mean square** *Srednji kvadrat*	**F value** *F-vrijednost*	**P <0.05**
2	A (Wood)	3	3339.197	1113.066	109.2308	0.0000
4	B (Process)	2	2753.601	1376.801	135.1125	0.0000
6	AB	6	3542.337	590.389	57.9380	0.0000
-7	Error	48	489.121	10.190		
	Total	59	10124.256			

Table 11 Column strength averages and Duncan test homogeneity groups
Tablica 11. Prosjeci čvrstoće na izvijanje i skupine homogenosti Duncanova testa

Wood type *Vrsta drva*	**Averages, N/mm²** *Srednja vrijednost,* N/mm²	**HG.**
Oak (O)	43.57	A
Scotch pine (Sp)	42.93	A
Chestnut (Ch)	29.94	B
Cedar (C)	27.02	C
LSD = 2.332, α = 0.050		

Process *Obrada*	**Averages, N/mm²** *Srednja vrijednost,* N/mm²	**HG.**
Control	44.65	A
175 °C heat treated	34.78	B
205 °C heat treated	28.16	C
LSD = 2.020, α = 0.050		

Wood type + process interaction *Interakcija vrste drva i obrade*	**Averages, N/mm²** *Srednja vrijednost,* N/mm²	**HG.**
O+Control	69.14	A
O+175 °C	50.87	B
Sp+Control	46.11	C
O+205 °C	33.72	D
Sp+175 °C	33.26	D
C+Control	32.52	DE
Ch+Control	30.81	DE
Ch+175 °C	30.16	DEF
Ch+205 °C	28.84	EFG
Sp+205 °C	26.38	FGH
C+175 °C	24.85	GH
C+205 °C	23.69	H
LSD = 4.040, α = 0.050		

The analysis of variance in Table 10 shows that the effects of wood type, treatment type and their binary interactions on the column strength are significant. It was found that the highest contribution to the change in column strength was made by heat treatment, followed by wood type and the lowest by the binary interaction.

The averages for the change in column strength values, the averages for the interaction of wood and heat treatment in terms of the effect on column strength and the homogeneity groups of these averages are given in Table 11.

In Table 11, in terms of wood species, the highest column strength was found in oak and Scotch pine, followed by chestnut and cedar samples, respectively. Compared to the column strength in the control samples, the column strength of each wood species decreased in the heat treated samples and the column strength decreased further as the heat treatment temperature increased. It can be said that the decrease in column strength is due to the degradation of wood cell components (cellulose, lignin and haemicellulose) depending on the process temperature of heat treatment. These results are supported by the results of Gündüz *et al*. (2011) and Michiel *et al*. (2007). At the same time, in the dual interaction of these two factors, the highest column strength was found in the oak control group and oak – 175 °C samples. The lowest column strength was obtained in heat treated cedar samples. In the wood-treatment interaction, it can be said that the reason for the highest column strength in oak samples is that the cabin temperature of 175 °C is low for broadleaf oak and the heat treatment effect at this temperature is not sufficient for cellular degradation (cellulose and lignin). The low temperature (175 °C) created a pre-heat treatment causing a drying effect. In the 205 °C heat treatment processes, it is seen that Scotch pine and cedar lost more resistance and it can be said that this is due to the fact that coniferous samples undergo more degradation at high temperature causing collapse in the cell walls. These results are supported by the results Ates *et al*. (2010).

3.6 Hardness change
3.6. Promjena tvrdoće

To determine the variables causing variation in the hardness values of four wood species and two different heat treatment temperatures, multiple variance analysis was applied, and the results are presented in Table 12.

In the analysis of variance in Table 12, it is seen that the effects of wood type, treatment type and their binary interactions on hardness are significant. It was determined that the highest contribution to the change in hardness was made by heat treatment, followed by the binary interaction and the lowest by wood species.

Table 12 Hardness multiple variance analysis
Tablica 12. Višestruka analiza varijance za tvrdoću

K value *K-vrijednost*	Source *Izvor*	Degrees of freedom *Stupanj slobode*	Sum of squares *Zbroj kvadrata*	Mean square *Srednji kvadrat*	F value *F-vrijednost*	P <0.05
2	A (Wood)	3	6.429	2.143	0.096	0.0000
4	B (Process)	2	17.605	8.802	91.756	0.0000
6	AB	6	5.172	0.862	8.985	0.0000
-7	Error	48	4.605	0.096		
	Total	59	33.811			

Table 13 Hardness averages and Duncan test homogeneity groups
Tablica 13. Prosjeci tvrdoće i skupine homogenosti Duncanova testa

Wood type *Vrsta drva*	Averages, N/mm² *Srednja vrijednost,* N/mm²	HG.
Oak (O)	2.473	A
Scotch pine (Sp)	1.853	B
Cedar (C)	1.767	BC
Chestnut (Ch)	1.612	C
LSD = 0.2264, α = 0.050		

Process *Obrada*	Averages, N/mm² *Srednja vrijednost,* N/mm²	HG.
Control	2.641	A
175 °C heat treated	1.809	B
205 °C heat treated	1.330	C
LSD = 0.1961, α = 0.050		

Wood type + process interaction *Interakcija vrste drva i obrade*	Averages, N/mm² *Srednja vrijednost,* N/mm²	HG.
O+Control	3.616	A
C+Control	2.754	B
O+175 °C	2.462	BC
Sp+Control	2.180	CD
Ch+Control	2.014	D
Sp+175 °C	1.810	DE
Sp+205 °C	1.570	EF
Ch+175 °C	1.568	EF
C+175 °C	1.394	FG
O+205 °C	1.342	FG
Ch+205 °C	1.254	FG
C+205 °C	1.154	G
LSD = 0.3921, α = 0.050		

Table 14 Change in physical properties of wood species according to heat treatment
Tablica 14. Promjena fizičkih svojstava drva ovisno o toplinskoj obradi

Mechanics properties *Mehanička svojstva*	Wood type *Vrsta drva*	Control *Kontrolni uzorak*	175 °C	205 °C	Change % in (Control / 175 °C) *Postotna promjena (kontrola / 175 °C)*	Change % in (175 °C / 205 °C) *Postotna promjena (175 °C / 205 °C)*
Bending strength *čvrstoća na savijanje*	Cedar / *cedrovina*	32.52	24.85	23.69	-23.5	– 4.67
	Scotch pine / *borovina*	46.11	33.26	26.38	-27.8	-20.69
	Oak / *hrastovina*	69.14	50.87	33.72	-26,4	-33.71
	Chestnut / *kestenovina*	30.81	30.16	28.84	-2.1	– 4.38
Elastical modulus *modul elastičnosti*	Cedar / *cedrovina*	16050	12270	11700	-23.5	– 4.65
	Scotch pine / *borovina*	22760	16420	13020	-27.8	-20.71
	Oak / *hrastovina*	34130	25110	16650	-26.4	-33.69
	Chestnut / *kestenovina*	15210	14890	14230	-2,1	– 4.43
Compression strength *čvrstoća na tlak*	Cedar / *cedrovina*	46.58	44.22	44.14	-5.0	– 0.18
	Scotch pine / *borovina*	44.03	41.72	39.68	-5.2	– 4.89
	Oak / *hrastovina*	63.00	62.86	62.86	-0.2	0.00
	Chestnut / *kestenovina*	49.42	45.63	41.81	-7.6	– 8.37
Shock strength *čvrstoća na udarac*	Cedar / *cedrovina*	26.59	18.77	17.29	-29.4	– 7.88
	Scotch pine / *borovina*	42.87	35.16	31.47	-17.9	-10.49
	Oak / *hrastovina*	61.06	44.78	28.70	-26.6	-35.91
	Chestnut / *kestenovina*	44.41	38.78	36.28	-12.6	– 6.45
Column strength *čvrstoća na izvijanje*	Cedar / *cedrovina*	32.52	24.85	23.69	-23.5	– 4.67
	Scotch pine / *borovina*	46.11	33.26	26.38	-27.8	-20.69
	Oak / *hrastovina*	69.14	50.87	33.72	-26.4	-33.71
	Chestnut / *kestenovina*	30.81	30.16	28.84	-2.1	– 4.38
Hardness *tvrdoća*	Cedar / *cedrovina*	2.754	1.394	1.154	-52.2	-17.22
	Scotch pine / *borovina*	2.180	1.810	1.570	-16.9	-13.26
	Oak / *hrastovina*	3.616	2.462	1.342	-31.9	-45.49
	Chestnut / *kestenovina*	2.014	1.568	1.254	-22.1	-20.03

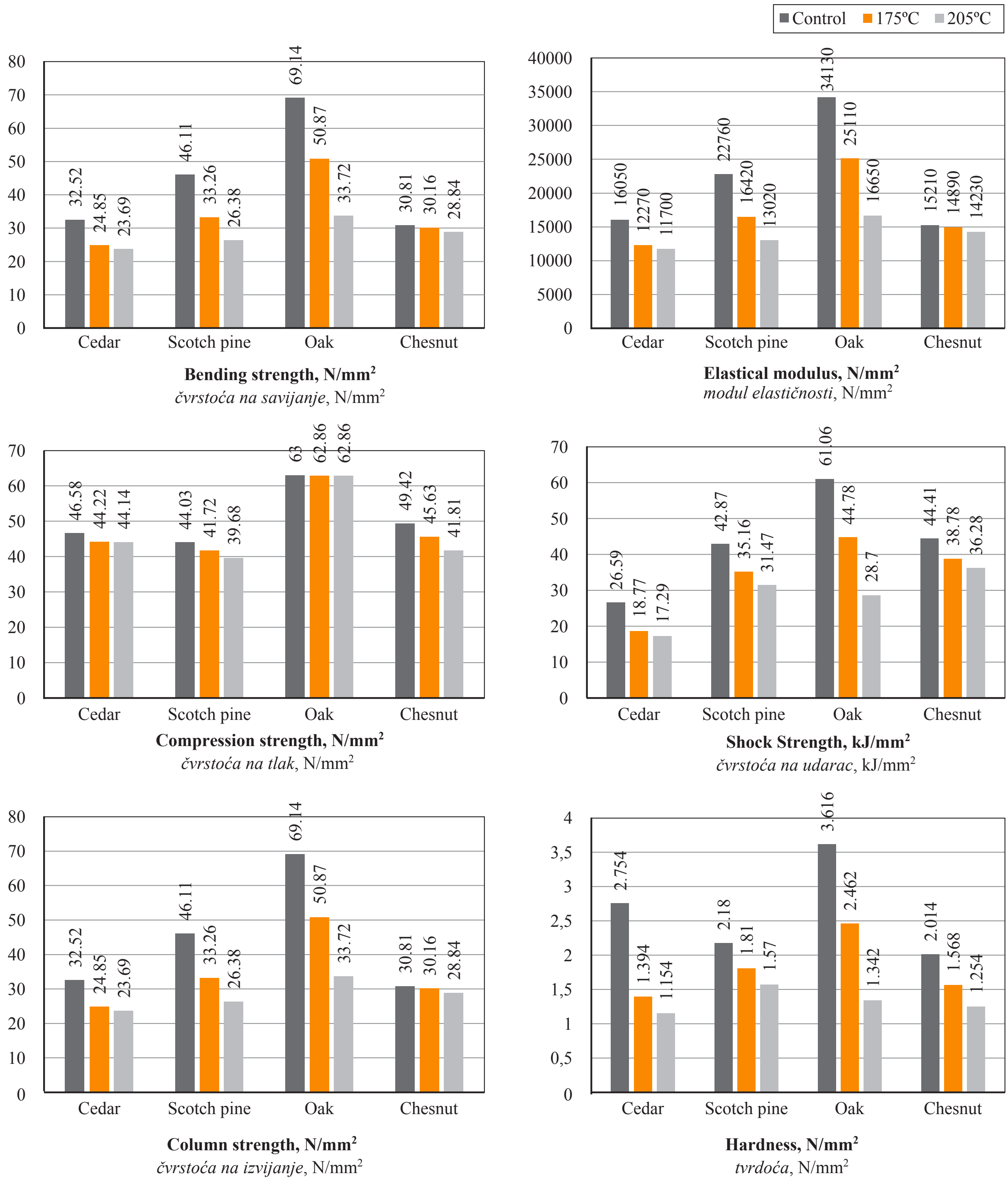

Figure 4 Changes in mechanical properties of wood species
Slika 4. Promjene mehaničkih svojstava drva

The averages for the change in hardness values, the averages for the interaction of wood and heat treatment in terms of the effect on hardness and the homogeneity groups of these averages are given in Table 13.

In terms of wood species in Table 13, the highest column strength was found in oak, followed by Scotch pine, cedar and chestnut samples, respectively. Compared to the hardness in the control samples, the hardness of each wood species decreased in the treated samples and the hardness decreased further as the heat treatment temperature increased.

It can be said that the decrease in hardness is due to the degradation of wood cell components (cellulose, lignin and hemicellulose) depending on the process temperature of heat treatment. These results are supported by the results of Gündüz *et al*. (2011) and Michiel *et al*. (2007). At the same time, in the dual interaction of these two factors, the highest hardness was found in oak control and oak – 175 °C samples. The lowest hardness was obtained in heat-treated cedar 205 °C samples. In the wood-treatment interaction, it can be said that the reason for the highest hardness in oak samples is that the cabin temperature of 175 °C is low for broadleaf oak and the heat treatment effect at this temperature is not sufficient for cellular degradation (cellulose and lignin). The low temperature (175 °C) created a pre-heat treatment causing a drying effect. In the heat treatment processes of 205 °C, it is seen that Scotch pine and cedar lost more resistance, and it can be said that this is due to the fact that coniferous samples undergo more degradation at high temperature causing more collapse in the cell walls. These results are supported by the results Türk *et al*. (2021), Zhou *et al*. (2024) and Adamcik *et al*. (2025).

4 CONCLUSIONS
4. ZAKLJUČAK

At the conclusion of this study, based on the changes in the mechanical properties of samples made from two different types of wood and subjected to heat treatment at two different oven temperatures, it was observed that at 175 °C heat treatment, there was a significant decrease (0.2-52.2 %) in the mechanical properties of all wood samples compared to the control samples (Table 14). At this temperature level, a significant thermal treatment effect occurred in all wood samples, reducing their mechanical properties by degrading the chemical properties of the wood species, despite their different structural properties.Changes in the mechanical properties of wood species are shown in Figure 4.

After applying heat treatment at 205 °C, the change values in the mechanical properties of the same wood types were compared with the heat treatment values at 175 °C. The change rates at the oven temperature level of 205 °C were quite low (0.18-4.67 %) for all mechanical properties of cedar and chestnut wood. Based on these results, it can be said that a heat treatment temperature level of 175 °C is sufficient for cedar and chestnut wood types, and that applying heat treatment at higher temperature levels would be unnecessary and wasteful of energy.

It was determined that the percentage change in mechanical resistance in yellow pine wood samples subjected to heat treatment at 175 °C decreased even further to between 10-20 % after heat treatment at 205 °C. This situation may be attributed to the prolonged dissolution and evaporation of resin and other extractive substances present in Scots pine at the initial temperature, causing a delay in the decomposition of wood components. It can be said that the full effect of heat treatment on Scots pine can be achieved by increasing the oven temperature by a few degrees (5-10).

However, in oak wood samples, it was determined that the changes in mechanical resistance after heat treatment at 175 °C continued to decrease further after heat treatment at 205 °C, with a decrease rate between 33.69 % and 45.45 %. In this case, it can be said that applying a heat treatment of 175 °C to oak wood is not sufficient for the heat treatment to be fully effective, and that an oven temperature of 205 °C would be more appropriate. The fact that the change in the compressive strength of oak wood was very low at both heat treatment levels could not be fully evaluated.

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5 REFERENCES
5. LITERATURA

1. Adamcık, L.; Giudice,V.; Todaro, L.; Dudiak, M.; Kminiak, R., 2025: Surface roughness of thermally modified and unmodified selected wood species after sanding. European Journal of Wood and Wood Products, 83:105. https://doi.org/10.1007/s00107-025-02260-w
2. Altunok, M.; Bülbül, R.; Güneş, M., 2023: Experimental ınvestigation of the effects of different heat treatment and climatic application on the physical and mechanical properties of structural wood. Gazi University Journal of Science and Technology, 11 (1): 263-272. https://doi.org/10.29109/gujsc.1190933
3. Ates, S.; Akyıldız, M.; Özdemir, H.; Gümüşkaya, E., 2010: Technological and chemical properties of chestnut (*Castanea sativa* Mill.) wood after heat treatment. Romanian Biotechnological Letters, 15 (1): 2010.
4. Aydemir, D.; Gündüz, G., 2009: The effect of heat treatment on physical, chemical, mechanical and biological properties of wood. Journal of Bartın Forest Faculty, 11 (15): 71-81.
5. Bal, B.; Akçakaya, E., 2016: Some physical properties and hardness of heat-treated pine wood Values. In: 1st International Mediterranean Science and Engineering Congress, 1523-1529: 443.
6. Bayraktar, S.; Pelit, H., 2022: Determination of density and bending strength of heat-treated wood materials with different methods. Turkish Journal of Forestry Research, 9: 355-362. https://doi.org/10.17568/ogmoad.1090574
7. Bayraktar, S., 2023: Investigation of some physical and mechanical properties of wood materials heat treated with different methods. M.Sc. Thesis, Düzce University, Department of Woodwork Industrial Engineering, Düzce.
8. Boonstra, M. J.; van Acker, J.; Tjeerdsma, B. F.; Kegel., E. V., 2007: Strength properties of thermally modified softwoods and its relation to polymeric structural wood constituents. Annals of Forest Science, 64 (7): 679-690. htpp://doi.org/10.1051/forest:2007048
9. Broda, M.; Popescu, C.; Poszwa, K.; Roszyk, E., 2024: How thermal treatment affects the chemical composition and the physical, mechanical and swelling properties of Scots pine juvenile and mature wood. Wood Science and Technology, 58: 1153-1180. https://doi.org/10.1007/s00226-024-01561-2
10. Bürüç, G.; Aydemir, D.; Bakır, K., 2019: The effect of heat treatment on some properties of eastern beech and stemmed oak wood. Journal of Bartin Faculty of Forestry, 21 (3): 713-721.
11. Cao, S.; Cheng, S.; Cai, J., 2025: Research progress and prospects of wood high-temperature heat treatment technology. BioResources, 17 (2): 3702-3717. https://doi.org/10.15376/biores.17.2.Cao
12. Doruk, Ş.; Perçin, O., 2010: Effects of heat treatment on flexural and compressive strength of some wood materi-

als. Journal of Polytechnic, 13 (2): 143-150. https://doi.org/10.2339/politeknik.1120778
13. Gündüz, G.; Aydemir, D.; Onat, S. M.; Akgün, K., 2011: The effects of tannin and thermal treatment on physical and mechanical properties of laminated chestnut wood composites. BioResources, 6 (2): 1543-1555. https://doi.org/10.15376/biores.6.2.1543-1555
14. Güntekin, E., 2024: Effects of heat treatment on elastic constants of cedar (*Cedrus libani*) wood. Tree and Forest, 5 (2): 72-78. https://doi.org/10.59751/agacorman.1483782
15. Hasanagic, R.; Fathi, L.; Hodzic, A.; Bahmani, M., 2023: Physical and mechanical changes in thermal modified wood: A review. Zastita materijala, 64 (3): 314-326. https://doi.org/10.5937/zasmat2303314H
16. Jancikova, V.; Jablonsky, M., 2025: Thermal modification of wood – A review. Sustainable Chemistry, 6 (3): 19. https://doi.org/10.3390/ suschem6030019
17. Kaymakci, A.; Bayram, B. Ç., 2021: Evaluation of heat treatment parameters' effect on some physical and mechanical properties of poplar wood with multi-criteria decision making techniques. BioResources, 16 (3): 4693-4703. http://doi.org/10.15376/biores.16.3.4693-4703
18. Korkut, S.; Karayilmazlar, S.; Hiziroglu, S.; Sanli, T., 2016: Some of the properties of heat-treated sessile oak (*Quercus petraea*). Forest Products Journal, 60 (5): 473-480. http://doi.org/10.13073/0015-7473-60.5.473
19. Perçin, O.; Doruk, Ş.; Altunok, M., 2023: Effects of ımpregnation and heat treatment on so me physical and mechanical properties of wood materials. Journal of Polytechnic, 26 (4): 1421-1429. https://doi.org/10.2339/politeknik.1120778
20. Perçin, O.; Altunok, M.; Doruk, Ş.; Saçl, C., 2017: The effect of ımpregnation and heat treatment on some mechanical properties of beech wood. Journal of Advanced Technology Sciences, 6 (3): 494-502.
21. Sundqvist, B., 2004: Divisions of wood material science. PhD Thesis, Lulea University of Technology, Skelleftea Campus, Skellefta, Sweden.
22. Toker, H.; Baysal, E.; Türkoğlu, T.; Kart, S.; Sen, F.; Peker, E., 2016: Surface characterıstıcs of orıental beech and scots pıne woods heat – treated above 200 °C. Wood Research, 61 (1): 43-54.
23. Türk, M.; Ayata, Ü., 2021: The effect of heat treatment on shore D hardness values of woods of some tree species grown in Turkey. Furniture and Wooden Material Research Journal, 4 (2): 166-173 (in Turkish). https://doi.org/10.33725/mamad.1005127
24. Xu, J.; Zhang, Y.; Shen, Y.; Li, C.; Wang, Y.; Ma, Z.; Sun, W., 2019: New perspective on wood thermal modification: Relevance between the evolution of chemical structure and physical-mechanical properties and online analysis of release of VOCs. Polymers, 11 (7): 1145. https://doi.org/10.3390/polym11071145
25. Yapıcı, F.; Esen, R.; Yörür, H.; Likos, E., 2012: The effects of heat treatment on the modulus of rupture and modulus of elastıcıty of Scots pıne (*Pinus sylvestris* L.) wood. MWSA – Technological Applied Science, 8 (1): 1-6.
26. Zhou, C.; Tian, Q.; Nie, J.; Cao, P.; Tan, Z., 2024: Mechanical properties and damage mechanisms of woods under extreme environmental conditions. Case Studies in Construction Materials, 20: e03146. https://doi.org/10.1016/j.cscm.2024.e03146.
27. ***TS ISO 13061-3, 2021: Wood – Determination of Ultimate Strength in Static Bending.
28. ***TS 13061-4, 2014: Determination of modulus of elasticity in static bending.
29. ***TS EN 408 + A1, 2014: Determination of some physical and mechanical properties.
30. ***TS ISO 13061-12, 2021. Physical and mechanical properties of wood – Test methods for small clear wood specimens. Part 12: Determination of static hardness.
31. ***TS ISO 13061-10, 2021: Physical and mechanical properties of wood – Test methods for small clear wood specimens. Part 10: Determination of impact bending strength.

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Comparison and Investigation of the Behavior of Reinforced Wooden Beams with Notches at the Ends

Istraživanje i usporedba ponašanja ojačanih drvenih greda s urezima na krajevima

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ABSTRACT • *When manufacturing wooden beams for spanning, notches are often formed at the ends. Under load, stresses develop at these notches, often causing cracks and beam failure. This study theoretically and experimentally investigated methods to reinforce such beams. Two types of calibrated beams were tested: solid timber and glued laminated beams. In experimental tests, beams were fixed in a machine to simulate mid-span "three-point" bending. Parallel theoretical evaluations followed EN 1995-1-1: Eurocode 5 and STR 2.05.07:2005 design standards. For each beam type, three groups of specimens were prepared: unreinforced, end-reinforced with dowels, and end-reinforced with plywood strips. All beams failed similarly: cracks formed at the notches and grew until the beam lost the load-bearing capacity. Failure behavior differed from typical bending tests, but the mechanical properties of unreinforced beams depended on cross-section. Dowel reinforcement effectiveness theoretically increased with the number of dowels, though excessive dowels risked splitting the wood. In tested beams, dowels nearly doubled the load capacity (6.5–24.0 kN on average). Plywood strip reinforcement improved resistance by up to 10 kN, equivalent from several percent to 2.5 times the original capacity.*
Beams with end notches, used in spans, can be evaluated under load using EN 1995-1-1: Eurocode 5 and STR 2.05.07:2005 methods. The study showed that differences between theoretical calculations and experimental results on calibrated structural timber did not exceed 17 %.

KEYWORDS: *timber beam; glulam timber beam; plywood strips; reinforced; strengthening*

SAŽETAK • *Pri proizvodnji drvenih greda velikih raspona na njihovim se krajevima često formiraju urezi. Pod opterećenjem se na tim urezima stvaraju naprezanja, što nerijetko uzrokuje pukotine i lom grede. U ovoj su studiji teorijski i eksperimentalno istraživane metode ojačanja tih greda. Ispitane su dvije vrste kalibriranih greda: grede od masivnog drva i lamelirane lijepljene grede. U eksperimentalnim ispitivanjima grede su učvršćene u stroju kako bi se simuliralo savijanje u tri točke na sredini raspona. Za paralelne teorijske procjene primijenjeni su standardi za projektiranje EN 1995-1-1: Eurocode 5 i STR 2.05.07:2005. Za svaku vrstu grede pripremljene su tri skupine uzoraka: neojačane grede, grede s čeonim ojačanjem moždanicima i grede s čeonim ojačanjem letvicama*

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furnirske ploče. Sve su grede pucale na sličan način: pukotine su nastajale na urezima i širile se sve dok greda nije izgubila nosivost. Ponašanje loma razlikovalo se od tipičnih ispitivanja savijanja, ali mehanička svojstva neojačanih greda ovisila su o njihovu presjeku. Učinkovitost ojačanja moždanicima teorijski se povećavala s brojem moždanika, iako je prevelik broj moždanika značio i rizik od cijepanja drva. Na testiranim gredama moždanici su gotovo udvostručili nosivost (u prosjeku 6,5 – 24,0 kN). Ojačanja od furnirske ploče poboljšala su otpornost do 10 kN, što je ekvivalentno iznosu od nekoliko postotaka do 2,5 puta izvorne nosivosti. Nosivost grede s urezima na krajevima može se procijeniti primjenom metoda EN 1995-1-1: Eurocode 5 i STR 2.05.07:2005. Studija je pokazala da razlike između teorijskih izračuna i eksperimentalnih rezultata na kalibriranom građevnom drvu nisu bile veće od 17 %.

KLJUČNE RIJEČI: *drvena greda; lamelirana lijepljena greda; letvice furnirske ploče; ojačanje*

1 INTRODUCTION
1. UVOD

Natural and glued timber are commonly used in construction due to their versatility and relatively straightforward processing. Glued timber is composed of wood chips of various dimensions, bonded together with adhesive, the quality of which is crucial for the properties of the structure and the risk of delamination (Ferreira *et al*., 2017; O'Loinsigh *et al.*, 2012). Structures constructed from glulam timber are stable; however, the wood responds to environmental humidity, which can result in dimensional changes in the wooden elements (Smulski, 2004).

Wooden beams are often used to overlap spans. Structurally, they are frequently cut at their ends. They are formed at the supports, which weakens the structure. The strength of beams cut at the supports diminishes due to transverse stresses, potentially leading to the formation of cracks. In such cases, it is essential to analyse and design the structures carefully. In renovation projects, cut-outs in beams are often prohibited to prevent weakening the structure (Todorovic *et al.*, 2019; Soltis *et al.*, 1998). Possible longitudinal cracks at the ends of beams are classified into three types: the crack surfaces may separate from each other vertically (in a perpendicular direction), horizontally (where shear occurs between the crack surfaces), or as a combination of these two types (Todorovic *et al.*, 2019).

In structural design, the behaviour of beams can be assessed using various methodologies. One of them, described in the standard EN 1995-1-1: Eurocode 5: "Design of timber structures", stipulates that beams with notches should be designed taking into account stress concentrations, which can be ignored in certain cases, e. g. if the bending of the beam does not cause significant tensile stresses. Shear stresses are generated at the supports with notches; therefore the beams must be of a certain height. It is also stated that notches should be made only at the supports, avoiding them in the centre of the beam. Furthermore, if notches are necessary, they should be rounded (Butler, 2002).

To prevent cracks and increase load-bearing capacity, beams can be reinforced. Recently, Şimşek Türker and his colleagues have devoted significant attention to improving the mechanical properties of glulam beam and column connections using FRP (fibre-reinforced polymers) (Şimşek Türker, 2024; Şimşek Türker and Kilincarslan, 2024; Şimşek Türker *et al.*, 2024). Their studies investigated various reinforcement methods, including carbon, glass, basalt, and aramid FRP fabrics, and their effects on connection stiffness, bending strength, and energy dissipation. Experimental tests demonstrated that FRP reinforcement significantly enhances connection performance, with carbon fibre generally proving the most effective and glass fibre the least. Additionally, numerical models were employed to predict beam behaviour, and the results showed high prediction accuracy.

Threaded rods, wood screws, bolts, and various plates made of steel, carbon or fibreglass are used for this purpose. Wood screws used for connecting or reinforcing wooden structures are categorised into full-thread and partial-thread types, chosen according to the specific requirements of each situation. Full-thread wood screws possess a greater load-bearing capacity under axial loads [Aytekin, 2008]. Screws or fully threaded screws can either be glued or simply screwed in. They enhance the resistance of the beam from cracking. There are methodologies for various types of wood, as well as glulam beams and LVL, to assess the behaviour of such reinforced beams under load. In calculations, it is generally assumed that the screws are inserted into the beams perpendicular to the wood grain (Todorovic *et al.*, 2019; Jockwer, 2014).

Occasionally, beams are strengthened using plywood strips. Plywood is a readily processed material with appropriate mechanical properties for reinforcing the ends of beams. It is advisable to use plywood that has a thickness of at least 10 mm, adhered to both sides of the beam. In order to ensure good adhesion to the beam surface, the plywood strips must be well pressed, and nails or wood screws can also be used as fasteners. Epoxy resin or polyvinyl acetate resin-based adhesives can be used for glueing plywood. The choice of adhesive is usually determined by the strength and ecological requirements of the structure (Ebnesajjad and Landrock, 2015; Broughton and Hutchinson, 2001).

Other methods of strengthening the ends of beams are sometimes used. One such methods is the use of fibreglass rods. It is said that this increases the load-bearing capacity of the beam by up to 194 %. Epoxy adhesives are used to bond the rods. Although this method of strengthening beams is effective and durable, these rods are not environmentally friendly and their recycling is difficult (Tao *et al.*, 2023; Todorovic *et al.,* 2019). Another material used is carbon fibre fabric. It is a light and strong material that allows the beams to withstand more than 2.5 times the load. Epoxy glue is used to bond the carbon fibre. This strengthening method is rarely used because it is expensive, environmentally unfriendly, and the glue can take up to 7 days to cure (Ebnesajjad and Landrock, 2015; Broughton and Hutchinson, 2001). Another way to strengthen beams is to use steel threaded rods. They are effective in cutouts where precise load transfer is required. When installing the rods, larger diameter holes need to be drilled to allow for glueing. In this case, the strength of the beam is greatly influenced by the adhesive, the quality of the glueing, and the mechanical properties of the rods. The rods can also be installed at an angle, which allows them to be fixed closer to the edge of the cutout (Branco *et al.*, 2021).

The selection of these beam reinforcement methods is influenced by cost, complexity, and environmental considerations.

Objective of the study: To evaluate the effectiveness of beam end reinforcement and to compare the practically obtained load resistance values with those theoretically calculated ones.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

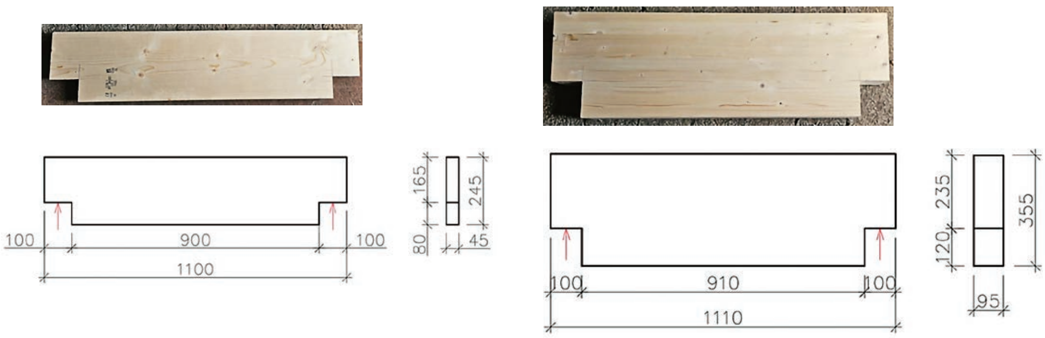
Two types of beams, made of solid and glulam spruce timber, were used for the research. The dimensions of the solid wood beams were 1100 mm × 245 mm × 45 mm, moisture content 11.3-11.8 %, density 457-471 kg/m^3; according to the manufacturer's declaration, they correspond to class C24. The dimensions of the glulam timber beams were 1110 mm × 355 mm × 95 mm, moisture content 11.2-11.5 %, density 478-489 kg/m^3; they correspond to class Gl24C.

The length of the specimens was measured using a ruler with a precision of 1 mm, while the width and thickness were measured with a calliper with a precision of 0.1 mm. The mass of the specimens was determined using scales with a precision of 1 g, and the moisture content was assessed employing an electronic moisture meter, adhering to standard EN 13183-2:2003, EN 13183-2:2003/AC:2004, with a precision of 0.1%. Notches were cut at the ends of the beams with a hand saw. There were 12 beams of both types in total. Their general view and diagram are presented in Figure 1.

Both types of beams were randomly divided into three groups of four pieces each, which were designated as follows: solid wood groups N1, N2, N3, and glulam timber groups GL1, GL2, GL3. The ends of the beams in groups N2 and GL2 were reinforced with wood screws "KLIMAS WKCP", measuring 6x180 mm and 8x240 mm, respectively, while groups N3 and GL3 were reinforced with plywood strips (plywood BB/WG, class 3, manufacturer AS "Latvijas Finieris"). The strips were glued with wood glue "Titebond Original" according to the manufacturer's recommendations. A general view and schemes of these reinforced beams are presented in Figures 2 and 3, respectively.

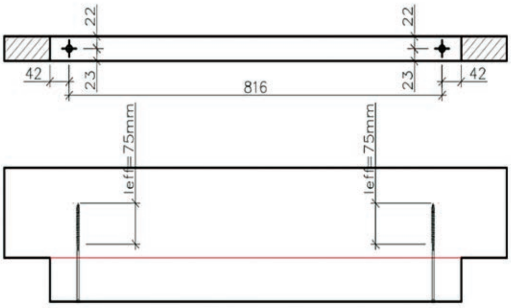
Before testing, the samples were conditioned in the laboratory for one week at a temperature of 19.5–20.0 °C and a relative humidity ranging from 52 % to 55 %.

The load-bearing capacity of the specimens was determined using the "three-point" scheme. When testing with this method, the sample is placed on two supports and pressed from above at one place (one point) in the middle. The pressure force is increased until the



a) b)

Figure 1 General view and diagram of beams made of solid (a) and glulam timber (b) used for the research
Slika 1. Opći prikaz i dijagram greda od masivnoga (a) i lijepljenog drva (b) izrađenih za istraživanje



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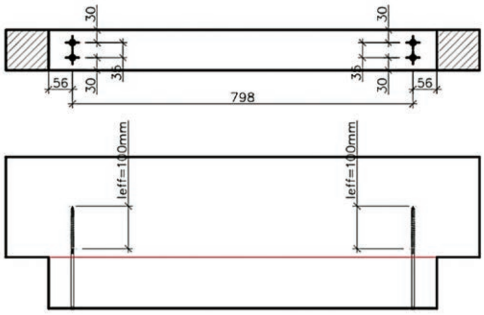

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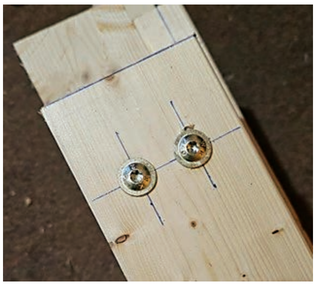
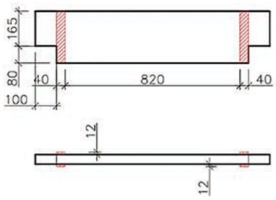
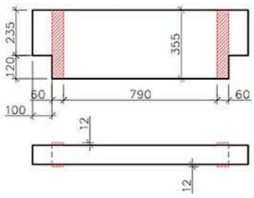


c)

Figure 2 Schemes (a, b) and a general view (c) of solid and glulam timber beams reinforced with wood screws
Slika 2. Sheme (a, b) i opći prikaz (c) masivnih i lijepljenih drvenih greda ojačanih vijcima za drvo



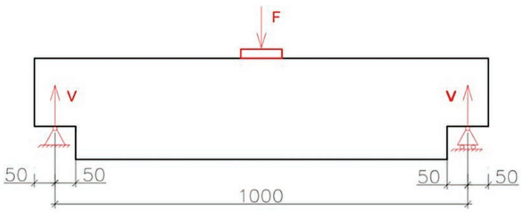
a)



b)

c)

Figure 3 Schemes (a, b) and an overview (c) of solid and glulam timber beams reinforced with plywood strips
Slika 3. Sheme (a, b) i pregled (c) masivnih i lijepljenih drvenih greda ojačanih letvicama od furnirske ploče



a)

b)

Figure 4 Scheme of the test (a) and general view (b)
Slika 4. Shema ispitivanja (a) i opći prikaz (b)

sample breaks and stops resisting. The distance between the lower supports and the geometric dimensions of the sample are evaluated during the calculation. The tests were carried out in accordance with the standard EN 310:1993. The principal test scheme and general view are presented in Figure 4.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The calculated and practically determined values of load resistance using methods "A" and "B", along with the statistical data assessing the dispersion of these values (standard deviation and coefficient of variation), are presented in Table 1.

First of all, it should be noted that the "false" strength of unreinforced beams differs (column 5). This difference is quite significant (4.15 and 3.66 N/mm^2 or MPa) and is about 12 %. However, this is not related to gluing, but to the dispersion of the mechanical properties and structural features of wood (Wagenführ, 2000; Wood handbook, 2010).

Data analysis showed that the glulam timber beams withstood higher loads than the solid ones (column 4). However, this is attributed to their significantly larger cross-section. To enable a comparison of these values, the load resistance (MPa) was calculated (column 5). Evaluating the nature of the beams failure (both glulam timber and solid beams, when subjected to loads, did not fracture, as is typical in the case of three-point bending, but delamination occurred at the ends with notches) and because they were reinforced, this does not accurately reflect the true bending strength of the material. Nonetheless, in the authors' opinion, it permits a more objective comparison of samples with differing cross-sections. It can be stated that, in the case of unreinforced beams, both glued and solid beams exhibited similar mechanical properties. In terms of MPa, the difference in the average values of the groups was approximately 12 %, which is quite small considering the dispersion of the mechanical properties of wood. Regarding reinforcement with wood screws, it can be concluded that the nature of beam failure significantly influences the number of screws used. Comparatively, in both glulam timber and solid wood beams, the specimens with wood screws endured nearly twice the load compared to those without wood screws. Specifically, when comparing the groups "N2" and "N1", this difference is 1.87 times, and when assessing the groups "GL2" and "GL1", the difference is 1.81 times. However, in terms of absolute values, the average difference with one wood screw is 6.5 kN, and with two screws, it is as much as 24.0 kN. Certainly, the strength properties of wood likely also played a role, but the trend is clear. A markedly different effect was achieved when reinforcing beams with plywood strips. In this instance, for both solid and glued beams, plywood strips "added" several kN (averaging about 8.9 for solid beams and approximately 7.0 kN for glued beams). Based on the nature of the samples breakdown, it can be concluded that this "additional resistance" was influenced by two factors – the area of the strip and the resistance of the wood to delamination. Given that these values are similar, the results were as follows. In terms of relative values, the strength of beams with a larger cross-section increased by about 1.23 times, whereas that of beams with a smaller cross-section increased significantly by 2.20 times.

When comparing the values of the load resistance of beams calculated theoretically with those determined practically, it can be stated that they are simi-

Table 1 Calculated and practically determined values of load resistance using methods "A" and "B" and statistical data assessing the dispersion of values
Tablica 1. Izračunane i praktično određene vrijednosti otpora opterećenju primjenom metoda A i B te statistički podatci prema kojima se procjenjuje raspršenost vrijednosti

Group No. *Broj skupine*	**Force calculated by method A, kN** *Sila izračunana prema metodi A, kN*	**Force calculated by method B, kN** *Sila izračunana prema metodi B, kN*	**Determined force within group, kN** *Sila utvrđena unutar skupine, kN*	**Determined force within group, kN** *Sila utvrđena unutar skupine, kN*	**Standard deviation within group, kN** *Standardna devijacija unutar skupine, kN*	**Variation coefficient within group, %** *Koeficijent varijacije unutar skupine, %*	**Difference between values in columns "2" and "4", %** *Razlika između vrijednosti u stupcima 2. i 4., %*	**Difference between values in columns "3" and "4", %** *Razlika između vrijednosti u stupcima 3. i 4., %*
1	2	3	4	5	6	7	8	9
N1	6.99	6.41	7.48	4.15*	0.38	5.08	6.55	14.30
N2	14.02	-	14.00	7.77**	0.65	4.64	0.14	-
N3	14.71	-	16.42	9.12***	0.70	4.26	10.41	-
GL1	33.00	24.49	29.50	3.66*	1.08	3.66	11.86	16.98
GL2	47.10	-	53.50	6.70**	2.14	4.00	11.96	-
GL3	31.38	-	36.48	4.57***	1.60	4.39	13.98	-

* – When evaluating the nature of the sample failure mode, this represents a false strength of the wood under load (bending).
** – This indicates a false strength of the wood under load, as wood screws affect the outcome.
*** – This signifies a false strength of the wood under load, with the result being influenced by glued plywood.
** – Pri procjeni načina loma uzorka predočuje lažnu čvrstoću drva pod opterećenjem (savijanje).*
*** – Upućuje na lažnu čvrstoću drva pod opterećenjem jer vijci za drvo utječu na rezultat.*
**** – Označava lažnu čvrstoću drva pod opterećenjem, pri čemu na rezultat utječe zalijepljena furnirska ploča.*

a)

b)

Figure 5 Predominant failure modes of solid timber (a) and glulam timber (b)
Slika 5. Prevladavajući načini loma punog drva (a) i lijepljenoga lameliranog drva (b)

lar (Table 1, columns 8 and 9). The largest difference was observed in the case of glulam timber unreinforced beams (group GL1), where the values calculated according to STR 2.05.07:2005 "Design of timber structures" (Method "B") and the practical values differed by nearly 17 %. In contrast, the smallest difference was noted for the group of specimens N2, with the values calculated according to EN 1995-1-1: Eurocode 5 "Design of timber structures" (Method "A") differing from the practical values by only 0.14 %. Method "B" does not permit the calculation of the strength properties of reinforced beams, so these were not computed. Overall, by assessing the differences between the calculated and practical values, it can be stated that the values computed by method "A" are closer to those obtained in practice (the difference was 0.14 – 14.0 %). Conversely, the values calculated by method "B" differed from the practical ones by 14.0 – 17.0 %.

The dispersion of results across all groups of specimens was small, with the coefficient of variation ranging from 3.6 % to 5.1 %. This was the smallest for unreinforced glulam timber beams and the largest for unreinforced solid beams (see Table 1, column 7).

Thus, on one hand, both the variability of values within groups and the discrepancies between theoretical and practical values stem from the considerable variation in the mechanical properties of wood as a material. On the other hand, the research used wood calibrated by the manufacturer, and therefore both the variability of values and the discrepancies between theoretical and practical values were relatively small.

General images of the prevailing nature of the collapse of solid and glued timber beams are presented in Figure 5.

The characteristics of beam failure and other defects that occurred under load were analysed individually. Regarding unreinforced beams (groups N1, GL1), both solid and glulam timber beams exhibited the formation of a crack at the beam cutout, leading to collapse once the specified load threshold was attained. When loading beams that are reinforced with wood screws (groups N2 and GL2), the wood fibres are initially compressed beneath the heads of the screws. In the case of solid wood beams, where one screw is installed at each end of the beam, the loads fluctuate within the range of 7.0 to 8.0 kN. In the case of glulam timber beams, two wooden bolts were twisted at the ends, and the forces exerted varied within the range of 21 to 27 kN. Furthermore, as the loads increased, the wooden bolts were extracted, resulting in the formation of cracks at the beam cutouts, similar to the behaviour observed in unreinforced beams. When loading beams reinforced with glued plywood strips (designated as groups N3 and GL3), the wood exhibited nearly simultaneous exfoliation at the adhesive joints that connected the beams to the plywood strips, accompanied by crack formation. It is noteworthy that cohesive failure predominantly occurred through the wood (primarily in the beams) at the adhesive joints.

The dependence of the beam deflection on the load was also evaluated. The curves show the average values of the mentioned groups. They are presented in Figure 6.

We see that both in case of solid timber and glulam timber, the largest deformations were observed in beams reinforced with wood screws. However, these differences are very small and are not related to the strengthening method, but to the viscous-elastic properties of the wood.

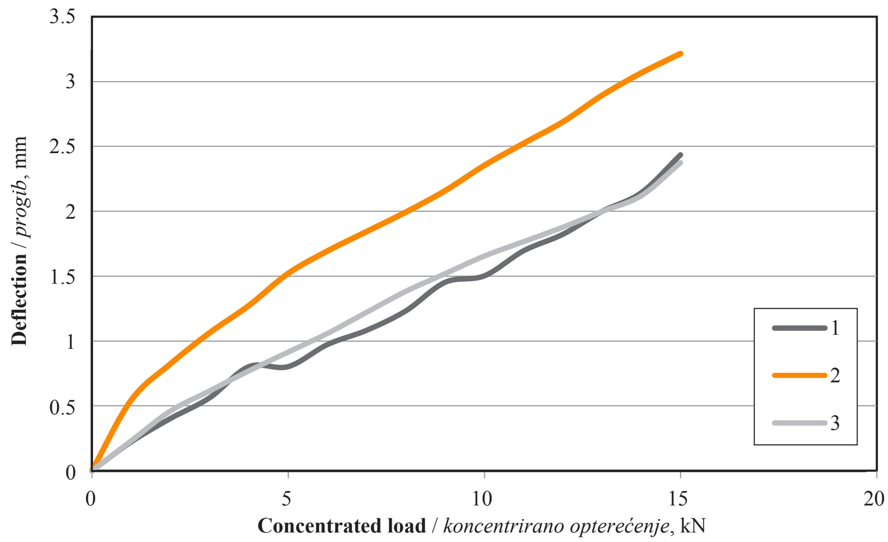
Summarising the results obtained, it can be stated that by choosing the right method of reinforcing the ends of the beams, a much stronger structure can be obtained. This has been confirmed by both theoretical calculations and practical research results.

When examining the results in general, in the context of the results obtained by other researchers, it can be stated that the fastening effect depends on the materials and method used. Another important aspect is the prediction of the strength properties of the structure. In many cases, it is complicated not so much by the method of reinforcement itself, but by the unevenness of the wood structure and the dispersion of mechanical properties.

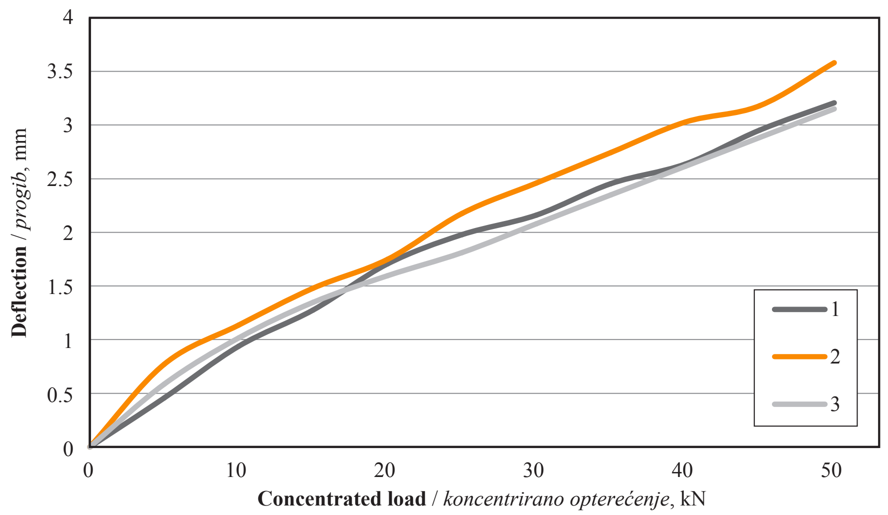
4 CONCLUSIONS
4. ZAKLJUČAK

1. By employing suitable methods for reinforcing the ends of the beams with notches under optimal conditions, the structural strength can be enhanced twofold or more.

2. In the installation of beams with cutouts at their ends – regardless of whether they are constructed



a)



b)

Figure 6 Beam deformations depending on the load: a) solid timber; b) glulam timber: 1 – unreinforced beams; 2 – reinforced with wood screws beams; 3 – reinforced with glued plywood strips beams
Slika 6. Deformacije greda ovisno o opterećenju: a) masivno drvo; b) lijepljeno lamelirano drvo: 1 – neojačane grede; 2 – grede ojačane vijcima za drvo; 3 – grede ojačane zalijepljenim letvicama od furnirske ploče

from solid wood or glulam timber, and irrespective of reinforcement – the nature of potential failure remains consistent. Due to the induced stresses, a crack may develop at the cutout, leading to the delamination of the wood.

3. Unreinforced beams with cutouts at the ends, positioned within the span, demonstrate a load resistance that is contingent upon the cross-sectional area; however, the failure pattern differs from the conventional failure modes associated with "three-point" or "four-point" bending.

4. A highly effective method for strengthening of beams with notched ends involves the use of dowels. An increased quantity of dowels may yield a more pronounced strengthening effect; however, there exists a risk of compromising the integrity of the beam, potentially leading to splitting and diminishing the wood capacity to securely accommodate the dowels. In the instances of the examined beams, their load-bearing resistance exhibited an approximate doubling after the implementation of dowels, with an average increase ranging from 6.5 to 24.0 kN.

5. When using glued plywood strips to reinforce beams with cutouts at the ends, their effect, in absolute terms, does not depend on the beam load resistance and, in specific instances, can increase the resistance by up to 10.0 kN. In the cases examined, this varied from a few percent to nearly 2.5 times.

6. In the assessment of deflection for beams featuring notches at their ends, which are used for installation across spans, the methodologies outlined in the normative documents EN 1995-1-1: Eurocode 5 "Design of Timber Structures" and STR 2.05.07:2005 "Design of Timber Structures" are deemed appropriate. Research indicates that the discrepancies between the theoretically calculated values and those derived from

practical testing of calibrated construction timber did not exceed 17 %. This difference is considered minimal, especially when considering the variability in the mechanical properties of wood.

5 REFERENCES
5. LITERATURA

1. Aytekin, A., 2008: Determination of screw and nail withdrawal resistance of some important wood species. International Journal of Molecular Sciences, 9 (4), 626-637. https://doi.org/10.3390/ijms9040626
2. Branco, J.; Tannert, T.; Dietsch, P., 2021: Reinforcement of timber structures: standardization towards a new section for EC 5. State-of-the-Art Report of the RILEM TC 245-RTE, Springer, Switzerland. https://doi.org/10.1007/978-3-030-67794-7
3. Broughton, J. G.; Hutchinson, A. R., 2001: Adhesive systems for structural connections in timber. International Journal of Adhesion and Adhesives, 21 (3): 177-186. https://doi.org/10.1016/S0143-7496(00)00049-X
4. Butler, R., 2002: Architectural Engineering Design: Structural Systems, McGraw Hill Professional.
5. Ebnesajjad, S.; Landrock, A. H., 2015: Adhesives Technology Handbook, 3rd ed., Elsevier Inc. https://doi.org/10.1016/C2013-0-18392-4
6. Ferreira, J. G.; Cruz, H.; Silva, R., 2017: Failure behaviour and repair of delaminated glulam beams. Construction and Building Materials, 154: 384-398. https://doi.org/10.1016/j.conbuildmat.2017.07.200
7. Jockwer, R., 2014: Structural behaviour of gluer laminated timber beams with unreinforced and reinforced notches. PhD Thesis, ETH Zurich.
8. O'Loinsigh, C.; Oudjene, M.; Shotton, E.; Pizzi, A.; Fanning, P., 2012: Mechanical behaviour and 3D stress analysis of multi-layered wooden beams made with welded-through wood dowels. Composite Structures, 94 (2): 313-321. https://doi.org/10.1016/j.compstruct.2011.08.029
9. Şimşek Türker, Y., 2024: Experimental investigation of rotational behavior of glulam column-beam connection reinforced with carbon, glass, basalt and aramid FRP fabric. Drvna industrija, 75 (2): 259-270. https://doi.org/10.5552/drvind.2024.0162
10. Simsek Turker, Y.; Kilincarslan, S., 2024: Experimental and numerical investigation of flexural properties of larch beams reinforced with different layer numbers. Revista De La Construcción, 23 (1): 47-57. http://dx.doi.org/10.7764/rdlc.23.1.47
11. Simşek Türker, Y.; Kilinçarslan, Ş.; Yilmaz Ince, E., 2024: Performance of ANN, Random Forest and XG-Boost methods in predicting the flexural properties of wood beams reinforced with carbon-FRP. Wood Material Science & Engineering, 20 (3): 657-668. https://doi.org/10.1080/17480272.2024.2370942
12. Simsek Turker, Y.; Kilinçarslan, S.; Avcar, M., 2024: Enhancement of mechanical properties in FRP-reinforced glulam column-beam connections: A FEM approach. GeoStruct Innovations, 2 (1): 10-20. https://doi.org/10.56578/gsi020102
13. Smulski, S., 2004: Solid wood products | Structural use of wood. Encyclopedia of Forest Sciences, 2004: 1318-1327. https://doi.org/10.1016/B0-12-145160-7/00047-8
14. Soltis, A. L.; Ross, R. J.; Rammer, D. R., 1998: Localized notch reinforcement for wooden beams. United States patent No. 5 852 909.
15. Tao, Y.; Hadigheh, S. A.; Wei, Y., 2023: Recycling of glass fibre reinforced polymer (GFRP) composite wastes in concrete: A critical review and cost benefit analysis. Structures, 53: 1540-1556. https://doi.org/10.1016/j.istruc.2023.05.018
16. Todorovic, M.; Glisovic, I.; Stevanovic, B., 2019: Experimental investigation of cracked end-notched glulam beams repaired with GFRP bars. Wood Research, 64 (6): 1077-1086.
17. Wagenführ, R., 2000: Holzatlas (5). Fachbuchferlag Leipzig im Carl Hanser Verlag. Leipzig, p. 707.
18. ***Forest Products Laboratory, 2010: Wood handbook – Wood as an engineering material. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, pp. 508
19. *** Standard EN 13183-2:2002/AC:2003 Moisture content of a piece of sawn timber. Part 2: Estimation by electrical resistance method European Committee for Standardization, Brussels.
20. *** Standard EN 1995-1-1, 2004: Design of timber structures. Part 1-1: General – Common rules and rules for buildings European Committee for Standardization, Brussels.
21. *** Standard EN 310, 1993: Wood-based panels – Determination of modulus of elasticity in bending and of bending strength European Committee for Standardization, Brussels.
22. *** Standard STR 2.05.07, 2005: Design of wooden structures, Construction technical regulation, Ministry of the Environment of the Republic of Lithuania, Vilnius
23. *** Standard EN 310, 1993: Wood-based panels – Determination of modulus of elasticity in bending and of bending strength European Committee for Standardization, Brussels.

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Experimental and Numerical Study on Strengthening Timber Beams Using Carbon and Glass Fibers

Eksperimentalna i numerička studija ojačavanja drvenih greda upotrebom ugljikovih i staklenih vlakana

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ABSTRACT • *This research investigates the flexural behavior of laminated spruce timber beams strengthened with carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) composites. A total of 28 specimens, fabricated in accordance with TS EN 408+A1 standards, comprising twelve CFRP reinforced, twelve GFRP reinforced, and four unreinforced control beams, were subjected to four-point bending tests. Three distinct reinforcement configurations rods, plates, and fabrics were systematically applied and comparatively evaluated. The results consistently demonstrated that CFRP reinforcements significantly outperformed GFRP counterparts in enhancing stiffness and flexural strength. Among the reinforcement types, double carbon rods and wide CFRP plates exhibited the most pronounced improvements, while spiral-wrapped CFRP fabrics showed superior performance relative to flat fabric applications. Additionally, the study highlights the critical influence of reinforcement configuration on the mechanical response of timber beams and underscores the impact of inherent wood defects on experimental outcomes. Complementary numerical simulations conducted using ANSYS software corroborated the experimental findings, thereby validating the effectiveness of the proposed reinforcement strategies for timber rehabilitation.*

KEYWORDS: *fiber reinforced polymer (FRP); timber beams; strengthening; laminate; ANSYS*

SAŽETAK • *U radu je predstavljeno istraživanje savijanja lameliranih drvenih greda od smrekovine ojačanih polimernim kompozitima s ugljikovim vlaknima (CFRP) i staklenim vlaknima (GFRP). U skladu sa standardom TS EN 408+A1, ukupno je izrađeno 28 uzoraka: 12 uzoraka ojačanih CFRP-om, 12 uzoraka ojačanih GFRP-om i četiri neojačane kontrolne grede. Na uzorcima je provedeno ispitivanje savijanja u četiri točke. Sustavno su primijenjena i usporedno ocijenjena tri različita sustava ojačanja: šipke, ploče i tkanine. Rezultati su dosljedno pokazali da u povećanju krutosti i čvrstoće na savijanje ojačanje CFRP-om znatno nadmašuje GFRP ekvivalente. Dvostruke ugljikove šipke i široke CFRP ploče pokazale su najveća poboljšanja, dok su za spiralno omotane*

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CFRP tkanine utvrđene superiorne performanse u usporedbi s primjenom ravnih tkanina. Osim toga, u studiji se ističe znatan utjecaj sustava ojačanja na mehanički odziv drvenih greda i naglašava utjecaj inherentnih grešaka drva na eksperimentalne rezultate. Komplementarne numeričke simulacije provedene uz pomoć ANSYS softvera potvrdile su eksperimentalne rezultate, čime je ujedno potvrđena i učinkovitost predloženih sustava ojačanja za poboljšanje svojstava drvenih konstrukcija.

KLJUČNE RIJEČI: *polimer ojačan vlaknima (FRP); drvene grede; ojačanje; laminat; ANSYS*

1 INTRODUCTION
1. UVOD

Wood has long been used as a principal structural material due to its favorable mechanical properties and environmental sustainability. As a lightweight, renewable, and biodegradable resource, timber offers excellent thermal and acoustic insulation, making it suitable for energy-efficient and eco-friendly construction (Ramage *et al*., 2017). Moreover, its inherent flexibility and ductility provide notable advantages in seismic applications, as demonstrated in recent studies on displacement-based seismic design of timber structures (Loss *et al*., 2018). The development of engineered wood products, such as glued laminated timber (glulam) and laminated veneer lumber (LVL), has further improved the structural reliability and expanded the applicability of timber in both contemporary and traditional architecture (Abed *et al*., 2022; Wang *et al*., 2021).

Despite these benefits, timber's organic nature makes it vulnerable to environmental degradation caused by moisture, UV radiation, insect infestation, and fungal decay, all of which can compromise long-term structural performance (Jirouš Rajković and Miklečić, 2021; Bazli *et al*., 2022). Flexural members, especially timber beams, are particularly susceptible to fatigue and cracking under cyclic or dynamic loading conditions frequently encountered in seismic zones. To address these challenges, fiber-reinforced polymer (FRP) composites have emerged as a highly effective reinforcement strategy, enhancing the durability and load-bearing capacity of timber elements (Çankal *et al*., 2023).

Among modern strengthening techniques, the application of FRP composites, especially carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP), has gained considerable attention. These materials are characterized by high tensile strength, low density, corrosion resistance, and ease of application (Li *et al*., 2022). When externally bonded to timber beams, particularly in the form of CFRP sheets or plates, FRP reinforcements have been shown to significantly enhance flexural stiffness, ultimate load capacity, and post-elastic behavior without introducing a substantial increase in structural dead load (Zhao *et al*., 2024). Numerous experimental studies have confirmed the effectiveness of FRP reinforcement in timber structures. Fiorelli and Dias (2003) reported notable improvements in bending strength and stiffness of glulam beams strengthened with CFRP plates, while Borri *et al*. (2011) observed enhanced ductility and delayed crack propagation in beams reinforced with GFRP. Similarly, D'Ambrisi *et al*. (2014) demonstrated improved structural performance in aged timber floor systems strengthened using externally bonded CFRP sheets.

Several previous studies have investigated the strengthening of timber and laminated wood elements using fiber-reinforced polymer (FRP) materials, primarily focusing on specific reinforcement concepts and limited cross-sectional configurations. Novosel *et al*. (2021) examined the structural performance of bidirectional oak-wood laminations reinforced with carbon-fiber (CFRP) implants, reporting significant improvements in stiffness and load-bearing capacity; however, their work was restricted to implant-based reinforcement within a predefined laminated cross-section. In a subsequent study, Novosel *et al*. (2023) extended this approach to standard and prestressed glass-fiber (GFRP) implants, confirming the efficiency of implant reinforcement while remaining confined to a single wood species and a specific internal reinforcement technique. In addition, Alsheghri and Akgül investigated the use of FRP plates as substitutes for steel sheets in timber structural joints, emphasizing joint performance, corrosion resistance, and material efficiency rather than the global flexural strengthening of timber beams. Their study addressed connection behavior rather than beam-level structural response and did not consider comparative strengthening layouts within the same timber member. In addition, Alsheghri and Akgül (2021) investigated the use of FRP plates as substitutes for steel sheets in timber structural joints, emphasizing joint performance, corrosion resistance, and material efficiency rather than the global flexural strengthening of timber beams. Their study addressed connection behavior rather than beam-level structural response and did not consider comparative strengthening layouts within the same timber member.

In contrast to these studies, the present research proposes a different and more comprehensive cross-sectional strengthening design for laminated timber beams, allowing direct comparison of multiple reinforcement strategies within a unified experimental and numerical framework. Specifically, the study investigates externally bonded FRP fabrics**,** near-surface mounted (NSM) FRP rods, and NSM FRP plates/strips, using both CFRP and GFRP materials. This comparative cross-sectional approach enables a systematic evaluation of the influence of reinforcement type, geometry, and placement on flexural behavior, stiffness enhancement, and failure mechanisms, thereby addressing key limitations identified in previous research.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

In this study, a total of 28 timber beam specimens were prepared, including 12 beams reinforced with carbon fiber-reinforced polymer (CFRP), 12 beams reinforced with glass fiber-reinforced polymer (GFRP), and 4 unreinforced control specimens. All beams were fabricated from spruce wood (*Picea* spp.) and machined to standardized dimensions of 90 mm × 150 mm × 2500 mm to ensure geometric consistency and structural relevance under flexural loading.

The control group consisted of two glued-laminated timber (Glulam) beams and two solid (non-laminated) spruce beams, allowing direct comparison between laminated and solid wood configurations without reinforcement. The FRP reinforcements were bonded using a high-performance epoxy resin, which served both as the adhesive agent and polymer matrix, ensuring effective stress transfer between the timber substrate and the composite reinforcement.

All specimens were tested under four-point bending in accordance with relevant international standards to evaluate flexural strength, stiffness, and failure behavior. This experimental program enabled a systematic assessment of the influence of wood configuration and reinforcement type on the flexural response of timber beams. In parallel, three-dimensional finite element analyses (FEA) were conducted using ANSYS software to numerically simulate the bending behavior and to support interpretation of the experimental results.

2.1 Materials
2.1. Materijali

2.1.1 Glued-laminated timber (Glulam)
2.1.1. Lamelirane drvene grede

Glued-laminated timber (Glulam) is a structural engineered wood product manufactured by bonding multiple timber lamellae with structural adhesives under controlled pressure, resulting in a composite member characterized by enhanced load-bearing capacity, dimensional stability, and reduced susceptibility to defects commonly associated with solid sawn timber (Wang *et al*., 2021). In this study, Glulam elements were produced from *Picea orientalis* (spruce), a softwood species recognized for its straight grain, low density, and favorable adhesive bonding performance. Due to its homogeneous anatomical structure and widespread availability in Turkey as well as Central and Northern Europe, *Picea orientalis* is commonly used in the production of engineered wood products, including Glulam and cross-laminated timber (CLT) (Öztürk *et al*., 2017). The physical and mechanical properties of the timber were determined through standardized laboratory tests and are summarized in Table 1.

2.1.2 Fiber-reinforced polymers (FRP)
2.1.2. Polimeri ojačani vlaknima

In this study, two types of fiber-reinforced polymers (FRP) were used to strengthen timber beams: carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP). These materials are

Table 1 Mechanical and physical properties of wood
Tablica 1. Mehanička i fizička svojstva drva

Property *Svojstvo*	***Picea* wood** *Smrekovina*	**Range in literature** *Raspon u literaturi*	**Standard/Reference** *Standard/Referenca*
Physical properties / *Fizička svojstva*			
Moisture content, % *sadržaj vode,* %	12.7	10-15	TS EN 13183-1:2012
Density, g/cm^3 *gustoća,* g/cm^3	0.42	0.38-0.45	TS ISO 13061-2
Specific gravity *specifična gustoća drva*	0.43	0.38-0.45	**TS ISO 13061-3:**2017
Mechanical properties / *Mehanička svojstva*			
Young's modulus MOE, MPa *Youngov modul elastičnosti,* MPa	10345.8	9000–12000	TS ISO 13061-4:2022
Compressive strength (fc,0), MPa *čvrstoća na tlak (fc,0),* MPa	29.152	C27=28	TS ISO 13061-17 EN 338
Compressive strength (fc,90), MPa *čvrstoća na tlak (fc,90),* MPa	2.948	2-5	TS ISO 13061-5
Tensile strength, MPa *čvrstoća na vlak,* MPa	60.217	40-90	TS ISO 13061-6 ASTM D143-14

renowned for their high tensile strength, lightweight nature, and resistance to environmental degradation, making them particularly suitable for structural reinforcement applications (Saad and Lengyel, 2022).

The reinforcement was applied in different forms, including rods, panels, and fabrics, to investigate how each configuration influences the performance of the strengthened timber beams. The main objective of this research was to evaluate and compare the flexural behavior of timber beams reinforced with various FRP forms through four-point bending tests.

The mechanical and physical properties of the CFRP and GFRP materials used in this research, such as Young's modulus, Poisson's ratio, density, bulk modulus, and shear modulus, were obtained from manufacturer technical datasheets and verified through reliable online sources (Fibertech Composite, 2023; Sika Services AG, 2024; Matek Fiber, 2025a, 2025b; Fiber Market, 2024; Karbontech Tekstil, 2025). These parameters, summarized in Table 2, were used as essential input data for evaluating the contribution of each FRP type to the flexural response of the strengthened

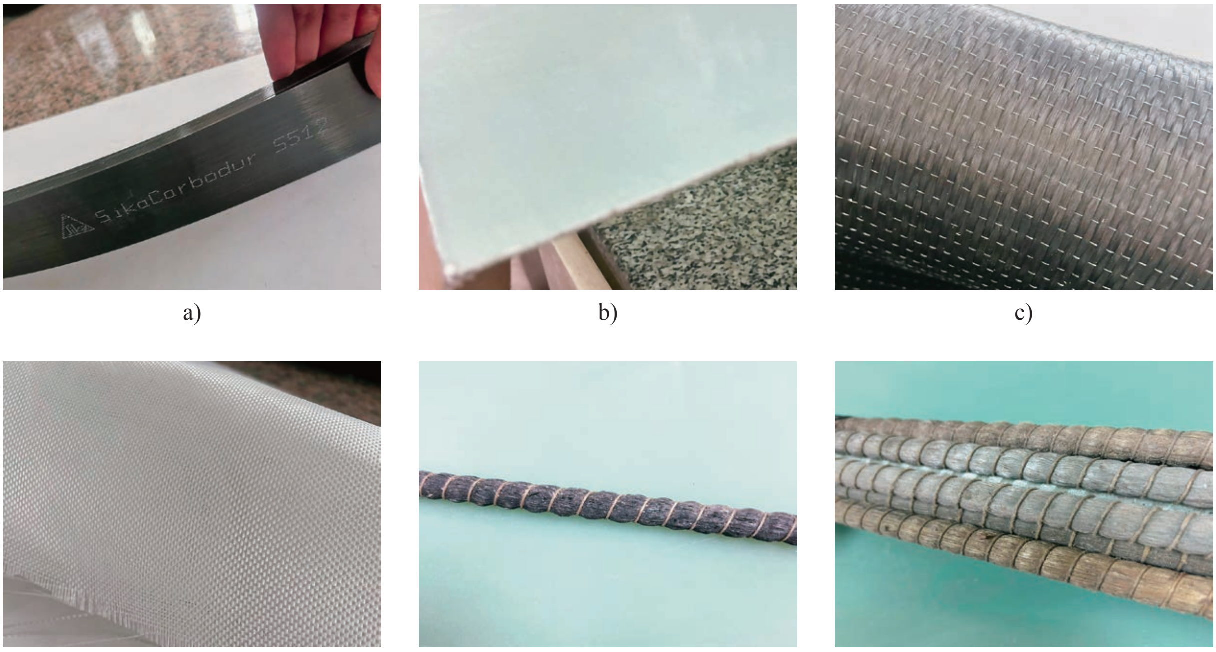


Figure 1 Different types and configurations of FRP reinforcement materials used in the study: a) CFRP Strip; b) GFRP Panel; c) CFRP fabric; d) GFRP fabric; e) CFRP rod; f) GFRP rod
Slika 1. Različite vrste i sustavi polimera s vlaknima za ojačavanje drvenih greda ispitivanih u studiji: a) CFRP traka; b) GFRP ploča; c) CFRP tkanina; d) GFRP tkanina; e) CFRP šipka; f) GFRP šipka

Table 2 Mechanical and physical properties of FRP reinforcement materials
Tablica 2. Mehanička i fizička svojstva materijala za ojačavanje drvenih greda

Parameter *Parametar*	**Strip/ Panel** *Traka / Ploča*		**Rod** / *Šipka*		**Fabric** / *Tkanina*	
	Glass panel *Staklena ploča*	Carbon strip *Karbonska traka*	Glass rod *Staklena šipka*	Carbon rod *Karbonska šipka*	Glass fabric *Staklena tkanina*	Carbon fabric *Karbonska tkanina*
Poisson`s ratio *Poissonov omjer*	0.23	0.30	0.20	0.25	0.22	0.25
Young`s modulus, MPa *Youngov modul,* MPa	70000	165000	90000	200000	70000	230000
Density, g/cm^3 *gustoća,* g/cm^3	2.5	1.6	2.2	1.5	2.5	1.8
Bulk modulus, MPa *modul stlačivosti,* MPa	35000	137500	40000	15000	30000	50000
Shear modulus, MPa *modul smičnosti,* MPa	25000	63400	25000	15000	30000	30000
Thickness, mm *debljina,* mm	1.5	1.2	D=10	D=10	1	1

timber beams. Figure 1 illustrates the different FRP reinforcement forms employed in this study, including (a) CFRP strip, (b) GFRP panel, (c) CFRP fabric, (d) GFRP fabric, (e) CFRP rod, and (f) GFRP rod.

2.1.3 Adhesive
2.1.3. Ljepilo

An epoxy resin was used as the bonding agent between the fiber-reinforced polymer (FRP) sheets and the glued-laminated timber (Glulam) surfaces. Vaněrek *et al*. (2017) reported that epoxy adhesives exhibit high adhesion capacity, mechanical strength, and resistance to moisture and chemical exposure, making them suitable for durable FRP–wood bonding. The two-component system, consisting of resin (A) and hardener (B), was applied uniformly to ensure full surface contact and minimize the risk of debonding. The technical properties of the epoxy adhesive used in this study are provided in Table 3, and its components are shown in Figure 2.

Table 3 Technical data of epoxy resin
Tablica 3. Tehnički parametri epoksidnog ljepila

Parameter / *Parametar*	**Value** / *Vrijednost*
Elastic modulus, MPa *modul elastičnosti,* MPa	3800
Density, g/cm^3 *gustoća,* g/cm^3	1.31
Compressive strength, MPa *čvrstoća na tlak,* MPa	80

Figure 2 Scalica epoxy adhesive system resin (A) and hardener (B)
Slika 2. Epoksidni sustav ljepila Scalica (A) i očvršćivač (B)

2.2 Specimen preparation
2.2. Priprema uzoraka

The preparation and strengthening of the laminated timber specimens followed a structured methodology, as outlined schematically in Figure 3. The process began with the selection of timber based on its strength grade and moisture condition to ensure material uniformity and compliance with required standards. The selected wood boards were then bonded using epoxy adhesive, producing laminated timber elements with consistent structural characteristics.

Subsequently, fiber-reinforced polymer (FRP) systems were prepared using either carbon or glass fibers embedded in a polymer matrix. These composites were manufactured using appropriate fabrication methods and designed to function compatibly with the laminated timber substrate. Epoxy resins served both as the adhesive medium and, where applicable, as part of the composite matrix, enabling efficient stress transfer between the fibers and the wood. Two reinforcement approaches were applied: external surface reinforcement and near-surface internal reinforcement.

In the external method, FRP materials were bonded directly onto the surface of the laminated wood elements, while the near-surface method involved positioning the FRP materials within shallow grooves close to the wood surface before applying epoxy. Each method resulted in reinforced laminated wood elements with distinct reinforcement mechanisms. Finally, the strengthened specimens were subjected to bending tests to evaluate the structural response. The examination focused on load-bearing capacity, stiff-

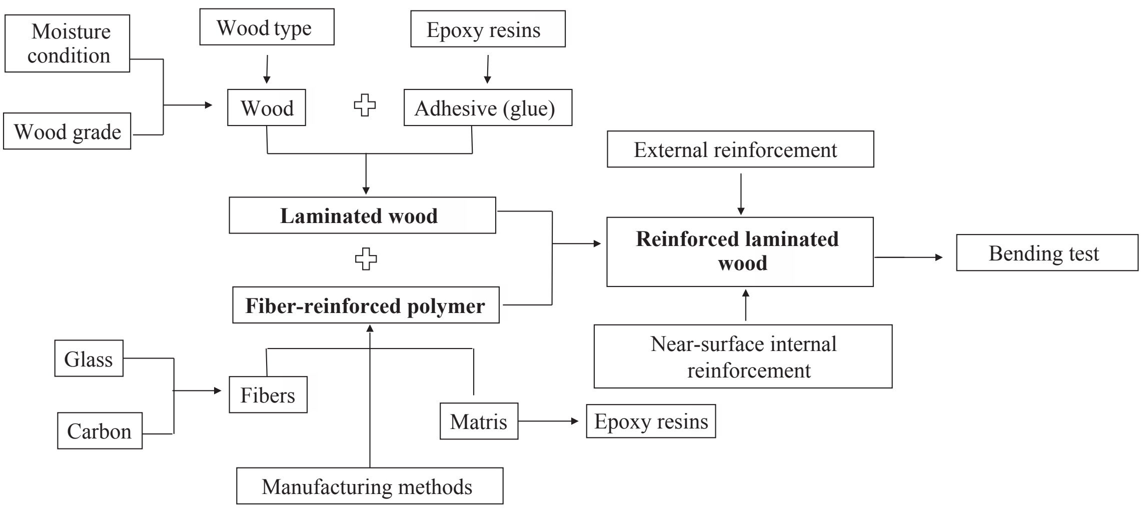


Figure 3 Thesis study flowchart
Slika 3. Dijagram toka istraživanja

ness, and overall performance under flexural loading. This integrated methodology enabled a systematic assessment of how timber type, adhesive selection, fiber material, and reinforcement approach influence the mechanical behavior of reinforced laminated wood.

2.2.1 Preparation of glulam
2.2.1. Priprema lameliranih drvenih greda

The glued-laminated timber (Glulam) elements used in this study were manufactured from spruce wood (*Picea* spp.), selected for its uniform mechanical properties and widespread use in structural applications. All timber materials were sourced from a certified supplier to ensure consistency, quality, and compliance with relevant standards.

The Glulam panels were fabricated by bonding five individual spruce laminae, each 30 mm thick, using an epoxy-based adhesive. After lamination, the panels were cut into standardized beam specimens with final dimensions of 90 mm × 150 mm × 2500 mm using a precision cutting system.

Prior to testing, the specimens were conditioned to achieve a target moisture content of approximately 12 %. The moisture content of each specimen was measured using a handheld moisture meter to ensure consistency across all samples. All conditioning and testing procedures were carried out under controlled laboratory conditions, with ambient temperature maintained between 20-23 °C and relative humidity between 50-60 %.

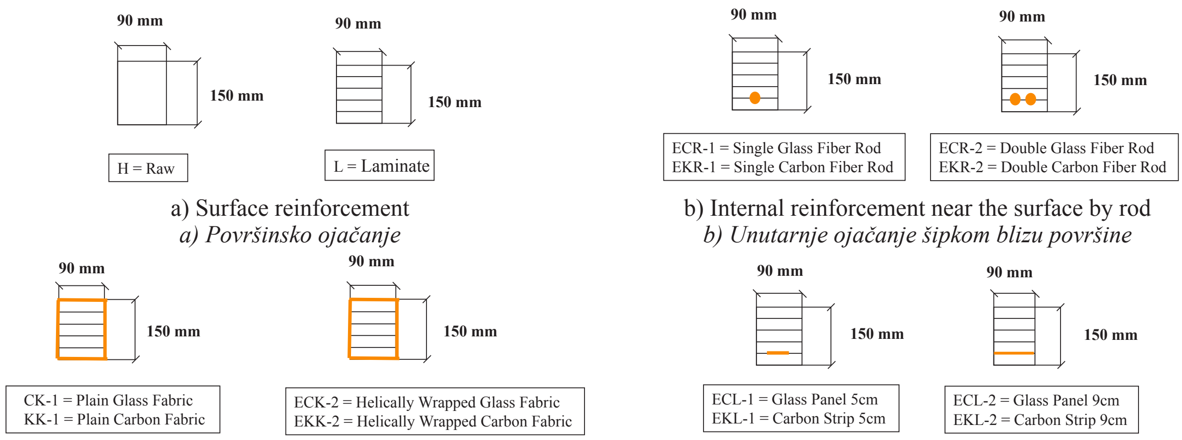
2.2.2 Application of FRP reinforcement
2.2.2. Primjena FRP ojačanja

The reinforcement process employed two primary configurations: external surface reinforcement and internal reinforcement. Tables 1, 2 and 3 outline the mechanical and physical properties of the materials used in this study, including different forms of glass and carbon fiber composites (plates, rods, and fabrics), as well as wood and epoxy-based adhesives. The fabrication procedures for the reinforced timber columns are illustrated in Figure 4. The detailed steps involved in the implementation of each reinforcement configuration are described below.

For external reinforcement, the surfaces of the Glulam beam specimens were carefully sanded and thoroughly cleaned to remove dust, grease, and other contaminants that could adversely affect the adhesive bond. A two-component epoxy adhesive was prepared in accordance with the manufacturer's instructions and applied uniformly to the prepared surfaces. Subsequently, Fiber-Reinforced Polymer (FRP) fabrics, either Carbon (CFRP) or Glass (GFRP), were bonded to the beam surfaces. Two different fabric configurations were adopted. In Configuration 1, the fabric was applied in a helical pattern at an angle of 45° relative to the longitudinal axis of the beam, orienting the fibers diagonally to improve crack control and enhance flexural performance. In Configuration 2, the fabric was applied with fibers aligned parallel and perpendicular to the beam's longitudinal axis (0°/90°), aiming to increase flexural stiffness and load-carrying capacity under bending. The original 1 m wide fabric rolls were cut to an appropriate width to ensure full coverage of the beam surfaces. In both configurations, the fabrics were applied in two layers with a lap length of 120 mm to ensure adequate bonding and to prevent premature debonding or delamination. The same two-component epoxy adhesive was used both for laminating the timber layers forming the Glulam beams and for bonding the external FRP reinforcement. The laminated beams were initially cured for one week, followed by an additional one-week curing period after the application of FRP fabrics. Consequently, the total curing duration for the externally reinforced beam specimens was two weeks before conducting the flexural tests. A cross-sectional view of the externally reinforced beam specimens is presented in Figure 4a.

The internal reinforcement of the Glulam beams was implemented using the near-surface mounted (NSM) technique by embedding FRP materials between the fourth and fifth laminae. Two different NSM reinforcement configurations were adopted. FRP Rods: Precision-cut grooves with dimensions of 12 mm × 12 mm were formed along the tensile zone of the beams. In the first configuration, a single FRP rod (carbon or glass) was installed, while in the second configuration, two parallel FRP rods were embedded to enhance flexural stiffness and bending capacity. The rods were bonded using a two-component epoxy adhesive, and the specimens were cured under the same conditions as those applied to the externally reinforced beams. A schematic cross-sectional view of the rod-reinforced specimens is shown in Figure 4b. FRP Strips/Panels: Continuous FRP strips or panels (carbon or glass) were embedded between the fourth and fifth laminae along the beam length. Two different strip/panel widths were considered: 5 cm for the first configuration and 9 cm for the second configuration. The strips/panels were bonded using epoxy adhesive to provide continuous internal reinforcement and to improve the flexural performance of the beams. A cross-sectional representation of both strip/panel configurations is presented in Figure 4c.

The preparation and strengthening stages of the laminated timber beams are illustrated in Figure 5. First, the wooden specimens were selected, cut, and surface-polished to ensure dimensional accuracy and improve bonding quality. Fiber reinforcements were then applied using rods, sheets, and fabrics bonded with epoxy adhesive. Finally, the beams were compressed during the curing stage to ensure full adhesion between the wood and fiber components before testing.



a) Surface reinforcement
a) Površinsko ojačanje

b) Internal reinforcement near the surface by rod
b) Unutarnje ojačanje šipkom blizu površine

c) Internal reinforcement near the surface by panel/strip
c) Unutarnje ojačanje pločom/trakom blizu površine

d) Raw material sample and wood laminate
d) Lamelirano drvo bez ojačanja

Figure 4 Design sample shapes for wood laminates
Slika 4. Načini ojačanja lameliranog drva

a) Wooden specimens used
a) Uzorci drva

b) Softening and polishing wood
b) Priprema površine drva

c) Bonding process of wood and fiber rods
c) Lijepljenje drva i šipki od vlakana

d) Bonding process of wood and fiber sheets
d) Lijepljenje drva i ploča od vlakana

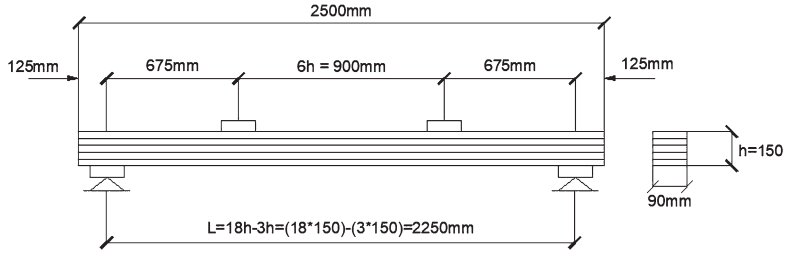
e) Bonding process of wood and fiber fabrics
e) Lijepljenje drva i tkanine

f) Application of compression on the specimens
f) Prešanje uzoraka

Figure 5 Preparation and manufacturing of beams
Slika 5. Proces pripreme i izrade greda

3 LABORATORY AND FINITE ELEMENT ANALYSIS
3. LABORATORIJSKA ANALIZA I ANALIZA KONAČNIH ELEMENATA

The application of fiber-reinforced polymers (FRPs) for strengthening wooden beams has attracted considerable research interest in recent years, owing to their high strength-to-weight ratio, resistance to corrosion, and ease of installation. Among the various FRP types, glass fiber-reinforced polymers (GFRP) and carbon fiber-reinforced polymers (CFRP) have demonstrated significant potential in enhancing the flexural performance of timber beams. GFRP is recognized for its cost efficiency, whereas CFRP offers superior mechanical properties, including higher stiffness and tensile strength, making it more suitable for demanding structural applications. This study focuses on evaluating the flexural behavior of wooden beams strengthened with GFRP and



a) Test sample dimensions
a) Dimenzije uzoraka

b) Bending test
b) Ispitivanje savijanja

Figure 6 Dimensions of bending test specimen
Slika 6. Dimenzije uzoraka za ispitivanje savijanja

CFRP, utilizing both experimental bending tests and numerical modeling through finite element analysis (FEA) performed using ANSYS software.

3.1 Laboratory experiments
3.1. Laboratorijska ispitivanja

The four-point bending test is a method used to evaluate the flexural strength and behavior of laminated materials. The test specimens had dimensions of 90 mm × 150 mm × 2500 mm (thickness × width × length) (see Figure 6). This study investigates how the mechanical properties of laminated wood panels change when reinforced with different types of fibers, specifically glass fiber and carbon fiber. A total of 28 laminated wood specimens were tested: 12 reinforced with glass fiber, 12 with carbon fiber, and 4 unreinforced specimens serving as control samples. The testing procedure was conducted in accordance with the Turkish standard TS EN 408 + A1, which specifies the methods for determining the mechanical properties of timber structures.

3.1.1 Experimental result – Failure modes of wooden beams under bending loads
3.1.1. Rezultati laboratorijskog ispitivanja – načini loma drvenih greda pri savijanju

In structural systems, wooden beams exhibit various failure behaviors under bending loads, including cracking, fiber separation, and ultimate rupture behaviors influenced by factors such as fiber orientation, geometric characteristics, and internal defects (Brougui and Szabó, 2022). To enhance the mechanical performance of timber, fiber-reinforced polymer (FRP) composites specifically carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) have been increasingly applied as strengthening methods. These materials are prized for their high tensile strength, low weight, and environmental durability, and they have been shown to effectively improve flexural capacity, stiffness, and ductility in timber beams (Saad and Lengyel, 2022). In this study, the failure behaviors of wooden beams under bending loads were investigated, and the effects of FRP reinforcement were evaluated based on the experimental findings. The bending tests revealed distinct failure patterns between unreinforced and FRP-strengthened wooden beams. Unreinforced specimens generally exhibited brittle behavior, characterized by tensile cracking in the bottom fibers and, in some cases, longitudinal splitting or local failures near knots. In laminated and solid wood samples, cracks developed in the lower layers due to tensile stress, and in some cases, severe crushing occurred in the top compression zones. In contrast, beams strengthened with CFRP or GFRP showed improved performance and modified failure mechanisms. Specimens reinforced with CFRP or GFRP rods primarily failed due to localized delamination or partial rupture in the tension zone, along with visible cracking in the lower layers. Beams with FRP plates (either 5 cm or 9 cm wide) demonstrated crack development across multiple layers, with some showing signs of shear-induced or tension-induced collapse in the lower regions. The most ductile behavior was observed in specimens wrapped with carbon or glass fabrics, either in spiral or straight configurations. These beams typically failed by rupture in the bottom layer and tearing in the external FRP fabric, indicating effective redistribution of stress and delayed failure. Overall, FRP strengthening significantly altered the failure modes from brittle to more ductile and enhanced the flexural capacity of the wooden beams. Figure 7 illustrates various failure modes observed in the tested specimens.

3.1.2 Experimental result – Analysis of flexural behavior in wooden beam specimens under loading perpendicular to fibers
3.1.2. Rezultati laboratorijskog ispitivanja – analiza savijanja uzoraka drvenih greda pod opterećenjem okomito na vlakanca

To analyze the structural behavior of the samples, force-displacement relationships were plotted under loading conditions, as illustrated in the following figures.

Figure 8 illustrates the force–displacement behavior of the tested Glulam beam specimens, revealing

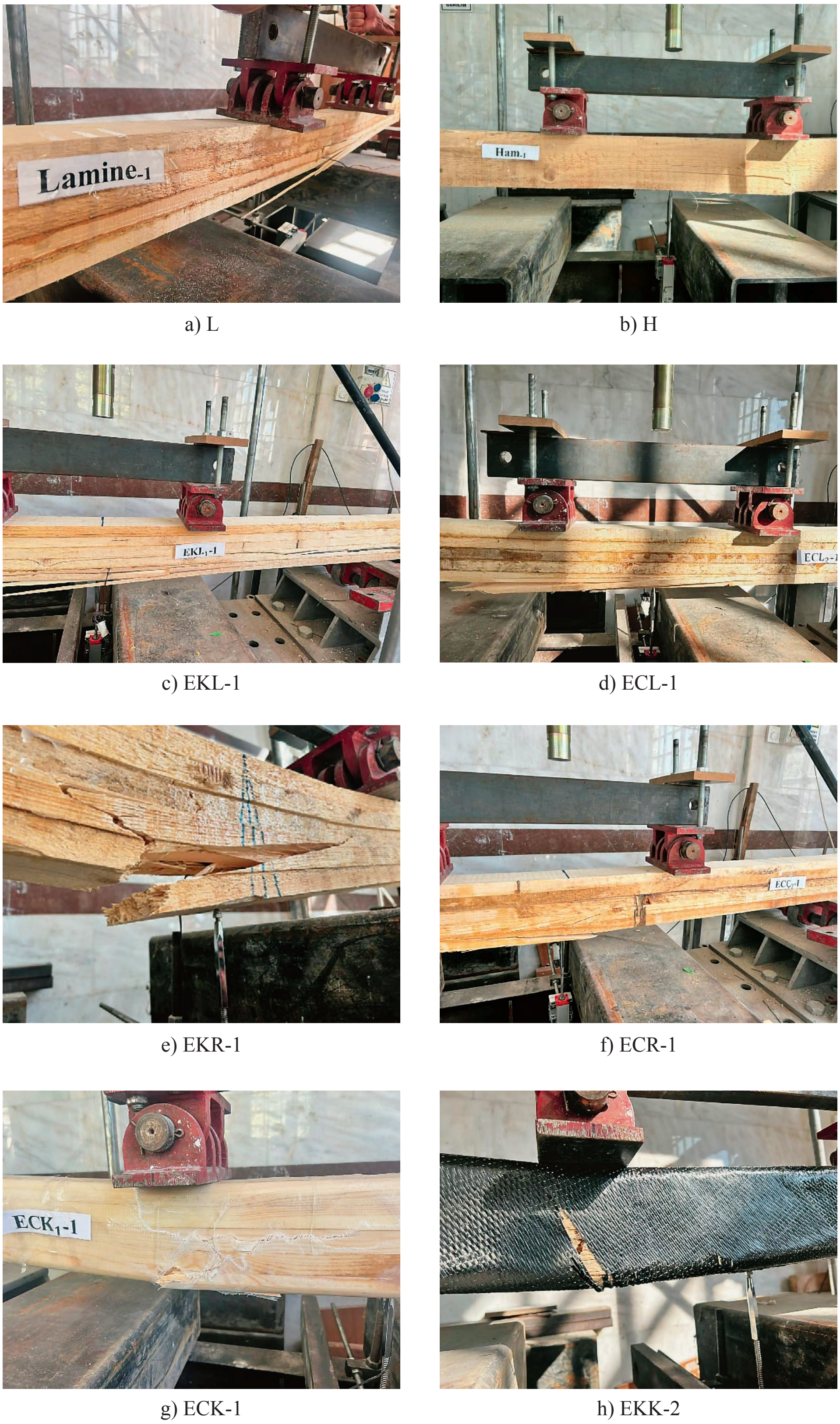


Figure 7 Failed conditions of test specimens
Slika 7. Pregled lomova ispitnih uzoraka

clear performance differences among reinforcement types and configurations. Beams reinforced with carbon rods (ECR-1 and ECR-2) exhibit higher stiffness and peak load capacity compared to those reinforced with glass rods (EKR-1 and EKR-2), reflecting the superior mechanical properties of carbon fibers. Furthermore, specimens strengthened with double rods demonstrate a more pronounced increase in load-bearing capacity than single-rod configurations, confirming the positive contribution of increased reinforcement area. All strengthened beams outperform the unreinforced specimens (H and L), indicating a substantial enhance-

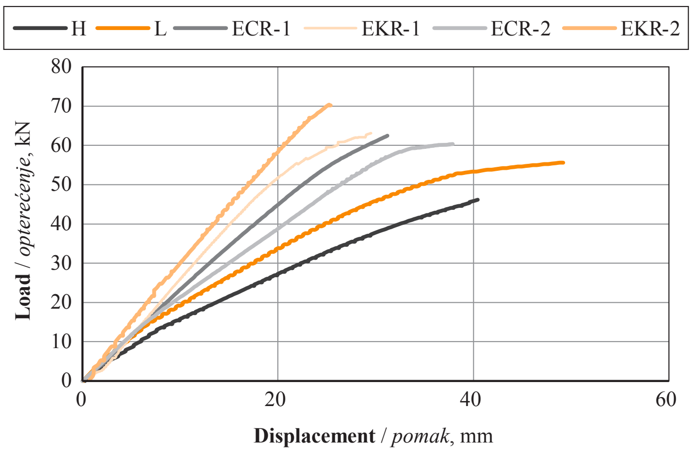


Figure 8 Load versus displacement curves for tested specimens (carbon and glass rod reinforcement)
Slika 8. Krivulje opterećenja u odnosu prema pomaku za ispitane uzorke (ojačane ugljikovim i staklenim šipkama)

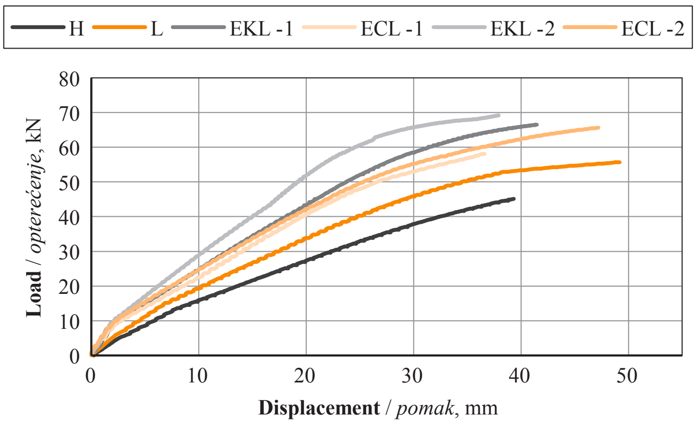


Figure 9 Load versus deflection curves for tested specimens (carbon and glass strip/panel reinforcement)
Slika 9. Krivulje opterećenja u odnosu prema pomaku za ispitane uzorke (ojačane ugljikovim i staklenim trakama/pločama)

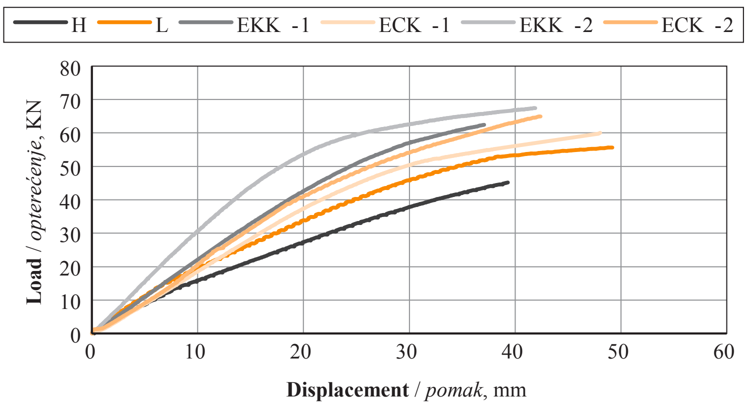


Figure 10 Load versus deflection curves for tested specimens (carbon and glass fiber fabric reinforcement)
Slika 10. Krivulje opterećenja s obzirom na pomak za ispitane uzorke (ojačane ugljikovim i staklenim tkaninama)

ment in flexural resistance and deformation performance due to FRP reinforcement.

Figure 9 presents the load–deflection behavior of Glulam beam specimens reinforced with carbon and glass strips/panels. The curves indicate that carbon-reinforced specimens (ECL) achieved greater stiffness and higher ultimate load capacity than glass-reinforced specimens (EKL), confirming the superior mechanical efficiency of carbon composites under flexural loading.

In addition, partial reinforcement using 5 cm strip width demonstrated a more effective structural response compared to specimens fully reinforced with 9 cm strips. This trend suggests that optimal reinforcement width can enhance flexural behavior while reducing material use, reflecting a more efficient stress distribution mechanism.

Figure 10 illustrates the load deflection response of the fabric-reinforced specimens, highlighting the in-

Table 4 Test results of loading
Tablica 4. Rezultati ispitivanja opterećenja

Sample name *Uzorak*	**Symbols** *Oznaka*	***MOE*, MPa**	***MOR*, MPa**
Raw wood / *masivno drvo*	H	10537.57	68.37
Laminated wood / *lamelirano drvo*	L	13449.22	82.39
Single glass fiber rod / *jednostruka šipka od staklenih vlakana*	ECR-1	15666.21	92.57
Single carbon fiber rod / *jednostruka šipka od karbonskih vlakana*	EKR-1	17840.11	96.67
Double glass fiber rod / *dvostruka šipka od staklenih vlakana*	ECR-2	17158.42	91.63
Double carbon fiber rod / *dvostruka šipka od karbonskih vlakana*	EKR-2	19612.65	103.98
Glass sheet 5 cm / *staklena ploča debljine 5* cm	ECL-1	16869.06	89.48
Glass sheet 9 cm / *staklena ploča debljine 9* cm	ECL-2	17514.72	97.13
Carbon sheet 5 cm / *karbonska ploča debljine 5* cm	EKL-1	18078.72	98.52
Carbon sheet 9 cm / *karbonska ploča debljine 9* cm	EKL-2	19857.21	103.70
Helically wrapped glass fabric *spiralno omotana tkanina od staklenih vlakana*	ECK-2	15613.52	95.81
Plain glass fabric / *obična tkanina od staklenih vlakana*	ECK-1	13958.21	88.55
Plain carbon fabric / *obična tkanina od karbonskih vlakana*	EKK-1	14598.10	89.89
Helically wrapped carbon fabric *spiralno omotana tkanina od karbonskih vlakana*	EKK-2	16814.90	99.85

fluence of reinforcement configuration and material type. Beams strengthened with two-layer spiral fabrics (ECK-2 and EKK-2) exhibited higher stiffness and greater ultimate load capacity compared to straight-form fabric reinforcement (ECK-1 and EKK-1), demonstrating the efficiency of spiral wrapping in improving composite action and delaying crack propagation. Additionally, carbon fabric reinforcement resulted in superior flexural performance relative to glass fabric reinforcement, as reflected by higher peak loads and improved deformation capacity. All reinforced specimens showed marked enhancement over the unreinforced reference beams (H and L), confirming the effectiveness of fiber fabric strengthening in increasing flexural resistance.

3.1.3 Experimental result – Bending test
3.1.3. Rezultati laboratorijskog ispitivanja – ispitivanje savijanja

According to the bending test results summarized in Table 4, all FRP-reinforced specimens exhibit higher modulus of elasticity (*MOE*) and modulus of rupture (*MOR*) than the raw wood (H) and laminated wood (L) references, which recorded the lowest values. Among the rod-reinforced beams, the double carbon fiber rod specimen (EKR-2) achieved the highest *MOR* (103.98 MPa) and a markedly increased *MOE*, outperforming both single carbon rod (EKR-1) and glass rod configurations (ECR-1, ECR-2).

For strip/panel reinforcement, the 9 cm carbon sheet (EKL-2) provided the highest *MOE* (19857.21 MPa) and a *MOR* comparable to EKR-2, indicating the strong efficiency of carbon plates, particularly at greater widths. Carbon sheets (EKL-1, EKL-2) also exceeded their glass counterparts (ECL-1, ECL-2) in both *MOE* and *MOR*. In the fabric group, helically wrapped carbon fabric (EKK-2) showed superior performance relative to glass fabrics (ECK-1, ECK-2), confirming the beneficial effect of both carbon material and spiral wrapping. Overall, the results demonstrate that carbon-fiber reinforcement, especially in double-rod and wide-plate configurations, provides the most effective enhancement of flexural stiffness and strength.

Figure 11 illustrates the comparative variation of the modulus of elasticity (*MOE*) and modulus of rupture (*MOR*) for unreinforced and FRP-reinforced timber beam specimens subjected to four-point bending. The unreinforced specimens (H and L) exhibit the lowest *MOE* and MOR values, confirming the limited stiffness and flexural capacity of untreated and non-reinforced timber. In contrast, all FRP-strengthened specimens demonstrate a clear improvement in both stiffness and strength, indicating the effectiveness of composite reinforcement in enhancing flexural performance. Among the reinforced groups, specimens strengthened with carbon-based reinforcements generally show higher *MOE* and *MOR* values than those reinforced with glass fibers, reflecting the higher elastic modulus and tensile strength of CFRP materials. In particular, double-reinforcement configurations and wider plate applications (e.g., EKR-2 and EKL-2) achieve the highest stiffness and load-carrying capacity, highlighting the positive influence of reinforcement amount and geometry. Fabric-based reinforcements also contribute to notable performance gains, although their effectiveness remains slightly lower than that of rod and plate systems.

Overall, the combined presentation of *MOE* and *MOR* in a single figure enables a clear comparison between stiffness enhancement and strength development across different reinforcement types and layouts, demonstrating that both reinforcement material and con-

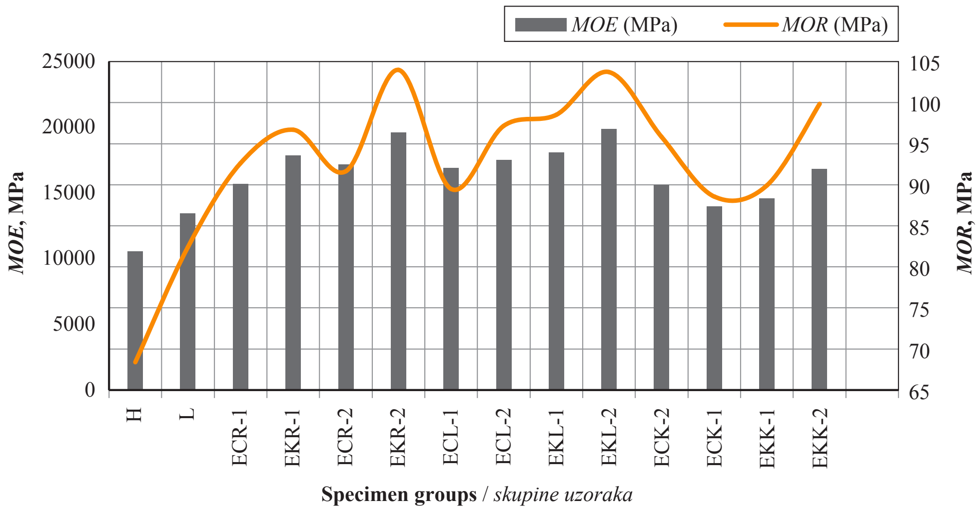


Figure 11 Flexural stiffness and strength (*MOE* and *MOR*) of timber beams with different FRP reinforcement configurations
Slika 11. Krutost i čvrstoća na savijanje (*MOE* i *MOR*) drvenih greda s različitim sustavima FRP ojačanja

figuration play a critical role in the flexural behavior of laminated timber beams.

3.1.4 Numerical analysis: results and discussion
3.1.4. Numerička analiza: rezultati i rasprava

The numerical investigation was carried out using the finite element method implemented in ANSYS in order to replicate the experimental testing conditions and evaluate the structural response of both unreinforced and FRP-reinforced laminated timber beams. Three-dimensional finite element models were developed to represent the exact geometry of the test specimens, ensuring consistency between the numerical simulations and laboratory experiments.

Timber was modeled as a three-dimensional orthotropic elastic plastic material to capture its anisotropic mechanical behavior in the longitudinal, radial, and tangential directions. The orthotropic elastic moduli, shear moduli, and Poisson's ratios were adopted

Table 5 Comparison of laboratory results and software predictions
Tablica 5. Usporedba laboratorijskih rezultata i softverskih predviđanja

Specimen / *Uzorak*	**Experimental** *Eksperimentalno* Equivalent stress (Lap), MPa *Ekvivalentno naprezanje (Lap),* MPa	**F.E.A** Equivalent stress (Ansys), MPa *Ekvivalentno naprezanje (Ansys),* MPa	**Error rate, %** *Pogreška,* %
Raw wood / *masivno drvo*	46.151	46.612	1 %
Laminated wood / *lamelirano drvo*	55.613	56.169	1 %
Single glass fiber rod *jednostruka šipka od staklenih vlakana*	62.486	65.610	5 %
Single carbon fiber rod *jednostruka šipka od karbonskih vlakana*	63.066	67.481	7 %
Double glass fiber rod *dvostruka šipka od staklenih vlakana*	60.342	62.756	4 %
Double carbon fiber rod *dvostruka šipka od karbonskih vlakana*	70.370	75.804	8 %
Glass sheet 5 cm / *staklena ploča debljine 5* cm	66.503	70.493	6 %
Glass sheet 9 cm / *staklena ploča debljine 9* cm	58.067	62.712	8 %
Carbon sheet 5 cm / *karbonska ploča 5* cm	69.190	75.417	9 %
Carbon sheet 9 cm / *karbonska ploča debljine 9* cm	65.655	69.266	6 %
Helically wrapped glass fabric *spiralno omotana tkanina od staklenih vlakana*	62.437	66.808	7 %
Plain glass fabric *obična tkanina od staklenih vlakana*	60.070	62.473	4 %
Plain carbon fabric *obična tkanina od karbonskih vlakana*	67.396	72.788	8 %
Helically wrapped carbon fabric *spiralno omotana tkanina od karbonskih vlakana*	64.941	70.136	8 %

from established literature for softwood species with comparable physical and mechanical characteristics. The CFRP and GFRP reinforcements were defined as linear orthotropic composite materials with high stiffness along the primary fiber direction. A perfect bond assumption was adopted at the timber FRP interface, implying full strain compatibility and neglecting interfacial slip or debonding.

Quadratic solid elements were employed in the three-dimensional analyses to enhance the accuracy of stress and strain predictions. Both material and geometric nonlinearities were included, and the solution was performed using an incremental–iterative procedure to ensure numerical convergence throughout the loading process. A mesh sensitivity analysis was conducted using element sizes of 5 mm, 10 mm, and 15 mm, and the 5 mm mesh was selected for all subsequent simulations due to its superior agreement with the experimental load–displacement response.

Boundary conditions and loading protocols were defined to replicate the experimental setup. Fixed supports were applied at the specimen base, while displacement-controlled loading was imposed at the loading point. Reaction forces obtained during incremental displacement steps were used to generate numerical load–displacement curves. This analysis methodology ensured reliable numerical predictions and allowed for a direct and consistent comparison with the experimental results.

Table 5 compares the experimental and finite element (FEA) equivalent stress values for all tested specimens. The results show a strong agreement between laboratory measurements and numerical predictions, with error rates ranging from 1 % to 9 %. The smallest deviations were observed for unreinforced and laminated wood specimens, while slightly higher discrepancies occurred in FRP-reinforced configurations, particularly for wider sheets and multi-layer reinforcements. These differences are mainly attributed to the inherent heterogeneity of wood and the idealized assumptions adopted in the numerical modeling, such as perfect bonding between timber and FRP. Overall, the results confirm the reliability and accuracy of the proposed finite element approach.

4 COMPARATIVE PERFORMANCE AND CONFIGURATION-BASED ASSESSMENT OF CFRP AND GFRP REINFORCEMENT SYSTEMS IN LAMINATED TIMBER BEAMS

4. USPOREDBA UČINKOVITOSTI I KONFIGURACIJSKA PROCJENA CFRP I GFRP SUSTAVA OJAČANJA LAMELIRANIH DRVENIH GREDA

The experimental results demonstrated that the application of fiber-reinforced polymer (FRP) materials substantially improved the flexural behavior of laminated timber beams compared to both raw wood and unreinforced laminated specimens. Among the investigated strengthening systems, carbon-based reinforcements consistently outperformed glass-based alternatives in terms of stiffness (*MOE*) and flexural strength (*MOR*).

Reinforcing Elements with CFRP: Carbon fiber reinforced polymer (CFRP) was confirmed as the most effective strengthening material in this study, attributable to its high tensile capacity, lightweight properties, and fatigue resistance. Three types of reinforcement rods, plates/strips, and fabrics were applied, each producing notable gains in mechanical response relative to unreinforced and GFRP-strengthened beams. The double-rod CFRP configuration (EKR-2) yielded the highest enhancement, achieving a modulus of elasticity (*MOE*) of 19,612.65 MPa and a modulus of rupture (*MOR*) of 103.98 MPa, indicating significant increases in both stiffness and load-bearing capacity. Closely following this performance was the 9 cm external CFRP plate (EKL-2), which recorded *MOE* and *MOR* values of 19,857.21 MPa and 103.70 MPa, respectively. This reflects the effectiveness of surface-bonded CFRP plates in distributing tensile stress and improving flexural resistance. Among fabric-based systems, the helically wrapped CFRP fabric (EKK-2) achieved the most favorable results (16,814.90 MPa *MOE*; 99.85 MPa *MOR*), outperforming flat fabric arrangements. The results suggest that wrapping geometry contributes to improved confinement and stress redistribution, reinforcing the suitability of CFRP for flexural strengthening of timber members.

Reinforcing Elements with GFRP: Glass fiber reinforced polymer (GFRP), widely recognized for its cost efficiency and adequate tensile strength, also contributed to measurable improvements in beam performance. Three GFRP systems rods, plates/strips, and fabrics were applied, each demonstrating structural enhancement relative to unreinforced samples, though generally falling below the effectiveness of CFRP. The double GFRP rod configuration (ECR-2) provided the most notable improvement within the GFRP group, reaching an *MOE* of 17,158.42 MPa and *MOR* of 91.63 MPa. These values represent a substantial improvement compared with the control specimens (*MOE* 10,537.57 MPa; *MOR* 68.37 MPa). Among plate-based systems, the 9 cm GFRP plate (ECL-2) achieved superior results (*MOE*: 17,514.42 MPa; *MOR*: 97.13 MPa) compared with the 5 cm plate, demonstrating the influence of increased bonding area on load transfer and stress distribution. For fabric configurations, the spiral-wrapped GFRP fabric (ECK-2) outperformed the flat arrangement (ECK-1), recording an *MOE* of 15,613.52 MPa and *MOR* of 95.81 MPa. This confirms the benefit of wrapping geometry in improving confinement and fiber-to-wood interaction. Although GFRP systems did not match the structural performance of CFRP, the observed improvement highlights GFRP as a viable option for applications requiring moderate-strength enhancement at reduced cost.

Comparative Analysis of CFRP and GFRP: A comparative evaluation revealed clear differentiation in performance between the two FRP types. CFRP consistently generated higher MOE and MOR values due to its superior mechanical properties and more efficient stress transfer mechanisms. For instance, the double CFRP rod system (EKR-2) recorded significantly higher values than the double GFRP rod configuration (ECR-2). However, certain GFRP configurations performed competitively in terms of *MOR*, particularly the 9 cm GFRP plate (ECL-2), which approached the *MOR* values of its CFRP equivalent (EKL-2). These findings indicate that geometric optimization can influence strengthening efficiency, especially regarding flexural capacity. Overall, the comparative results highlight that while CFRP offers maximum performance, GFRP serves as a cost-effective alternative for moderate-strengthening applications.

Reinforcement Configuration Impact: The reinforcement configuration significantly affected structural response across all FRP types. Rod systems, especially double rods, achieved the highest stiffness and strength improvements due to their ability to transfer tensile forces efficiently along the longitudinal axis. Plate systems produced more uniform tensile stress distribution and delayed crack formation, with wider plates demonstrating additional performance gains. Fabric-based systems enhanced ductility and energy absorption, particularly when applied using helical wrapping. Although fabric reinforcements yielded slightly lower stiffness values than rods and plates, the improved confinement effects contributed to favorable post-peak behavior. Collectively, the results emphasize the importance of selecting reinforcement type and geometry based on required stiffness, strength, material efficiency, and economic considerations, particularly in timber rehabilitation and strengthening applications.

5 CONCLUSIONS
5. ZAKLJUČAK

The results of this experimental study clearly demonstrate that the flexural behavior of laminated timber beams can be substantially enhanced through fiber-reinforced polymer (FRP) strengthening. Among the evaluated reinforcement systems, carbon-based materials consistently delivered the highest mechanical performance, achieving superior gains in both stiffness (*MOE*) and strength (*MOR*) compared to glass-based alternatives. Although GFRP offered measurable improvement over unreinforced specimens, its structural contribution remained moderate relative to CFRP. The findings further confirm that reinforcement configuration plays a decisive role in flexural response. Continuous or helical wrapping systems showed greater efficiency than partial, single-direction plate or fabric applications, owing to improved stress distribution and enhanced confinement effects. Similarly, increased reinforcement area, particularly in double-rod (EKR-2) and wide-plate (EKL-2) configurations, significantly elevated load-bearing capacity and deformation resistance. A distinguishing contribution of this study is its comparative assessment of three reinforcement forms (Rods, Strip/Plates, and Fabrics) applied to laminated spruce beams under identical test conditions, providing a comprehensive performance evaluation rather than focusing on a single system. The results indicate that the spiral CFRP fabric configuration (EKK-2) achieved the most ductile response and delayed failure initiation, highlighting the importance of reinforcement geometry in optimizing structural behavior. Minor variations among specimens were largely attributed to natural wood heterogeneity, including knots, grain deviation, and internal micro-defects. Such factors are intrinsic to timber and must be considered in full-scale structural design and material selection. Overall, the study confirms that CFRP reinforcement, particularly when applied in optimized configurations, offers a highly effective solution for increasing the flexural capacity, stiffness, and ductility of timber beams. These outcomes support the broader applicability of advanced FRP systems in timber construction, rehabilitation, and strengthening projects, especially when high performance and long-term durability are required.

6 REFERENCES
6. LITERATURA

1. Alsheghri, A.; Akgül, T., 2022: Use of the FRP plates instead of steel sheets in the joints of wooden structures. Emerging Materials Research, 11 (1): 167-173. https://doi.org/10.1680/jemmr.21.00057
2. Abed, J.; Rayburg, S.; Rodwell, J.; Neave, M., 2022: A review of the performance and benefits of mass timber as an alternative to concrete and steel for improving the sustainability of structures. Sustainability, 14 (9): 5570. https://doi.org/10.3390/su14095570
3. Bazli, M.; Heitzmann, M.; Villacorta, B., 2022: Durability of fiber reinforced polymer wood composite members: An overview. Composite Structures, 295: 115827. https://doi.org/10.1016/j.compstruct.2022.115827
4. Borri, A.; Corradi, M.; Grazini, A., 2011: A method for flexural reinforcement of old wood beams with CFRP materials. Composites: Part B, 42 (1): 148-155. https://doi.org/10.1016/j.compositesb.2010.10.003
5. Brougui, M.; Szabó, P., 2022: Timber beams reinforced with fiber-reinforced polymer: Advanced wood engineer-

ing. In: Proceedings of Structural Engineering Conference, Austria. https://doi.org/10.5281/zenodo.15115870
6. Çankal, D.; Şakar, G.; Çelik, H. K., 2023: *A criticism on strengthening glued laminated timber beams with fibre reinforcement polymers: numerical comparisons between different modelling techniques and strengthening configurations*. Revista de la Construcción, 22 (3): 661-678. https://doi.org/10.7764/RDLC.22.3.661
7. D'Ambrisi, A.; Focacci, F.; Luciano, R., 2014: Experimental and analytical evaluation of the bond behavior between CFRP sheets and timber. Journal of Composites for Construction, 18 (3): 04013054. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000409
8. Fiorelli, J.; Dias, A. A., 2003: Analysis of the strength and stiffness of timber beams reinforced with carbon fiber and glass fiber. Materials Research, 6 (2): 193-202. https://doi.org/10.1590/S1516-14392003000200013
9. Jirouš-Rajković, V.; Miklečić, J., 2021: *Enhancing weathering resistance of wood – a review.* Polymers, 13 (12): 1980. https://doi.org/10.3390/polym13121980
10. Li, H.; Wang, Y.; Zhang, X.; Su, L., 2022: *A review on strengthening of timber beams using fiber reinforced polymers*. Journal of Renewable Materials, **10** (8): 47594. https://doi.org/10.32604/jrm.2022.021983
11. Loss, C.; Tannert, T.; Tesfamariam, S., 2018: State-of-the-art review of displacement-based seismic design of timber buildings. Construction and Building Materials, 191: 481-497. https://doi.org/10.1016/j.conbuildmat.2018.09.205
12. Novosel, A.; Sedlar, T.; Čizmar, D.; Turkulin, H.; Živković, V., 2021: Structural reinforcement of bi-directional oak-wood lamination by carbon fibre implants. Construction and Building Materials, 298: 123073. https://doi.org/10.1016/j.conbuildmat.2021.123073
13. Novosel, A.; Sedlar, T.; Čizmar, D.; Turkulin, H.; Živković, V., 2023: Improvement of mechanical properties of oak-wood by bi-directional laminations: Efficacy of standard and pre-stressed glass fibre implants. Composite Structures, 304: 116465. https://doi.org/10.1016/j.compstruct.2022.116465
14. Ramage, M. H.; Burridge, H.; Busse-Wicher, M.; Fereday, G.; Reynolds, T.; Shah, D. U.; Wu, G.; Yu, L.; Fleming, P.; Densley-Tingley, D.; Allwood, J.; Dupree, P.; Linden, P. F.; Scherman, O., 2017: *The wood from the trees: The use of timber in construction*. Renewable and Sustainable Energy Reviews, 68: 333-359. https://doi.org/10.1016/j.rser.2016.09.107
15. Saad, K.; Lengyel, A., 2022: Strengthening timber structural members with CFRP and GFRP: A state-of-the-art review. Construction and Building Materials, 14 (12): 2381. https://doi.org/10.3390/polym14122381
16. Öztürk, H.; Birinci, A. U.; Demirkır, C., 2017: Yapısal ahşap ürünlerinin ısı yalıtım özellikleri. *İleri Teknoloji Bilimleri Dergisi, 6* (3): 522-527.
17. Vaněrek, J.; Šmak, M.; Kusák, I.; Misák, P., 2017: Durability of FRP / wood bonds glued with epoxy resin. Materials and Technologies, 51: 889-895. https://doi.org/10.17222/mit.2016.321
18. Wang, J.; Jeong, G. Y.; Bulleit, W. M., 2021: Mechanical behavior of laminated veneer lumber and its application in construction. Journal of Materials in Civil Engineering, 33 (2): 04020470. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003565
19. Zhao, J.; Chen, Y.; Li, D., 2024: *Improving the flexural response of timber beams using externally bonded carbon fiber-reinforced polymer (CFRP) sheets*. Materials, **17** (2): 321. https://doi.org/10.3390/ma17020321
20. ***ASTM D143-14, 2014: Standard Test Methods for Small Clear Specimens of Timber. West Conshohocken, PA.
21. ***EN 338, 2016: Structural timber – Strength classes. Brussels: CEN.
22. ***Fiber Market, 2024: Glass fiber fabric (GFRP): Product technical sheet. Istanbul, Turkey.
23. ***Fibertech Composite, 2023: GFRP flat sheets: Technical data sheet. Istanbul, Turkey.
24. ***Karbontech Tekstil, 2025: 600 g bidirectional 12K carbon fiber reinforcement fabric (25 m^2): Product page. Istanbul, Turkey.
25. ***Matek Fiber, 2025a. Glass fiber reinforced polymer (GFRP) rebars: Product specifications. Matek Composite Technologies, Istanbul, Turkey.
26. ***Matek Fiber, 2025b: Carbon fiber reinforced polymer (CFRP) rebars: Product specifications. Matek Composite Technologies, Istanbul, Turkey.
27. ***Sika Services AG, 2024: Sika® CarboDur® S: Product data sheet (Version 05.03). Zurich, Switzerland.
28. ***TS EN 13183-1, 2012: Moisture content of a piece of sawn timber. Part 1: Determination by oven dry method. Turkish Standards Institution – TSE.
29. ***TS ISO 13061-2, 2014: Physical and mechanical properties of wood – Test methods for small clear wood specimens.Part 2: Determination of density for physical and mechanical tests. Turkish Standards Institution – TSE.
30. *** TS ISO 13061-3, 2017: Determination of specific gravity. Turkish Standards Institution – TSE.
31. ***TS ISO 13061-4, 2022: Determination of modulus of elasticity in static bending. Turkish Standards Institution – TSE.
32. ***TS ISO 13061-17, 2017: Determination of ultimate stress in compression parallel to grain. Turkish Standards Institution – TSE.
33. ***TS ISO 13061-5, 2014: Determination of compressive strength perpendicular to grain. Turkish Standards Institution – TSE.
34. ***TS ISO 13061-6, 2014: Determination of tensile strength parallel to grain. Turkish Standards Institution – TSE.
35. ****TS EN 408+A, 2012: Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties*. Turkish Standards Institution – TSE.

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The Effects of Wood Material Selection on Sound Absorption Performance in Industrial Noise Insulation

Utjecaj odabira drvnog materijala na učinkovitost apsorpcije zvuka industrijske zvučne izolacije

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ABSTRACT • *This study investigates the sound insulation performance of various wood-based materials used to mitigate industrial noise generated by an air compressor in a furniture workshop. LA_{eq} measurements were conducted at eight different locations within the facility, including classrooms, faculty offices, corridors, and near the noise source. Fourteen wood-based scenarios involving solid wood and engineered panels of varying thicknesses were tested. Statistical analysis using the Kruskal–Wallis test revealed significant differences in noise reduction across scenarios ($p < 0.05$), and Dunn's post-hoc test identified the most effective materials. Hierarchical clustering grouped scenarios into five clusters, enabling systematic comparison of similar acoustic performances. Among all tested materials, 6 mm MDF-laminate demonstrated the highest cumulative noise reduction (17.23 %), outperforming even thicker materials like 18 mm MDF. Notably, certain materials were found to contribute to elevated noise levels in proximity to the compressor, which may be attributed to their inherent acoustic reflectivity and vibrational response characteristics, rather than their capacity for sound absorption. Correlation analysis further revealed that sound reduction effectiveness varied across spatial contexts, with positive correlations decreasing and negative ones increasing after insulation, indicating heterogeneous acoustic effects. In conclusion, thinner MDF-laminate panels offer effective, space-efficient, and economical solutions for industrial noise control. These findings underscore the importance of material selection and spatial analysis in assessing acoustic performance and suggest promising directions for sustainable soundproofing applications in industrial environments.*

KEYWORDS: *acoustic performance; industrial noise; LA_{eq} measurement; sound insulation; wood-based materials*

SAŽETAK • *U ovoj je studiji istraživana učinkovitost zvučne izolacije različitih drvnih materijala koji se upotrebljavaju za ublažavanje industrijske buke što je stvara kompresor zraka u stolarskoj radionici. Mjerenja razine zvuka LA_{eq} provedena su na osam različitih lokacija unutar objekta, uključujući učionice, urede, hodnike i prostor oko izvora buke. Ispitano je 14 varijanti zvučnih izolacija na bazi drva koje obuhvaćaju masivno drvo i drvne plo-*

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če različitih debljina. Statistička analiza primjenom Kruskal-Wallisova testa otkrila je znatne razlike u smanjenju buke među varijantama (p < 0,05), a Dunnovim post-hoc testom identificirani su najučinkovitiji materijali za tu namjenu. Hijerarhijskim grupiranjem varijante su svrstane u pet klastera kako bi se omogućila sustavna usporedba sličnih akustičnih svojstava. Od svih ispitnih materijala MDF debljine 6 mm, obložen laminatom, pokazao je su najveće kumulativno smanjenje buke (17,23 %), nadmašivši čak i deblje materijale poput MDF-a debljine 18 mm. Zabilježena je i pojava da određeni materijali pridonose povišenim razinama buke u blizini kompresora, što se može pripisati njihovoj inherentnoj akustičnoj reflektivnosti i obilježjima vibracijskog odziva, a ne njihovoj sposobnosti apsorpcije zvuka. Analiza korelacija dodatno je otkrila da se učinkovitost smanjenja buke razlikuje ovisno o prostornim kontekstima. Utvrđene su pozitivne korelacije koje se smanjuju i negativne korelacije koje se povećavaju nakon izolacije, što upućuje na heterogene akustične učinke. Zaključno, tanje MDF ploče obložene laminatom pridonose djelotvornim, prostorno učinkovitim i ekonomičnim rješenjima za industrijsku kontrolu buke. Ti rezultati naglašavaju važnost odabira materijala i prostorne analize u procjeni akustične učinkovitosti te sugeriraju obećavajuće smjerove za održivu primjenu zvučne izolacije u industrijskim okruženjima.

KLJUČNE RIJEČI: *akustična učinkovitost; industrijska buka;* LA_{eq} *mjerenje; zvučna izolacija; drvni materijali*

1 INTRODUCTION
1. UVOD

With the rapid advancement of technology today, the use of machinery in industrial and manufacturing sectors has significantly increased. This trend introduces new risks in terms of occupational health and safety (Çakıroğlu *et al*., 2025). Noise, in particular, is a major environmental factor that negatively affects both the physical and psychological health of workers. From a health perspective, noise can lead not only to hearing loss but also to various psychological and behavioral disorders such as restlessness, insomnia, irritability, lack of concentration, stress, anxiety, and decreased cognitive performance (Işık *et al*., 2022; Andrews, 1982; Feldman and Grimes, 1985). Furthermore, noise is known to damage the nervous system, cause communication difficulties, and reduce work productivity. Studies have shown that noise exposure may cause vascular damage through stress mechanisms, and this effect has also been observed in human trials (Eriksson *et al*., 2018).

In industrial settings, noise primarily originates from machinery used during the production process. In this context, equipment such as compressors – along with pumps, manifolds, ventilation ducts, fans, and cooling systems – generate significant levels of noise (Andrews and Kornas, 1982). Particularly in wood processing facilities, the machines in use can produce disturbing sound levels for both workers and the surrounding environment. In a study conducted by Şahin *et al*. (2017), noise levels of 22 different machines across 56 facilities engaged in furniture and door manufacturing were analyzed. According to the findings, the highest noise level during production was recorded at (95.17 ± 4.50) dBA for the planing machine. Among idle machines, the highest average noise level was identified as (88.09 ± 0.36) dBA for surface finishing machines. Similarly, in another study by Ülker (2018), noise measurements were carried out at 21 different locations during both active production and downtime in a furniture manufacturing plant using high-tech machines such as CNC equipment.

One of the most effective methods for noise reduction is the use of physical barriers. These barriers enclose noise sources, thereby limiting the propagation of sound energy into the surrounding environment and preventing reverberation. The use of composite materials in noise control emerges as an effective strategy for enhancing sound insulation performance. For instance, in a study conducted by Owoyemi *et al*. (2016), it was demonstrated that sound-absorbing panels significantly reduced noise levels by 4 – 6 dB through high sound energy absorption, resulting in an overall noise reduction of approximately 20 – 30 %. In composite materials, the type of filler used, particle size, surface characteristics, and pore structure significantly affect performance criteria such as mechanical strength, vibration isolation, and noise attenuation (Barrera and Tardiff, 2022; Jong *et al*., 2014; Masek *et al*., 2021).

In a study conducted by Mago *et al*. (2022), it was demonstrated that biochar-based composites derived from bamboo waste can be used as effectively as commercial fillers for vibration and noise control. When evaluated in conjunction with green processing technologies, such environmentally sustainable materials can offer significant benefits in production processes, both in terms of environmental impact and occupational health (Gowri *et al*., 2023; Wang *et al*., 2023).

Noise-induced hearing loss is one of the most frequently encountered occupational health problems today. In Europe, noise is the leading cause of hearing loss, affecting 34.4 million people in 2019 alone, with an annual economic impact exceeding €185 billion due to productivity loss (Shield, 2022). Various studies on industrial workers have demonstrated a direct relationship between exposure to high noise levels and occupational accidents and injuries (Ali, 2011; Eleftherou, 2002; Palmer *et al*., 2008). Daily exposure to noise levels above 90 dB increases the risk of hearing loss,

Table 1 Examples of noise exposure levels in occupational and non-occupational environments
Tablica 1. Primjeri razina izloženosti buci u radnim i neradnim okruženjima

Safe sound level / *Sigurna razina zvuka*	
Breathing / *Disanje*	10 dB
Ticking watch / *Otkucavanje sata*	20 dB
Average room noise / *Prosječna buka u sobi*	30-50 dB
Normal conversation / background music *Normalni razgovor / glazba u pozadini*	60 dB
Levels at which long-term exposure can lead to hearing loss *Razine pri kojima dugotrajna izloženost buci može rezultirati gubitkom sluha*	
Landscaping equipment *oprema za uređenje okoliša*	75 dB
Vacuum / inside an airplane *usisavač / unutrašnjost zrakoplova*	75-80 dB
City traffic / noisy restaurant *gradski promet / bučni restoran*	80-85 dB
Subway / shouted conversation *podzemna željeznica / glasni razgovor*	85 dB
Pro sports events, car horn at 16 ft *profesionalni sportski događaji, automobilska sirena na udaljenosti do 5* m	90-100 dB
Motorcycle, stereo *motocikl, stereouređaj*	95-100 dB
Chainsaw, leaf blower, snowmobile *motorna pila, puhač lišća, motorne saonice*	106-115 dB
Levels that may lead to sudden and permanent hearing loss from a single close exposure *Razine koje mogu dovesti do iznenadnoga i trajnoga gubitka sluha zbog samo jednog bliskog izlaganja buci*	
Music concert, ambulance siren *glazbeni koncert, sirena hitne pomoći*	120 dB
Jet engine taking off *polijetanje mlaznog zrakoplova*	130 dB
Gun shot / *pucanj*	140-160 dB

making the implementation of protective measures essential in such conditions.

According to data obtained from the National Institute for Occupational Safety and Health (NIOSH) and hearing health resources in the United States, Table 1 presents examples of noise exposure levels in both occupational and non-occupational environments (NIOSH, 2024). This table covers a wide spectrum, ranging from safe levels such as breathing sounds to levels capable of causing sudden and permanent hearing loss, such as jet engine noise.

In the scope of this study, the potential of absorbing noise generated by the screw-type air compressor located in the furniture workshop at the Seyitler campus of Artvin Çoruh University was evaluated using different wood-based materials. Specifically, the focus was on the portion of the noise transmitted into the classroom and office spaces of the workshop building. In this context, LA_{eq} measurements were conducted at eight different locations to comparatively assess the noise reduction performance of various wood species and panel materials. The primary objective of this study is to evaluate and compare the sound absorption effectiveness of different wood species and panel materials in mitigating compressor-generated noise in a furniture workshop, with a focus on minimizing noise transmission to adjacent educational and office spaces.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

In this study, the potential of absorbing noise generated by the air compressor located in the furniture workshop was evaluated using different wood species. The sound insulation performance of various wood types and panel materials was comparatively analyzed. The materials used in the study include 30 mm particleboard with melamine coating, 8 mm MDF Laminate, 18 mm laminated particleboard, 16 mm spruce plywood, 30 mm Solid sapelli Wood Panel, 18 mm solid beech wood beech panel, 10 mm poplar plywood, 18 mm solid pine panel, 12 mm MDF covered with sapelli veneer, 4 mm double-sided MDF Laminate, and 8 mm double-sided MDF Laminate.

The production section of the furniture workshop consists of a single-story space with a high ceiling, while the administrative section is a two-story structure. A top-view layout of the workshop and the noise measurement points are presented in Figure 1. The first floor contains the production area, the air compressor

Table 2 Locations and characteristics of noise measurement points
Tablica 2. Lokacije i obilježja mjernih mjesta buke

Point No *Broj mjernog mjesta*	**Floor** *Kat*	**Point description** *Opis točke*
P1	Second Floor *drugi kat*	Faculty office *fakultetski ured*
P2	Second Floor *drugi kat*	Faculty office *fakultetski ured*
P3	Second Floor *drugi kat*	Corridor *hodnik*
P4	Second Floor *drugi kat*	Meeting room *soba za sastanke*
P5	First Floor *prvi kat*	Classroom *učionica*
P6	First Floor *prvi kat*	Laser CNC room *soba s CNC laserom*
P7	First Floor *prvi kat*	Compressor room *soba s kompresorom*
P8	First Floor *prvi kat*	Above the compressor unit *prostor iznad kompresorske jedinice*

room, changing rooms, and one classroom. The upper floor includes three faculty offices, a meeting room, a kitchen, and restrooms. Noise measurements were conducted at eight locations (Points P) representing different areas of the workshop. Detailed information regarding the measurement points is provided in Table 2.

2.1 Noise measurements
2.1. Mjerenje buke

In accordance with the hierarchy of control measures commonly employed in occupational health and safety – including hazard elimination, substitution, isolation, and the use of personal protective equipment – this study applied the isolation method. Wood-based insulation materials were used to create a physical barrier between the noise source (compressor) and the surrounding occupied areas to reduce noise exposure (Technical Guide for Noise Control, n.d.).

The technical specifications of the air compressor, which is the primary source of noise, are as follows: 7.5 bar pressure, 110 m^3/min flow rate, 6.4 PSI, and a motor power of 37/50 kW/HP.

The measurements were conducted using the CESVA SC310, a Class 1 integrating-averaging sound level meter in compliance with international standards. The SC310 provides high precision through full conformity with IEC 61672 and EN 61672 standards, and it also meets additional regulatory requirements such as IEC 60651, IEC 60804, EN 60651, and EN 60804. Furthermore, the device complies with American standards ANSI S1.4 and ANSI S1.43. The SC310 is capable of performing real-time one-third octave and full octave band spectrum analyses using Class 1 filters in accordance with IEC 61260, EN 61260, and ANSI S1.11 standards (CESVA, 2024).

In this study, noise measurements were carried out in accordance with the "Task-Based Measurement" method defined in the TS EN ISO 9612:2009 standard. This method involves analyzing noise levels in the work environment based on specific tasks or scenarios, with separate measurements performed for each scenario (TS EN ISO 9612, 2009). Figure 2A presents the noise absorbance method, while Figure 2B illustrates the measurement procedure.

During the measurement process, the noise reduction performance of enclosing the identified compressor noise source with different wood materials was evaluated. In this context, various scenarios were cre-

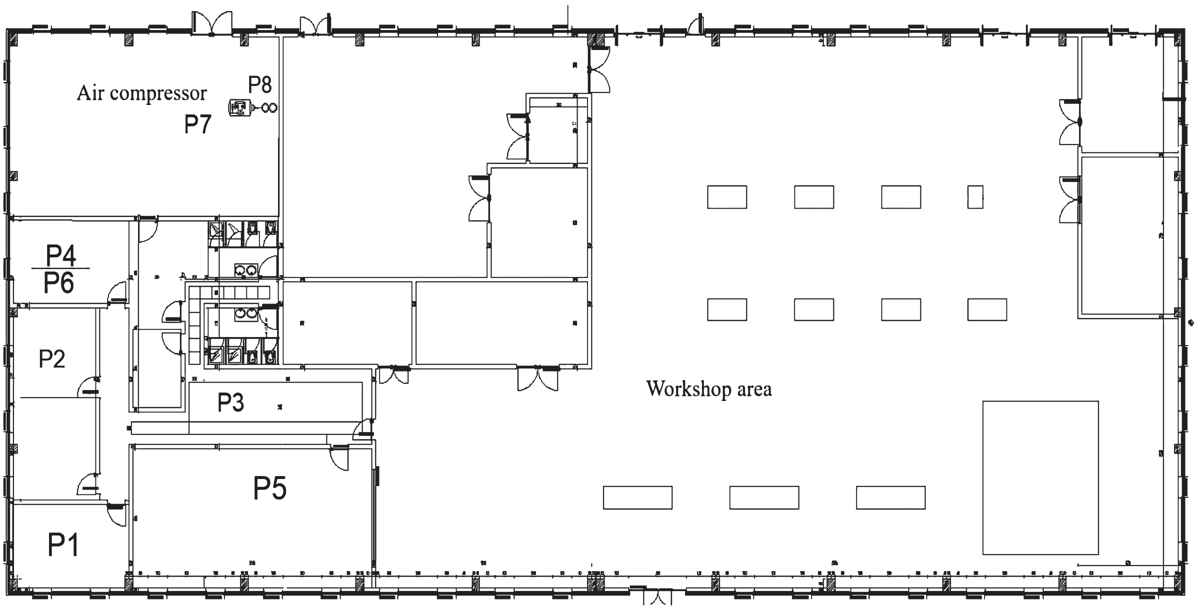

Figure 1 Workshop floor plan and measurement points
Slika 1. Tlocrt radionice i mjerna mjesta

ated by placing different types of solid wood and engineered wood panels over the compressor, and sound absorption was analyzed for each scenario (Figure 2A). Noise measurements were performed at eight distinct locations, with data collected over a 5-minute period at each point. This method provides a scientific approach for comparatively assessing the noise reduction effects of different materials and for optimizing noise levels in the working environment.

In this study, A-weighted Equivalent Continuous Sound Level (LA_{eq}) values were measured and analyzed for each scenario. LA_{eq} is an acoustic parameter that represents the energy-based average of fluctuating sound levels over a specific time period and is commonly used to assess environmental noise exposure. This value, calculated with A-weighting, takes into account the human ear varying sensitivity to different sound frequencies (Brambilla *et al*., 2023; Barbaresco *et al*., 2019). Mathematically, it is expressed as follows:

$$LA_{eq} = 10\,log\left(\frac{1}{N}\sum_{i=1}^{n} n_i 10^{\frac{LPi}{10}}\right) \qquad (1)$$

In this expression, *Lp(t)* represents the sound pressure level at time *t* (in dB); n_i denotes the number of sound level measurements taken within a specific time interval; and *N* indicates the total number of samples.

In the study, different scenarios were analyzed to evaluate their effects on noise levels. Each scenario was structured based on specific variables and examined systematically. The details of these scenarios are summarized in Table 3.

Table 3 Experimental scenarios investigating the effects of different wood materials on noise absorption
Tablica 3. Eksperimentalne varijante kojima se istražuju učinci različitih drvnih materijala na apsorpciju buke

Scenario *Varijanta*	**Description** / *Opis*
S1	Quiet environment *tiha okolina*
S2	Compressor only (No barrier) *samo kompresor (bez pregrade)*
S3	Standard layout *standardni raspored*
S4	30 mm particleboard *iverica debljine 30* mm
S5	18 mm Double-sided MDF lam *MDF od 18* mm *obostrano obložen laminatom*
S6	18 mm Double-sided particleboard *iverica od 18* mm *obostrano obložena melaminom*
S7	16 mm Spruce plywood *furnirska ploča debljine 16* mm *od smrekovine*
S8	30 mm Solid sapelli wood panel *ploča od drva sapeli debljine 30* mm
S9	18 mm Solid beech wood panel *ploča od bukovine debljine 18* mm
S10	10 mm Poplar plywood *furnirska ploča od topolovine debljine 10* mm
S11	18 mm Solid yellow pine *ploča od borovine debljine 18* mm
S12	12 mm MDF with solid sapelli veneer *MDF od 12* mm *obložen furnirom drva sapeli*
S13	4 mm Double-sided MDF laminate *MDF od 4* mm *obostrano obložen laminatom*
S14	8 mm Double-sided MDF laminate *MDF od 8* mm *obostrano obložen laminatom*

a) b)

Figure 2 A) modular ınsulation panel mounted on the compressor, (B) noise measurement setup at point P2
Slika 2. A) Modularna izolacijska ploča montirana na kompresor, B) postav za mjerenje buke u točki P2

2.2 Wood materials
2.2. Drvni materijali

Figure 3 illustrates the variety of solid wood species and engineered wood-based panel materials used as insulation components in the experimental scenarios of this study. These materials were selected to represent a range of structural and acoustic properties, including differences in density, thickness, and surface characteristics, which are critical factors influencing sound absorption performance. The figure provides a visual reference for the tested materials, including laminated particleboards, MDF laminates, plywood types, and various solid wood panels.

2.3 Statistical evaluations
2.3. Statističke analize

In this study, the effects of different wood species and experimental scenarios on noise reduction were evaluated using statistical methods based on experimental data. During the analysis process, non-parametric tests were preferred to ensure reliable results in cases where the data did not exhibit a normal distribution.

To determine differences in noise reduction, the Kruskal-Wallis test was applied to examine the relationship between different wood species and experimental scenarios. The Kruskal-Wallis test is a non-parametric method used to evaluate median differences among independent groups, particularly effective for multi-group comparisons when the assumption of normal distribution is not satisfied (Ostertagová *et al*., 2014). This test assesses whether the group medians are equal, and if the *p*-value is below the significance threshold of 0.05, it is accepted that a statistically significant difference exists between the groups. The hypotheses used for the Kruskal-Wallis test are as follows:

H_0 (Null Hypothesis): There is no statistically significant difference in noise reduction performance among the wood species.

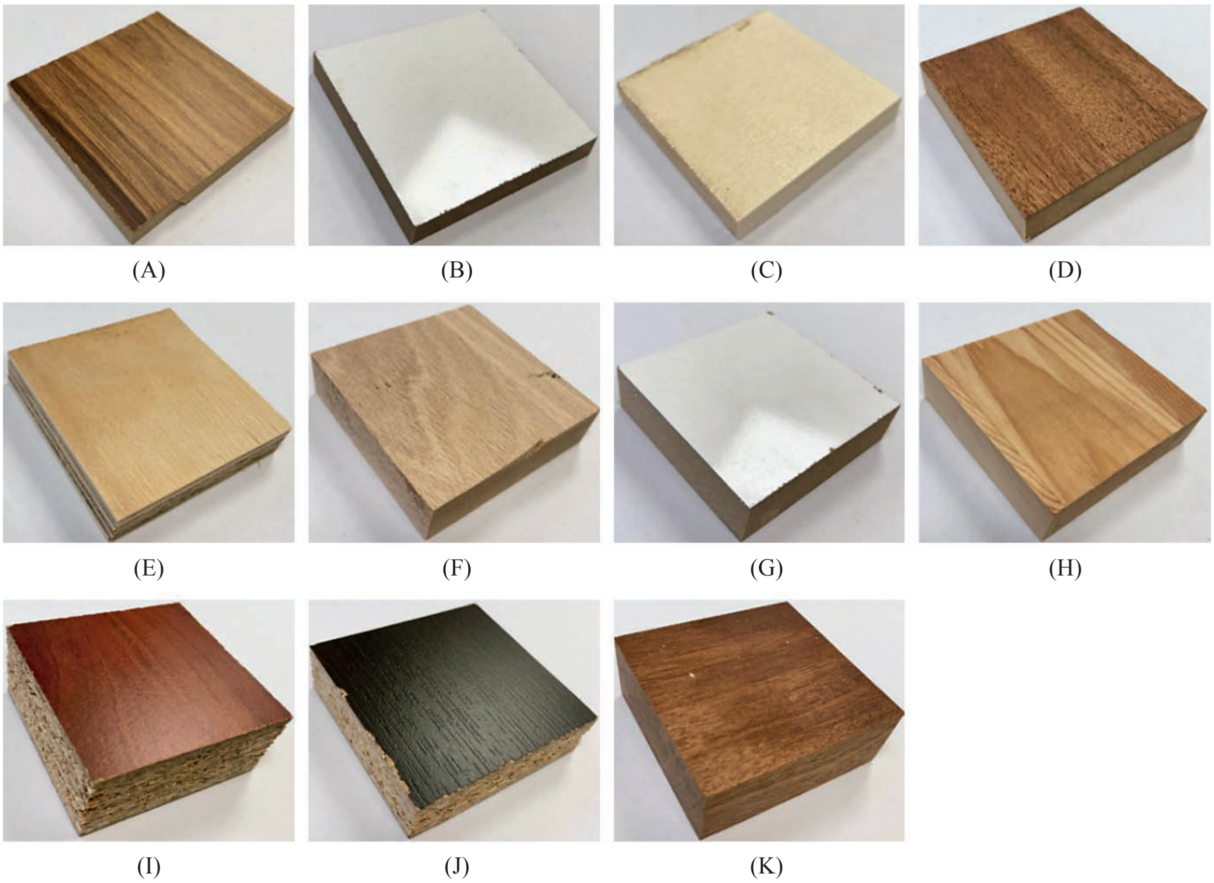

Figure 3 Types of solid wood and wood-based panel materials used in the study: (A) 6 mm MDF laminate, (B) 8 mm MDF laminate, (C) 10 mm poplar plywood, (D) 12 mm MDF covered with Sapelli veneer, (E) 16 mm spruce plywood, (F) 18 mm solid beech wood panel, (G) 18 mm double-sided MDF laminate, (H) 18 mm solid yellow pine wood panel, (I) 30 mm melamine-coated particleboard, (J) 18 mm double-sided melamine-coated particleboard, (K) 30 mm Solid sapelli wood panel
Slika 3. Vrste masivnog drva i drvnih ploča ispitivanih u studiji: A) MDF od 6 mm obložen laminatom; B) MDF od 8 mm obložen laminatom; C) furnirska ploča od topolovine debljine 10 mm; D) MDF od 12 mm obložen furnirom drva sapeli; E) furnirska ploča od smrekovine debljine 16 mm; F) 18 mm debela ploča od bukovine; G) MDF od 18 mm obostrano obložen laminatom; H) ploča od borovine debljine 18 mm; I) iverica od 30 mm obložena melaminom; J) iverica od 18 mm obostrano obložena melaminom; K) ploča od drva sapeli debljine 30 mm

H_1 (Alternative Hypothesis): At least one wood species exhibits a noise reduction performance that is significantly different from the others.

If the Kruskal-Wallis test revealed a statistically significant difference among the groups, a Dunn post-hoc test was applied to determine which specific group comparisons accounted for this difference (Al-Shammari, 2021; Kamrath, 2023). The Dunn test is a complementary post-hoc analysis to the Kruskal-Wallis test and enables pairwise comparisons between groups to identify statistically significant differences.

The hierarchical clustering method was employed to identify patterns within the dataset and to form groupings based on different experimental scenarios. Cluster analysis grouped observations with similar characteristics and resulted in five distinct clusters, thereby revealing a meaningful structure among the scenarios. Using these clusters, the effects of different wood species on noise reduction were systematically evaluated. The data within each cluster were analyzed to compare the sound insulation performance of the associated wood types and to examine the statistical differences in noise reduction across the scenarios.

In the hierarchical clustering process, Ward's method was employed, with Euclidean distance selected as the distance metric. Euclidean distance is used to calculate the straight-line distance between data points in a two-dimensional or multi-dimensional space and is expressed by the following formula (Murtagh and Legendre, 2014):

$$d(i,j) = \sqrt{\sum_{k=1}^{p}\left(x_{ik} - x_{jk}\right)^2} \tag{2}$$

Where, $d(i,j)$ denotes the Euclidean distance between two data points i and j; x_{ik} and x_{jk} represent the coordinates of points i and j in the kth dimension, respectively; and p indicates the total number of dimensions in the dataset.

Hierarchical clustering is a classification method that organizes data into nested hierarchical structures based on similarity or distance metrics between data points. It aims to construct a hierarchy by iteratively grouping the most similar data points or clusters (Murtagh & Contreras, 2017). The Ward's method used in this study is an agglomerative hierarchical clustering technique based on the minimum variance or error sum of squares (ESS) criterion. At each step, this method merges the clusters that result in the smallest increase in within-cluster variance, thereby aiming to maintain internal homogeneity within the resulting groups. The ESS is calculated using the following formula (Murtagh and Legendre, 2014):

$$ESS = \sum_{i \in C} \| x_i - \underline{x}_c \|^2 \tag{3}$$

Where x_i denotes each data point within the cluster, $\underline{x}_c$ represents the centroid (mean) of the cluster, and $\| x_i - \underline{x}_c \|^2$ indicates the squared Euclidean distance between each point and the cluster centroid. This formula serves as the core of Ward's method and aims to minimize the within-cluster error sum of squares.

Ward's method uses a formulation that takes into account both the distances between cluster centroids and the sizes of the clusters. Within the Lance-Williams update formula, specific coefficients are assigned for Ward's method to ensure optimal performance of the clustering process (Ran *et al*., 2023). During the formation of new clusters, Ward's method applies the following Lance-Williams update formula (Murtagh and Legendre, 2014):

$$d(i \cup j, k) = \alpha_i d(i,k) + \alpha_i d(j,k) + \beta d(i,j) + \gamma \left| d(i,k) - d(j,k) \right| \tag{4}$$

In this formula, the coefficients used for Ward's method are defined as follows (Murtagh and Legendre, 2014):

$$\alpha_i = \frac{|C_i| + |C_k|}{|C_i| + |C_j| + |C_k|}, \alpha_j = \frac{|C_j| + |C_k|}{|C_i| + |C_j| + |C_k|} \qquad \beta = \frac{-|C_k|}{|C_i| + |C_j| + |C_k|}, \gamma = 0 \tag{5}$$

Where, $d(i,j)$ denotes the distance between clusters i and j; Ci, Cj, and Ck represent the sizes (i.e., number of elements) of the respective clusters; and $d(i \cup j,k)$ indicates the updated distance between the newly merged cluster i and cluster k.

This method is considered a reliable clustering technique, particularly because it is designed to minimize differences between groups, ensuring internal homogeneity within clusters and optimizing inter-cluster distances. Finally, Ward's Minimum Variance Criterion is calculated using the following formula (Murtagh and Legendre, 2014):

$$D(C_i, C_j) = \frac{|C_i||C_j|}{|C_i| + |C_j|} \| \underline{x}_{ci} - \underline{x}_{cj} \|^2 \tag{6}$$

Where, $D(Ci,Cj)$ represents the total increase in within-cluster error resulting from the merging of clusters; $\underline{x}_{ci}$ and $\underline{x}_{cj}$ denote the centroids of the respective clusters; $|C_i|$ and $|C_j|$ indicate the number of elements in each cluster; and $\| \underline{x}_{ci} - \underline{x}_{cj} \|^2$ represents the squared Euclidean distance between the cluster centroids.

As a result, the groups identified through hierarchical clustering enabled a more detailed evaluation of the differences in noise reduction across various wood species and experimental scenarios. All statistical procedures were performed using MATLAB R2024a.

3 RESULTS
3. REZULTATI

This study investigates the effects of different wood species on compressor-generated noise through A-weighted equivalent continuous sound level (LA_{eq}) measurements conducted at eight distinct measurement points (P1 – P8).

In addition, a 1/3 octave band analysis was performed to identify the dominant frequency characteristics of the noise source. According to the results, the compressor generated a dominant frequency of approximately 125 Hz under the reference condition without any wood-based insulation material applied.

In this study, the Kruskal-Wallis test was initially conducted to evaluate whether there were statistically significant differences in noise reduction levels among the different scenarios (i.e., wood species). Upon identifying significant differences, the Dunn post-hoc test was applied to determine which specific pairs of scenarios contributed to these differences.

Accordingly, hierarchical clustering analysis was performed to group the statistically distinct scenarios. Clustering conducted for each measurement point revealed the internal structure of the data based on observed patterns and allowed for the joint evaluation of scenarios exhibiting similar acoustic performance.

During the clustering process, Ward's method (minimum variance criterion) was used, and Euclidean distance was selected as the distance metric. In this way, the cluster structures and relationships of the statistically significant scenarios were systematically evaluated, and the contributions of different wood species to sound insulation were analyzed both statistically and structurally.

This study investigates the effects of different wood species on compressor-generated noise through A-weighted equivalent continuous sound level (LA_{eq}) measurements conducted at eight distinct measurement points (P1–P8). Kruskal-Wallis tests applied to the measurement data indicated statistically significant differences among the scenarios at all points (p<0.05). The observed dBA values across all scenarios and locations are presented graphically in Figure 4.

Following the identification of significance, Dunn post-hoc tests were conducted to determine which wood species were more effective in absorbing noise. The percentage changes in dB levels based on scenarios at each of the eight measurement points are shown in Figure 4 (LA_{eq}).

In the study, the effect of different wood species on average noise levels was evaluated using the LA_{eq} parameter across eight distinct measurement points (P1–P8). The findings indicate that statistically significant differences were observed among the scenarios at all measurement points. When the scenarios associated with different wood types were compared to the reference scenario (S3) at each location, significant reductions in noise levels were generally recorded.

At measurement point P1, Scenario S14 achieved the highest noise reduction with a rate of −25.99 %, while the lowest reduction was observed in Scenario S6 at −10.02 %. This finding highlights the notable differences in sound insulation performance among the wood species. A similar trend was observed at point P2, where Scenarios S11, S4, and S13 exhibited prominent reductions in LA_{eq} levels, with −13.06 %, −12.77 %, and −11.92 %, respectively. The measurements at point P3 showed that all scenarios resulted in lower LA_{eq} values compared to the reference scenario (S3); here, the most substantial improvement was again observed in Scenario S14, with a reduction of −20.03 %.

At measurement point P4, Scenarios S13, S11, and S14 demonstrated notable average noise reductions of −18.04 %, −17.34 %, and −15.68 %, respectively. At point P5, all scenarios showed statistically significant reductions in comparison to the reference condition, with Scenario S13 yielding the best result at −25.09 %. At point P6, Scenarios S13 and S14 exhibited effective sound insulation performance, whereas Scenario S7 presented a negative outcome with a 9.01 % increase in noise level. This finding indicates that not all scenarios performed equally across all measurement points.

At measurement point P7, Scenario S14 demonstrated a positive effect with a −13.89 % reduction in LAeq. Finally, the data obtained at point P8 indicated that Scenarios S4 (−35.21 %) and S5 (−29.54 %) achieved the highest reductions in LA_{eq} levels. These findings reveal that the mentioned scenarios were particularly effective in mitigating continuous noise sources.

In the overall evaluation, Scenarios S13 and S14 emerged as the most effective solutions for controlling average sound levels, providing high levels of noise reduction across the majority of measurement points. It can be concluded that the botanical structures of these materials optimized the absorption of compressor-generated noise and should be considered among the preferred configurations in terms of acoustic performance.

The statistical analyses presented above revealed that different wood species have significant effects on noise reduction. The overall differences identified through the Kruskal–Wallis test were further examined using the Dunn post-hoc test, which specified which pairs of scenarios differed significantly.

Based on these findings, hierarchical clustering analysis was conducted to better identify patterns in sound insulation performance across the scenarios. All measurements were grouped into five clusters using

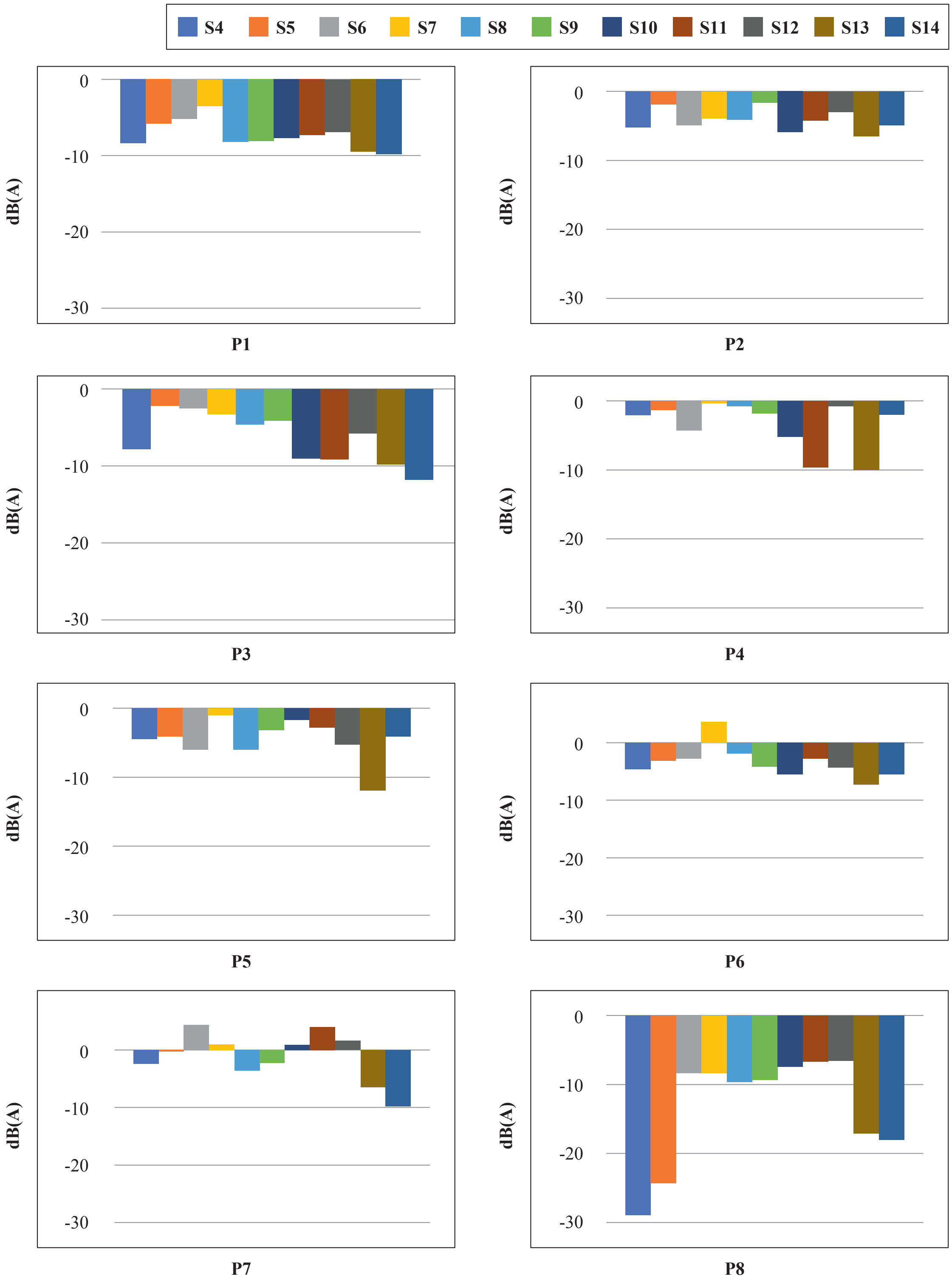

Figure 4 Percentage changes in LA_{eq} values (in dBA) observed for each scenario across all measurement points
Slika 4. Postotne promjene vrijednosti LA_{eq} (u dBA) uočene za svaku varijantu na svim mjernim mjestima

Ward's method and Euclidean distance, allowing for a systematic comparison of the wood species.

The LA_{eq} analyses conducted for each measurement point revealed the comparative sound insulation performance of the wood materials classified using the hierarchical clustering method. At point P1, the scenarios with the lowest average noise levels – S14 (38.8 dBA), S13 (42.9 dBA), and S4 (42.2 dBA) – demonstrated the best sound insulation. Similarly, at point P2, materials such as S4 (47.7 dBA), S10 (48.8 dBA), and S14 (49.8 dBA) stood out in terms of acoustic performance. At point P3, S14 (47.6 dBA) and S13 (49.7 dBA) were the most prominent, while S5 (57.3 dBA) showed relatively weak insulation performance. At measurement point P4, Scenarios S13 (45.2 dBA), S14 (46.5 dBA), and S11 (45.6 dBA) demonstrated high performance,

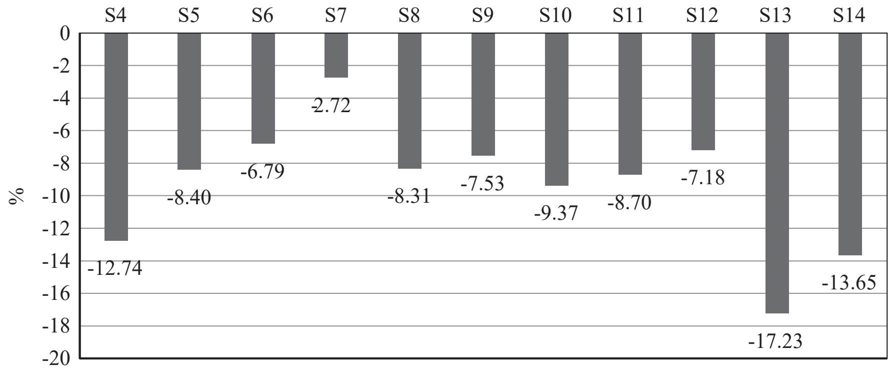

Figure 5 Cumulative representation of noise level changes across all measurement points (%)
Slika 5. Kumulativni prikaz promjena razine buke na svim mjernim mjestima (%)

Table 4 Material- and point-based mean distribution of LA_{eq} values based on hierarchical clustering results
Tablica 4. Srednja distribucija LA_{eq} vrijednosti za materijale i mjerna mjesta na temelju rezultata hijerarhijskog grupiranja

Scenario / *Varijanta*	**Mean LA_{eq}, dBA** *Srednja LA_{eq} vrijednost,* dBA
S13	45
S14	48.5
S11	49.5
S6	50
S8	52.5
S4	58
S7	60
S3	60
S5	61
S12	63
S9	65
S10	67

while S7 (54.9 dBA) and S12 (54.4 dBA) exhibited lower insulation efficiency. At P5, the lowest values were observed in Scenarios S13 (35.5 dBA) and S14 (40.8 dBA). At point P6, S13 (33.1 dBA), S14 (34.9 dBA), and S4 (35.8 dBA) yielded the best results, whereas S7 (44.0 dBA) showed the weakest performance.

A similar trend was observed at points P7 and P8, where S13 and S14 consistently recorded the lowest dB levels, standing out as the most effective materials in terms of sound insulation. To more systematically assess the noise reduction performance of different wood species, hierarchical clustering analyses were conducted for each measurement point. As a result, the data were grouped into five distinct clusters. This clustering approach enabled materials with similar acoustic characteristics to be grouped together, facilitating a more homogeneous and comparable evaluation process.

Considering the changes in noise levels across all measurement points, the material that achieved the greatest cumulative reduction was the 6 mm MDF-lam panel, with a total decrease of 78.6 dBA, as shown in Figure 5.

Table 4 presents the cluster-based LA_{eq} means for each material type across all measurement points. This table provides a comprehensive evaluation of sound insulation performance by accounting for both material diversity and measurement point variability.

4 DISCUSSION
4. RASPRAVA

As a result of the conducted study, noise measurements were performed for all scenarios at eight points within the facility. The wooden panels used for insulation led to varying degrees of noise reduction at all points except for the seventh measurement point. At point 7 – located closest to the noise source and at the same elevation – some materials resulted in an increase in noise levels.

The materials that caused an increase in noise at this point were identified as follows: 18 mm particleboard (4.4 dBA), 18 mm Scots pine solid panel (4.0 dBA), 12 mm MDF with sapelli veneer (1.6 dBA), 16 mm spruce plywood (1.0 dBA), and 12 mm poplar plywood (0.9 dBA).

In contrast, the materials that reduced the noise level at point 7 were: 8 mm MDF (9.8 dBA), 6 mm MDF (6.5 dBA), 30 mm sapelli solid panel (3.6 dBA), and 30 mm particleboard (2.4 dBA).

As shown in Figure 4, the noise level at this location increased due to sound reflection by certain materials, while it decreased through sound absorption by others. It can be concluded that the materials contributing to noise increase acted as sound reflectors, with the most reflective being the 18 mm particleboard. Specifically at point 7, the 18 mm particleboard and the 18 mm Scots pine solid panel appeared to reflect sound waves, thereby increasing the measured noise levels. In contrast, the 30 mm particleboard reduced the noise level, presumably due to greater sound absorption.

Additionally, while the 18 mm beech panel contributed to noise reduction at this location, the 18 mm Scots pine panel increased the noise level.

The eighth measurement point is located 50 cm above the insulation panels, making it the closest point to the noise source in vertical proximity. Based on the noise level measurements at this location, the materials providing the highest levels of noise absorption were identified as follows: 30 mm particleboard (28.9 dBA), 18 mm MDF (24.3 dBA), 8 mm MDF (18.0 dBA), and 6 mm MDF (17.1 dBA).

These results indicate that while material thickness generally has a positive impact on sound insulation, even thin MDF-laminate panels offer sufficient acoustic performance.

Accordingly, 6 mm and 8 mm MDF-lam panels are recommended for use as noise-absorbing panels among various solid wood and wood-based alternatives, due to their smaller spatial footprint, lighter weight, and lower cost.

In noise control applications, it is generally expected that materials used for sound insulation reduce noise levels not only at specific points, but throughout the entire workspace. In this context, the 6 mm MDF-lam panel outperformed all other materials used in the study in terms of cumulative noise absorption.

The exceptional acoustic performance of the 6 mm MDF-lam can be attributed to the structural properties of MDF itself. In the literature, Ünsal *et al*. (2003) identify MDF as the most efficient sound-insulating wood-based panel, due to its homogeneous fiber structure and high density. Similarly, Karademir and Özdemir (2005) state that the tight bonding of fibers within MDF facilitates the dispersion and attenuation of sound waves within the panel.

Based on the results of this study, it would be expected that increasing the thickness of MDF-lam panels would enhance sound absorption. However, this trend was not observed in the case of the 18 mm MDF-lam panel. Cumulatively across all measurement points, the 6 mm MDF-lam panel achieved a noise reduction rate of 17.23 %, whereas the 18 mm MDF-lam panel reached only 8.4 %.

Sound absorption occurs through the transformation of sound energy into other forms of energy. Materials such as MDF, which exhibit homogeneous fiber orientation, absorb part of the incoming sound waves through microscopic vibrations. These vibrations induce internal friction and damping within the material, leading to a loss of acoustic energy (Ünsal *et al*., 2003).

From this perspective, it can be inferred that the 6 mm MDF-lam panel exhibited more intense vibration than the 18 mm panel, thereby achieving greater sound wave attenuation.

In the furniture workshop that served as the study area, it was determined that changes in noise levels within faculty offices, classrooms, corridors, and laboratory spaces were generally linearly related to the distance from the noise source. However, measurements taken in the classroom and corridor did not show a proportional decrease relative to distance. According to the literature, the difference in sound levels between the source and a measurement point in an enclosed space is influenced not only by physical distance but also by the acoustic characteristics of the intervening structural elements–such as wall materials, ceiling height, furniture density, glass surfaces, and corridor geometry (Egan, 2007; Beranek and Vér, 1992; Long, 2014; ISO 3382-1, 2009).

Although similar levels of noise reduction would be expected between two measurement points located close to each other in terms of straight-line distance, discrepancies were observed at certain points (specifically points 3 and 5). Despite being only 15 meters away from the noise source, point 3 exhibited a smaller reduction in noise level compared to point 5, which was located 17 meters away. As noted in the literature, this inconsistency may be attributed to the ceiling height of the classroom and the fact that it shares a common ceiling with the noise source area.

Regarding the sound insulation performance of particleboard (suntalam), two panels with thicknesses of 30 mm and 18 mm were used. Similar noise reduction values were recorded across most measurement points, except for points 7 and 8. At these two points, the 30 mm particleboard demonstrated better noise attenuation performance than the 18 mm panel. This suggests that the effectiveness of increased thickness in particleboard becomes less distinguishable at measurement points farther from the noise source, where the sound attenuation performance of different thicknesses tends to converge. When examining the performance of MDF-lam panels, an inverse relationship was observed between panel thickness and noise attenuation at locations farther from the noise source. Specifically, the thinner panels – 6 mm and 8 mm – showed greater noise reduction compared to the 18 mm panel, indicating that thinner MDF-lam materials can be more acoustically effective in such contexts.

The correlation analysis conducted to examine the relationships among the measurement points revealed strong positive associations between several locations ($\rho > 0.7$). In particular, a high correlation was observed between points P1 and P5 ($\rho = 0.875$), as well as between P1 and P8 ($\rho = 0.764$). Similarly, strong correlations were found between P3 and P4 ($\rho = 0.864$) and P3 and P8 ($\rho = 0.911$). Additional significant associations were also reported between P4 and P8 ($\rho = 0.904$) and P5 and P8 ($\rho = 0.902$). These high correlation coefficients indicate that the corresponding measurement points exhibit similar sequential trends in noise level changes. In other words, when the noise level increases at one point, a corresponding increase is also likely to occur at the other correlated points.

As a result of the correlation analysis, strong negative correlations were identified between P2 and several other measurement points ($\rho < -0.7$). In particular, significant inverse relationships were observed between P2 and P3 ($\rho = -0.813$), P2 and P4 ($\rho = -0.853$), and P2 and P8 ($\rho = -0.772$), indicating an opposing trend in noise level changes among these points. These findings suggest that as the noise level increases at point P2, there may be a corresponding decrease in noise levels at points P3, P4, and P8. Following the implementation of insulation, a general pattern emerged in which positive correlations diminished while negative correlations became more pronounced. This indicates that the insulation application generated more heterogeneous effects across the measurement points, meaning that it influenced different areas to varying degrees. In other words, the insulation system did not produce a uniform impact throughout the space, resulting in certain zones exhibiting greater or lesser acoustic effectiveness.

5 CONCLUSIONS
5. ZAKLJUČAK

This study evaluated the sound insulation performance of various wood-based materials used to reduce industrial noise generated by an air compressor in a furniture workshop. LA_{eq} measurements were conducted at eight different points throughout the facility, and 14 different material scenarios were assessed using statistical analyses, including the Kruskal–Wallis and Dunn post-hoc tests. Hierarchical clustering further enabled systematic grouping of materials based on their acoustic behavior.

The findings revealed statistically significant differences in noise reduction performance among the tested materials. Notably, the 6 mm MDF-lam panel demonstrated the greatest cumulative noise reduction (17.23 %, corresponding to 78.6 dBA), surpassing even thicker panels such as the 18 mm MDF-lam. Among the tested materials, the 6 mm MDF-lam panel yielded the most favorable results in terms of noise reduction, which may be influenced by its structural properties; however, further investigation is required to confirm the underlying mechanisms.

Additionally, it was observed that certain materials – such as 18 mm particleboard and solid Scots pine panels – led to an increase in noise levels at measurement points closest to the compressor, likely due to sound wave reflection and lack of absorption. In contrast, materials like 30 mm particleboard showed better performance at these points, indicating the relevance of both material thickness and structural properties in localized noise control.

Overall, this study highlights the importance of material selection in industrial noise insulation, especially in environments where spatial constraints and cost-efficiency are significant considerations. The results support the use of thinner, high-density MDF-lam panels as viable alternatives for reducing compressor-related noise in workshop settings. Future research will incorporate frequency and vibration analysis to further investigate the acoustic behavior of wood-based materials under different installation conditions.

6 REFERENCES
6. LITERATURA

1. Ali, S. A., 2011: Industrial noise levels and annoyance in Egypt. Applied Acoustics, 72: 221-225.
2. Al-Shammari, M., 2021: An exploratory study of experiential learning in teaching a supply chain management course in an emerging market economy. Journal of International Education in Business, 15 (2): 184-201. https://doi.org/10.1108/jieb-09-2020-0074
3. Andrews, C. J.; Kornas, B., 1982: Ergonomics Fundamentals for Senior Pupils: Teachers Workbook. Napier College.
4. Andrews, G. J. A. B., 1982: Ergonomics Fundamentals of senior pupils. Napier College, Collington Road, Edinburgh.
5. Barbaresco, G. Q.; Reis, A. V. P.; Lopes, G. D. R.; Boaventura, L. P.; Castro, A. F.; Vilanova, T. C. F.; Cunha Júnior, E. C.; Pires, K. C.; Filho, R. P.; Pereira, B. B., 2019: Effects of environmental noise pollution on perceived stress and cortisol levels in street vendors. Journal of Toxicology and Environmental Health. Part A, 82 (5): 331-337. https://doi.org/10.1080/15287394.2019.1595239
6. Barrera, C. S.; Tardiff, J. L., 2022: Static and dynamic properties of eggshell filled natural rubber composites for potential application in automotive vibration isolation and damping. Journal of Cleaner Production, 353: 131656. https://doi.org/10.1016/j.jclepro.2022.131656
7. Beranek, L. L.; Vér, I. L., 1992: Noise and Vibration Control Engineering: Principles and Applications. Wiley-Interscience.
8. Brambilla, G.; Benocci, R.; Potenza, A.; Zambon, G., 2023: Stabilization time of running equivalent level LAeq for urban road traffic noise. Applied Sciences, 13 (1): 207. https://doi.org/10.3390/app13010207
9. Çakıroğlu, E. O.; Demirarslan, K. O.; Taşdemir, T., 2025: Characterization of wood dust emission according to some wood species in 3D machining applied with CNC machine. European Journal of Wood and Wood Products, 83: 59. https://doi.org/10.1007/s00107-025-02222-2
10. Dalgıç, N., 1992: Gürültü ve Sağlık, Sağlık ve Sosyal Yardim Vakfı Dergisi, 3: 5-7.
11. Egan, D. M., 2007: Architectural Acoustics. J. Ross Publishing. ISBN 10: 1-932159-78-9
12. Eleftherou, P. C., 2002: Industrial noise and its effect on human hearing. Applied Acoustics, 63: 35-42. http://dx.doi.org/10.1016/S0003-682X(01)00022-6
13. Eriksson, H. P.; Andersson, E.; Schiöler, L.; Söderberg, M.; Sjöström, M.; Rosengren, A.; Torén, K., 2018: Longitudinal study of occupational noise exposure and joint effects with job strain and risk for coronary heart disease

and stroke in Swedish men. BMJ Open, 8: e019160. https://doi.org/10.1136/bmjopen-2017-019160
14. Feldman, A. S.; Grimes, C. T., 1985: Hearing Conservations in Industry, Williams &Wilkings, London.
15. Işık, E.; Özoran, Y.; Çan, G., 2022: The psychosocial effects of noise level in hydroelectric power plants on employees. Iran Journal of Public Health, 51 (12): 2697-2705.
16. Jong, L.; Peterson, S. C.; Jackson, M. A., 2014: Utilization of porous carbons derived from coconut shell and wood in natural rubber. Journal of Polymers and the Environment, 22: 289-297. https://doi.org/10.1007/s10924-013-0637-4
17. Kamrath, B., 2023: Effectiveness of nutrient management for reducing phosphorus losses from agricultural areas. Journal of Natural Resources and Agricultural Ecosystems, 1 (2): 77-88. https://doi.org/10.13031/jnrae.15572
18. Karademir, A.; Özdemir, T., 2005: Ahşap esaslı levhaların fiziksel ve mekanik özellikleri üzerine bir inceleme. Gazi Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi, 20 (2): 231-238.
19. Long, M., 2014: Architectural Acoustics. Elsevier. https://doi.org/10.1016/C2009-0-64452-4
20. Mago, J.; Negi, A.; Pant, K. K.; Fatima, S., 2022: Development of natural rubber-bamboo biochar composites for vibration and noise control applications. Journal of Cleaner Production, 373: 133760. https://doi.org/10.1016/j.jclepro.2022.133760
21. Masek, A.; Cichosz, S.; Piotrowska, M., 2021: Biocomposites of epoxidized natural rubber/poly (lactic acid) modified with natural fillers (Part I). International Journal of Molecular Sciences, 22 (6): 3150. https://doi.org/10.3390/ijms22063150
22. Murtagh, F.; Contreras, P., 2017: Algorithms for hierarchical clustering: An overview, II. WIREs Data Mining and Knowledge Discovery, 7 (6): e1219. https://doi.org/10.1002/widm.1219
23. Murtagh, F.; Legendre, P., 2014: Ward's hierarchical agglomerative clustering method: Which algorithms implement Ward's criterion? Journal of Classification, 31 (3): 274-295. https://doi.org/10.1007/s00357-014-9161-z
24. Ostertagová, E.; Ostertag, O.; Kováč, J., 2014: Methodology and application of the kruskal-wallis test. Applied Mechanics and Materials, 611: 115-120. https://doi.org/10.4028/www.scientific.net/amm.611.115
25. Owoyemi, M. J.; Falemara, B.; Ayomide, J. O., 2016: Noise pollution and control in wood mechanical processing wood industries. Preprint, 2016080236. https://doi.org/10.20944/preprints201608.0236.v1
26. Palmer, K. T.; Harris, E. C.; Coggon, D., 2008: Chronic health problems and risk of accidental injury in the workplace: a systematic literature review. Occupational Environmental Medicine, 65 (11): 757-764. https://doi.org/10.1136/oem.2007.037440
27. Ran, X.; Xi, Y.; Lu, Y.; Wang, X.; Lu, Z., 2023: Comprehensive survey on hierarchical clustering algorithms and the recent developments. Artificial Intelligence Review, 56 (6): 8219-8264. https://doi.org/10.1007/s10462-022-10366-3
28. Şahin, Y.; Serin, H.; Demir, S., 2017: Research on noise level of wood processing machine groups. Kastamonu University Journal of Forestry Faculty, 17 (3): 450-457.
29. Sekar, V.; Fouladi, M. H.; Namasivayam, S. N.; Sivanesan, S., 2019: Additive manufacturing: a novel method for developing an acoustic panel made of natural fiber□reinforced composites with enhanced mechanical and acoustical properties. Journal of Engineering, 2019: 4546863. https://doi.org/10.1155/2019/4546863
30. Shield, B., 2019: Hearing Lloss – Numbers and costs, evaluation of the social and economic costs of hearing impairment. A report for Hear-It AISBL. https://www.ehima.com/wp-content/uploads/2021/01/Hear-it-Report-Hearing-Loss-Numbers-and-Costs-2019.pdf (Accessed: Mar. 18, 2025).
31. Ulker, O., 2018: Investigation of noise exposure at furniture production and analyzing noise levels. International Journal of Engineering Research and Development, 10 (2): 225-244.
32. Ünsal, Ö.; Korkut, S.; Büyüksarı, Ü., 2003: The sound absorption and air permeability properties of wood-based panels. Turkish Journal of Agriculture and Forestry, 27 (6): 345-352.
33. ***CESVA, 2024: SC310 Sound Level Meter Spectrum Analyser User's Manual. https://www.cesva.com/en/support/product/?model=sc310 (Accessed: Mar. 18, 2025).
34. ***Hearing Health Foundation. Decibel Levels (online). https://hearinghealthfoundation.org/decibel-levels (Accessed: Oct. 28, 2022).
35. ***ISO 3382-1, 2009: Acoustics – Measurement of room acoustic parameters. Part 1: Performance spaces. International Organization for Standardization.
36. ***NIOSH, National Institute for Occupational Safety and Health. Understand noise exposure. Centers for Disease Control and Prevention. https://www.cdc.gov/niosh/noise/prevent/understand.html (Accessed: Feb. 26, 2024).
37. ***Technical Guide for: Noise Control – Engineering Controls, Work Practices, & Administrative Controls. Technical guide/compendium. Internal document. https://oshainfo.gatech.edu/wp-content/uploads/2023/05/Technical-Guide-for-Noise-Controls.pdf (Accessed: Mar. 18, 2025).
38. ***TS EN ISO 9612, 2009: Acoustics – Determination of noise exposure in the working environment – Engineering method. Turkish Standards Institute.

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Artificial Neural Network-Based Optimization of CO_2 Laser Cutting Parameters for Beech Plywood and HDF: A Kerf Geometry Perspective

Optimizacija parametara rezanja bukove furnirske ploče i HDF-a CO_2 laserom, uz primjenu umjetne neuronske mreže: geometrija reza

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ABSTRACT • *This study presents the results of Artificial Neural Networks (ANN) predictions with the aim of optimizing the process of beech plywood and HDF laser cutting. A survey is given of the results of predictions of cutting kerf parameters made by Artificial Neural Networks to cover a wide spread of CO_2 laser parameters, as well as the results of experimental cutting with maximum laser power (P) equal to 135 W and maximum feed rate (v) equal to 20 mm/s. Validity of the best neural network was checked versus overfitting of the best neural networks, confirmed according to r value of the model (minimum 0.971), MAPE (%) (maximum 6.21 %) and compared with the results of other authors. The article also presents the effect of energy density values E on values of cutting kerf parameters and their variance. The results show that the optimal value of laser power (P) and feed rate (v) for beech plywood are (200-300 W; 10-15 mm/s), while for more dense and more homogenous high-density fibreboard (HDF) they are (300-500 W; 5-10 mm/s). Optimal energy densities (E) are then 133 MJ/m² for beech plywood and 433 MJ/m² for HDF. Similar as for other wooden materials, it follows that more dense species of wood should be cut with higher values of energy densities. The results can be applied to reduce the material and energy demands by optimizing the quality of cut with minimum symmetrical kerf widths.*

KEYWORDS: *artificial neural networks; laser cutting; cutting kerf; wood composite materials; optimization*

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SAŽETAK • *Studija predstavlja primjenu umjetnih neuronskih mreža (ANN) za optimizaciju procesa laserskog rezanja bukove furnirske ploče i HDF-a. Prikazani su rezultati predviđanja parametara geometrije reza primjenom umjetnih neuronskih mreža kako bi se pokrio širok raspon parametara CO_2 lasera te su izneseni rezultati eksperimentalnog rezanja laserom najveće snage (P) od 135 W i najvećom brzinom pomaka (v) od 20 mm/s. Validacija najbolje neuronske mreže provjerena je s obzirom na pretjerano prilagođivanje najboljih neuronskih mreža i potvrđena je prema r vrijednosti modela (najmanje 0,971), vrijednosti MAPE (%) (najviše 6,21 %) te je uspoređena s rezultatima drugih autora. Studija prikazuje i utjecaj vrijednosti gustoće energije E na parametre geometrije reza i njihovu varijancu. Iz prikazanih rezultata proizlazi da su optimalne vrijednosti snage lasera (P) i brzine pomaka (v) za bukovu furnirsku ploču 200 – 300 W i 10 – 15 mm/s, dok su optimalne vrijednosti za gušću i homogeniju tvrdu ploču vlaknaticu (HDF) 300 – 500 W i 5 – 10 mm/s. Optimalne gustoće energije (E) pritom su bile 133 MJ/m² za bukovu furnirsku ploču i 433 MJ/m² za HDF. Slično kao i za druge drvne materijala, proizlazi da je vrste drva veće gustoće bolje rezati uz veću gustoću energije. Rezultati se mogu primijeniti za smanjenje potreba za materijalom i energijom optimiziranjem kvalitete reza s minimalnom simetričnom širinom reza.*

KLJUČNE RIJEČI: *umjetna neuronska mreža; rezanje laserom; geometrija reza; kompozitni drvni materijali; optimizacija*

1 INTRODUCTION
1. UVOD

Laser cutting is considered one of the advanced and promising methods for processing wood materials. Its main advantages include improved cutting quality compared to conventional sawing, reduced heat-affected zones, and contactless operation. Several studies have investigated the use of CO_2 laser cutting for wood processing (Ready *et al*., 2001; Zhou and Mahdavian, 2004; Barcikowski *et al*., 2004; Aniszewska *et al*., 2020; Nath *et al*., 2020; Barcikowski *et al*., 2006; Eltawahni *et al*., 2011; Martínez-Conde *et al*., 2017).

Prior research has examined the impact of laser parameters on the cutting characteristics of medium-density fibreboard and plywood materials, but only on a limited scale of laser beam parameters or using different types of lasers. Optimization of laser cutting processes for wood-based agglomerates has been carried out primarily on materials such as plywood and medium-density fibreboard (MDF). For plywood, the influence of laser parameters on cut quality has been investigated by Pikuma *et al*. (2019) and Yung *et al*. (2021), focusing on factors such as laser power, feed rate, and beam type. In the case of MDF, Eltawahni *et al*. (2013) and Lum *et al*. (2000) optimized laser cutting by analyzing the effects of laser power and feed rate on kerf characteristics. These investigations highlight the importance of selecting appropriate laser parameters to achieve minimum thermal damage, improved edge quality, and efficient material removal during the cutting of engineered wood products.

Although laser cutting offers numerous advantages such as high precision, non-contact processing, and flexibility in cutting complex geometries across a wide range of materials including thermoplastics and composites, it also presents certain drawbacks. The most notable are the high initial investment costs for CO_2 laser systems, the need of material parameters optimization as well as energy consumption required to ensure cut quality of materials like polyethylene (PE), polypropylene (PP), and acrylonitrile-styrene-acrylate (ASA), which are thermally heterogeneous (Basar and Der, 2025; Der *et al*., 2024). Additionally, achieving desirable surface quality and minimizing heat-affected zones in 3D-printed parts – particularly those produced by fused filament fabrication (FFF) using carbon fibre-reinforced polylactic acid (PLA) or acrylonitrile-styrene-acrylate (ASA) – requires extensive experimental calibration due to the inherent anisotropy and layer-dependent thermal response of such materials, further complicating the standardization and scalability of the process in industrial applications (Der, 2025; Basar *et al.,* 2025).

These challenges can be effectively addressed through prediction models either by non-linear mathematic fitting procedures or by artificial neural networks (ANN). Both approaches serve to decrease the number of experimental tests required for full-scale optimization of cutting processes thus reducing energy and material demands. However, ANN has been more extensively adopted as a regression mathematical model. Due to its higher versatility, ANN improved statistical prediction accuracy and reduced computational time owing to its AI-based architecture (Ružiak *et al.,* 2022; Ružiak *et al.,* 2024; Ružiak *et al.,* 2025).

The ANN methodology has also been successfully applied for the optimization of wood processing technologies. Bedelean *et al*. (2023) employed this method in combination with Response Surface Methodology (RSM) to optimize the plywood drilling process, achieving improvements in surface quality and tool performance. Similarly, Ozsahin *et al*. (2019) utilized ANN to minimize energy consumption during the milling of both heat-treated and untreated wood. These studies demonstrate the adaptability of ANN models in predicting complex relationships between processing parameters and output responses in wood-based manufacturing. As a result, ANN serves as a powerful tool for enhancing process efficiency and reducing material or energy waste.

During CO_2 laser cutting of wood, the quality of the cut is typically evaluated by measuring the kerf widths and the extent of the heat-affected zones (HAZ) on both the upper and lower surfaces of the material. The kerf widths on the upper and lower surfaces, where the laser beam initially interacts with the material and exits, are denoted as WKU (upper kerf width) and WKL (lower kerf width), respectively, as illustrated in Figure 1. Similarly, the widths of the heat-affected zones on the upper and lower surfaces are represented by WHAZU and WHAZL, indicating the thermal influence of the laser on both sides of the workpiece. These parameters are crucial indicators of cutting quality, affecting dimensional accuracy and surface integrity. Process of kerf creation on former irradiated surface (upper) and on opposite surface (lower) depends on laser processing parameters, cutting direction, density of material and many other parameters. Upper surface kerf width depends mainly on processing parameters, while lower surface kerf width also depends on heat transfer rate to HAZ, which leads to differences between WKU and WKL, resulting in asymmetric kerf. Finding values of laser processing parameters that lead to symmetric kerf is important for technological processing of samples.

Optimization of CO_2 laser cutting, focusing on the kerf width ratio ($WKR = \frac{WKL}{WKU}$), has been conducted utilizing ANN for spruce wood in studies (Ružiak *et al.,* 2022; Ružiak *et al.,* 2024) and for spruce, beech and oak wood in studies (Ružiak *et al.,* 2025). These investigations analyzed the influence of laser parameters – power (P), feed rate (v) – and cutting orientation relative to the fibre direction and perpendicular to the fibres.

ANN was also successfully applied for the modelling of wood surface roughness and power consumption after CO_2 laser cutting in the studies conducted by Tiryaki *et al*. (2014, 2016, and 2017). These studies demonstrated that ANN models could accurately predict surface quality and energy requirements based on laser cutting parameters. By capturing the nonlinear relationships between input variables and output responses, ANN provided a reliable framework for performance evaluation and process optimization. This approach enables researchers and manufacturers to improve cut quality and energy efficiency without extensive trial-and-error experimentation.

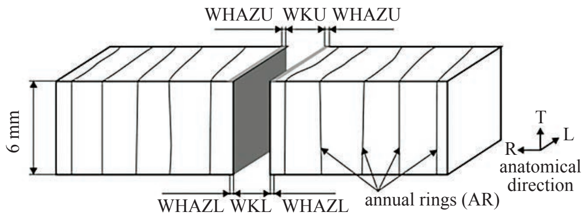


Figure 1 CO_2 laser cutting scheme of wood sample (Ružiak *et al.,* 2022)
Slika 1. Shema rezanja uzorka drva CO_2 laserom (Ružiak i sur., 2022.)

In this article the focus is on optimizing CO_2 laser cutting of beech plywood and high-density fiberboard (HDF) using ANN to model the relationship between laser power P, feed rate v, d as beam diameter in contact with upper surface, and energy density $E = \frac{P}{v{\cdot}d}$. The objective of the research is to identify the optimal P, v and E values (at which WKR value is closest to 1 and WKU, WKL are minimal), for each material individually within the complete range of P, with v applicable for these types of materials. Such routine lowers material and energy demands needed for inspection of cutting kerf parameters mentioned above. The objective of the research, therefore, is not only to determine the optimal laser parameter values for achieving ideal cuts, but also to compare these results regarding different microstructures of the material.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Experimental measurements were conducted on tangential sections of beech plywood and high-density fiberboard (HDF) samples, each with dimensions of 6 mm (thickness) × 70 mm (width) × 500 mm (length) acclimatized at T = (20±1) °C and at relative air humidity of 65 %. These conditions were selected to ensure consistency and represent typical material states encountered in industrial applications. Density of HDF samples used was 850 kg/m^3, with a density of 5-ply beech plywood of 750 kg/m^3.

The samples were cut using a CO_2 laser beam with maximum laser power of 135 W and maximum feed rate of 20 mm/s. The beam diameter was d = 0.15 mm and wavelength 10.6 μm. Maximum power of laser intensity I on upper surface, computed as power divided by area of spot, was 7643 W/m^2. The specified parameters P and v served as the experimental input data. For each P, v pair, the average values of parameters WKU and WKL were obtained experimentally from 30 measurements.

The WKU and WKL values were determined using the VHX-H5M software, which is integrated with the Keyence VHX-7000 digital microscope (Keyence

Table 1 Experimental and predicted values of delivered energy density *E* for agglomerated materials
Tablica 1. Eksperimentalne i predviđene vrijednosti gustoće isporučene energije *E* za drvne materijale

v, mm/s / *P*, W	54	81	108	135	200	300	400	500
5	72	108	144	180	267	400	533	667
10	36	54	72	90	133	200	267	333
15	24	36	48	60	89	133	178	222
20	18	27	36	45	67	100	133	167
30	12	18	24	30	44	67	89	111
40	9	14	18	23	33	50	67	83
50	7	11	14	18	27	40	53	67

Corporation, Osaka, Japan). The effects of other laser parameters were not studied, as they were kept constant throughout the experiments. The predicted values of the WKU, WKL, and WKR parameters were obtained outside the measured values of *P* and *v* for all combinations of *P* values (200, 300, 400, 500) W and *v* values (5, 10, 15, 20, 30, 40 and 50) mm/s. The values of the delivered energy density *E* are also shown in Table 1. Experimental values are highlighted in red, and predicted values are in black. First row corresponds to values of *P* and first column values of *v* in selected units. Numerical values outside the 1st row or column correspond to energy density values in MJ/m^2.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

In this section, we present the results of the ANN predictions, the effect of energy density value (E) on WKU, WKL, and WKR, and, in the final part, the full-scale optimization of WKR parameters with respect to laser power (*P*), feed rate (*v*), and energy density (*E*) for each material individually. All results are compared with reference values. This comprehensive analysis allows for a better understanding of how each parameter influences cutting quality across different material types.

Prediction validity depends on statistical parameters of the best neural networks. Therefore, the values of the above-mentioned statistical indicators for the best-performing network are first presented separately for beech plywood, and HDF, in Tables 2 to 3. The measured data are divided into training, validation, and testing datasets by a ratio of 60 % : 20 % : 20 %.

According to the above-mentioned statistical parameters of the best ANN, it is possible to predict how the values of WKL, WKU, and WKR parameters will be changed by laser parameters.

For the prediction of WKU, WKL and WKR values at non-measured values of *P*, *v* best neural networks must fulfil the condition of no overfitting of the training group. This condition was checked individually for beech plywood training and HDF training, through mean squared error (MSE). MSE for training, testing and validation group for beech plywood – HDF were equal to (3000-3150-3060; 450-480-469) (μm)^2. These results clearly show that the change of input data does not lead to change of best networks error, meaning that best neural networks are not overfitted. In the following sections, the predictions obtained, results of statistical tests, and optimized values of the observed parameters will be presented.

3.1 ANN prediction for beech plywood
3.1. Predviđanje ANN-a za bukovu furnirsku ploču

This section presents the results of the prediction for beech plywood in Figures 2 a, b, and c.

Figures 2a – c show:

– The parameters WKU and WKL decrease nonlinearly with *v*, especially for feed rates above 15 mm/s. This results from the fact that the change in the delivered energy density *E* depending on the feed rate *v* is inversely proportional. The inverse effect of *v* on widths of cutting kerfs WKU and WKL was recorded by many other authors dealing with wood composites (Eltawahni *et al.*, 2011; Barnekov *et al.*, 1989; Lazov *et al.,* 2017; Eltawahni *et al.,* 2013; Lum *et al.,* 2000; Lum *et al.,* 2000; Pikuma *et al.,* 2019; Yung *et al.,* 2021), and wood materials (Barnekov *et al.,* 1986; Corleto *et al.,* 2024; Hérnandez-Castaneda *et al.,* 2011; Keles and Oner, 2010; Nukman *et al.,* 2008; Xu *et al.,* 2017; Ružiak *et al.,* 2022; Ružiak *et al.,* 2024; Ružiak *et al.,* 2025).

Table 2 Statistical parameters for predicting WKU, WKL, and WKR for beech plywood
Tablica 2. Statistički parametri za predviđanje vrijednosti WKU, WKL i WKR za bukovu furnirsku ploču

Parameter *Parametar*	*r*	MAPE, %	Designation *Oznaka*	Activation functions *Aktivacijske funkcije*
WKU (10^{-6}m)	0.979	2.80	MLP 2-7-3	Logistic, Exponential
WKL (10^{-6}m)	0.986	6.21		
WKR (-)	0.976	5.73		

Table 3 Statistical parameters for predicting WKU, WKL, and WKR for HDF
Tablica 3. Statistički parametri za predviđanje vrijednosti WKU, WKL i WKR za HDF

Parameter *Parametar*	*r*	MAPE, %	Designation *Oznaka*	Activation functions *Aktivacijske funkcije*
WKU (10^{-6}m)	0.971	2.15	MLP 2-6-3	Exponential, Tanh
WKL (10^{-6}m)	0.988	3.70		
WKR (-)	0.986	3.86		

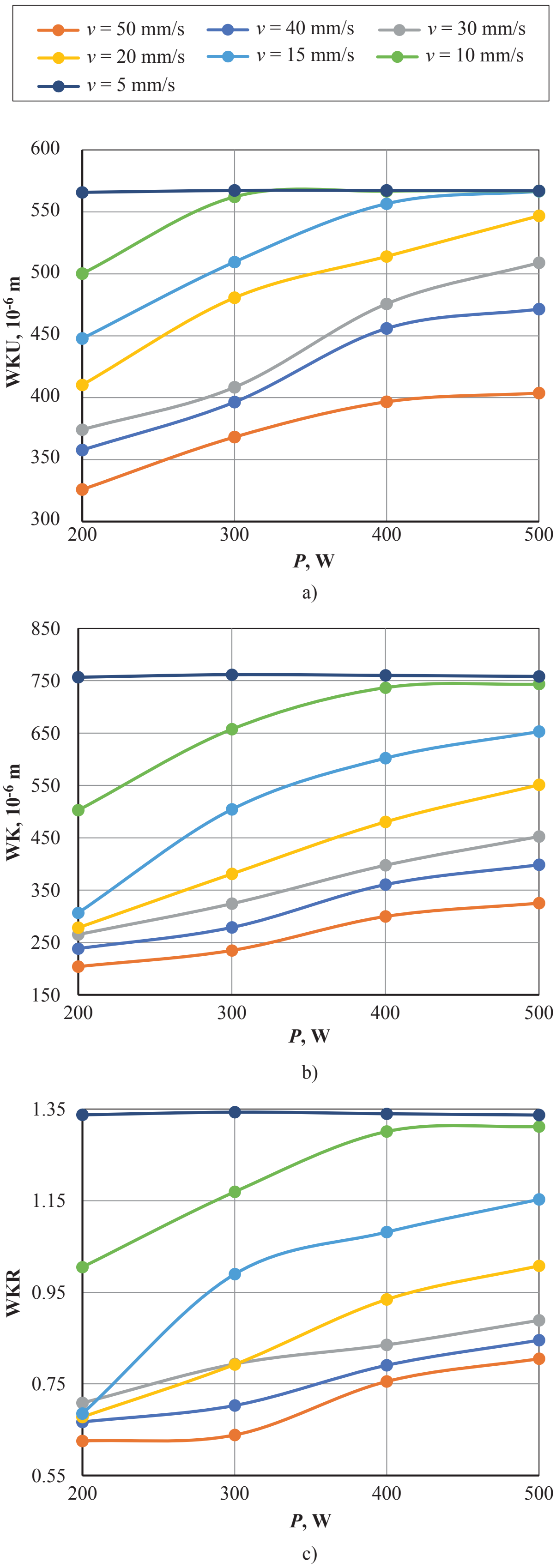


Figure 2 WKU (a), WKL (b), and WKR (c) versus *P*, *v* for beech plywood
Slika 2. WKU (a), WKL (b) i WKR (c) u odnosu prema *P*, *v* za bukovu furnirsku ploču

– The parameters *WKU* and *WKL* stabilize with increasing power, which is a typical trend reported by many authors (Eltawahni *et al.,* 2011; Nukman *et al.,* 2008; Xu *et al.,* 2017; Eltawahni *et al.,* 2013; Lum *et al.,* 2000; Lum *et al.,* 2000; Pikuma *et al.,* 2019; Yung *et al.,* 2021; Ružiak *et al.,* 2022; Ružiak *et al.,* 2024; Ružiak *et al.,* 2025).
– Given the definition of the parameter WKR, this parameter also stabilizes with increasing power.
– The width of the cutting kerf on both sides evens out at feed rate *v* of approximately 15 mm/s and at laser power *P* of 300 W.
– The parameter WKR shows a value close to 1 even at a feed rate *v* = 10 mm/s and laser power *P* of 200 W; nevertheless, both *P*, *v* combinations lead to the same value of the optimal energy density *E*, equal to 133 MJ/m^2.
– For feed rate *v* = 10 mm/s and lower, the ratio WKR values are significantly higher than 1, meaning that the WKU is significantly smaller than WKL.
– On the other hand, as the feed rate increases above 15 mm/s, the value of WKR decreases significantly below 1, meaning that the width of the cutting kerf on the lower surface WKL is significantly smaller than on the upper surface. This is caused by lowering value of WKL due to thermal losses to HAZ.

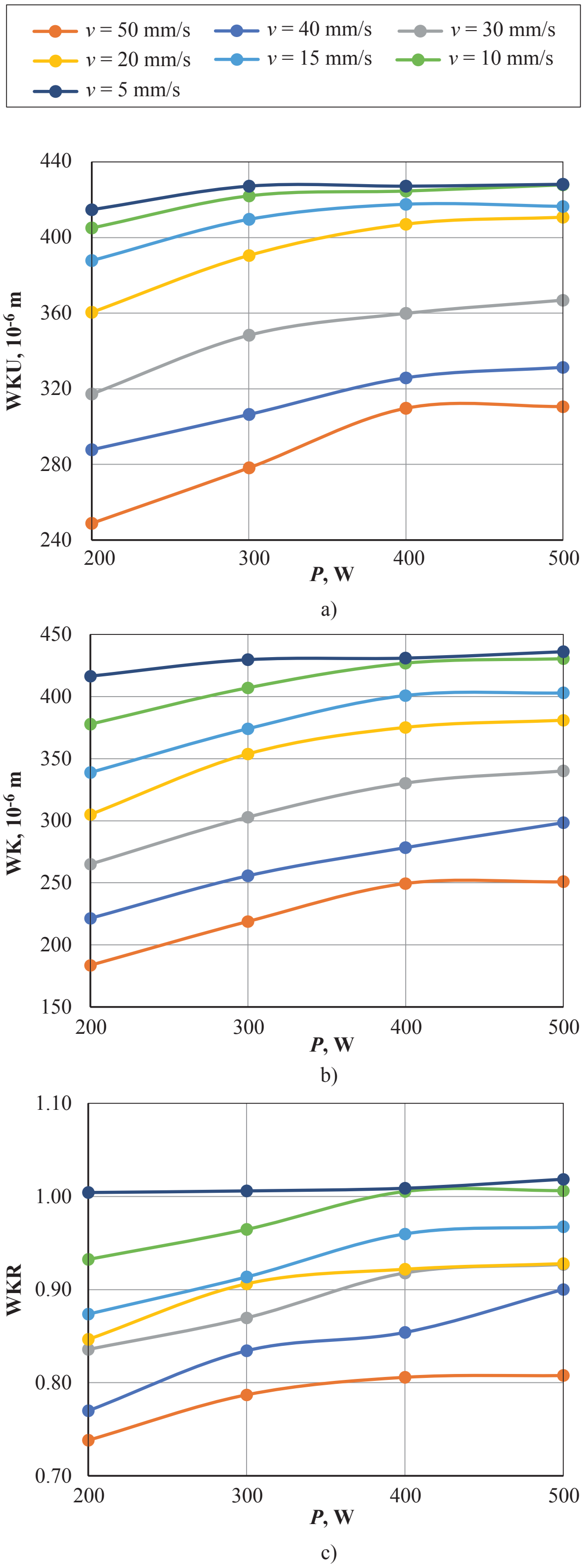
3.2 ANN prediction for HDF
3.2. Predviđanje ANN-a za HDF

Results of the prediction for HDF are presented in Figures 3 a-c.

From Figures 3a – c, the following can be concluded:
– The parameters WKL, WKU decrease nonlinearly with the feed rate v.
– For HDF material, the parameters WKU and WKL do not stabilize within the power range of up to 500 W. This is consistent with the fact that HDF has the highest density, and thus the optimal Energy density E is also maximum.
– The optimal value of WKR close to 1 is only achieved for minimum feed rates, up to 10 mm·s-1, which is because the HDF, as the densest wood species, requires the highest value of E for an optimal cut.
– For every higher feed rate, the value of WKU is greater than WKL, meaning that higher feed rates lead to increase in WHAZL thus lowering WKL value.

3.3 The study of *E* effect on WKU, WKL and WKR
3.3. Proučavanje utjecaja gustoće energije (*E*) na WKU, WKL i WKR

In this section, we will compare the results of WKU, WKL and WKR values for different energy densities. The results are extrapolated from the prediction graphs presented.



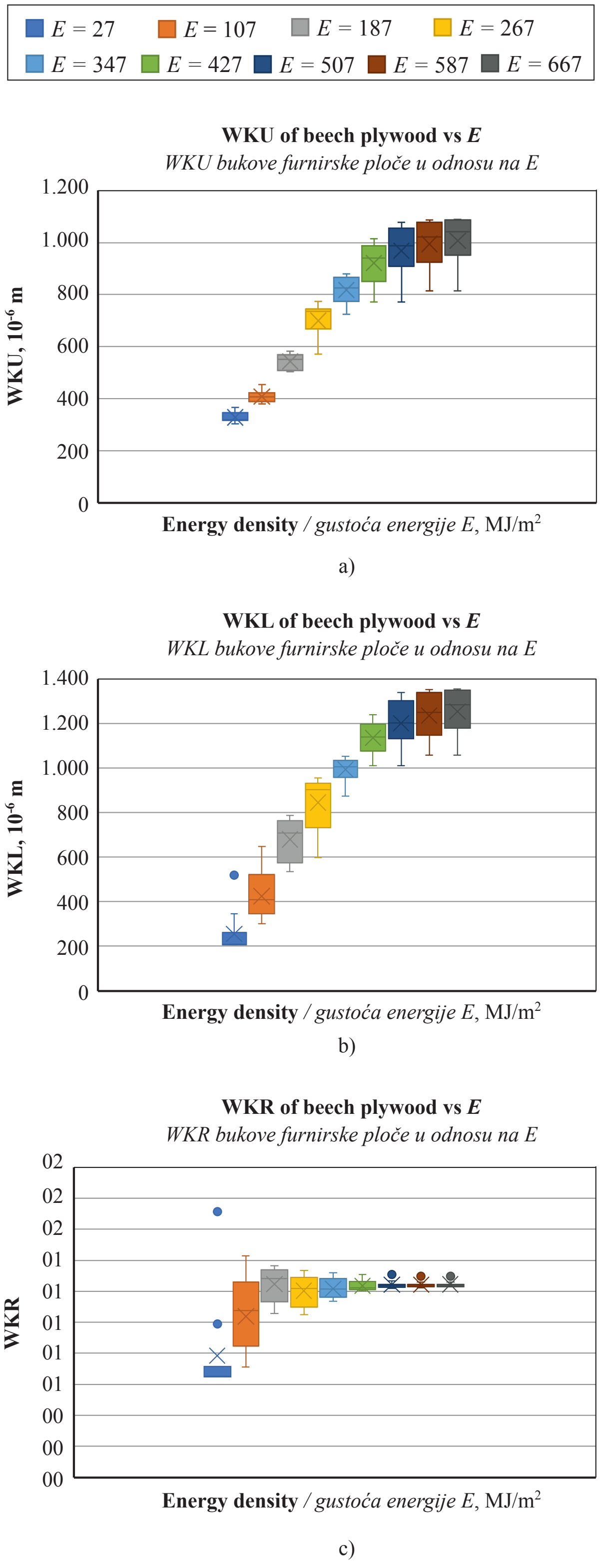


Figure 3 WKU (a), WKL (b), and WKR (c) versus *P*, *v* for HDF
Slika 3. WKU (a), WKL (b) i WKR (c) s obzirom na *P*, *v* za HDF

Figure 4 Effect of energy density *E* values on parameters of cutting kerf for beech plywood: WKU (a), WKL (b), and WKR (c)
Slika 4. Utjecaj gustoće energije *E* na parametre geometrije reza bukove furnirske ploče: WKU (a), WKL (b) i WKR (c)

The results are divided according to values of E = [27, 107, 187, 267, 347, 427, 507, 587, 667] MJ/m^2 in the form of box whisker plots for WKL, WKU and WKR in Figures 4 a, b, c for beech plywood. Similarly, for HDF the values are shown in Figures 5.

From the results presented in Figure 4, the following can be concluded:

- WKU variance increases with increased value of E. This occurs since the most significant amount of energy density is found on the upper board. Lower value of feed rate causes longer heat generation in cutting kerf, which raises together with the value of cutting kerf, with variance of this statistic.
- WKL variance is higher for lower E values. This is due to the fact that at the lower board, the value of E does not have such a significant effect as feed rate, which therefore increases the variance of WKL.
- Similar effect of E can also be seen for WKR, where even at very high values of E, lowering of WKR variance follows.
- Figures a, b, c show that the variance of WKL and WKU with increased E value is getting equal, which then also results in lowering of WKR variance.
- All three figures show that the effect of E is exponentially stabilizing similar to P effect.
- The most important information is that the intersection of boxes in Figure 4c with WKR=1 is obtained for E = 107 MJ/m^2.

From the results in Figure 5, the following can be concluded:

- WKU, WKL, WKR variance decrease with increased value of E.
- Figures a, b, c show that the variance of WKL and WKU with increased E value is getting equal, which then also results in lowering of WKR variance.
- All three figures show that the effect of E is exponentially stabilizing similar to P effect.
- The most important information is that the intersection of boxes in Figure 5c with WKR=1 is obtained for E > 187 MJ/m^2.

The results presented clearly show that optimal E value for HDF as the densest material is higher in comparison with beech plywood characterized by a little bit lower density. It should be noted here that Figures 4 and 5 present box-whisker plots and thus values of WKU, WKL, and WKR, regardless of P, v values which only fulfil the condition of WKR, are equal to some specific value. Such graph tells how variance is changing and which is the mean value, but it does not

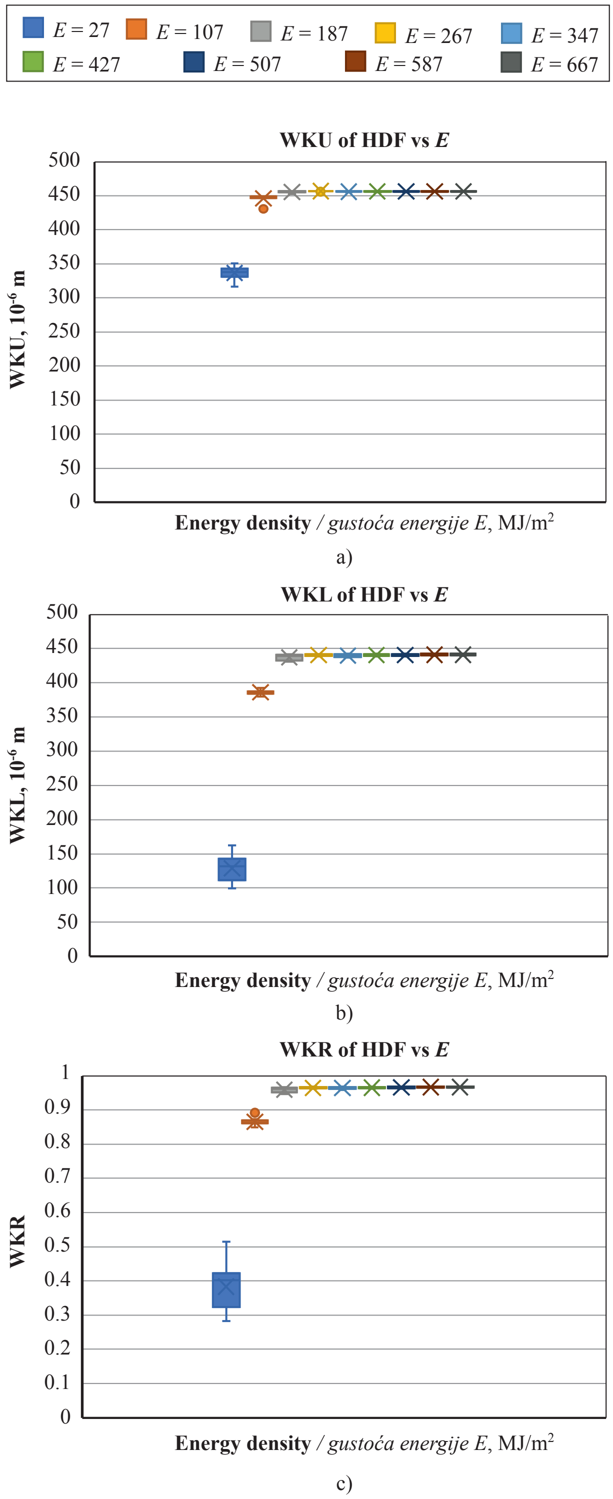


Figure 5 Effect of energy density E values on parameters of cutting kerf of HDF: WKU (a), WKL (b), and WKR (c)
Slika 5. Utjecaj gustoće energije E na parametre geometrije reza HDF-a: WKU (a), WKL (b) i WKR (c)

Table 4 Optimal values of P, v and E for beech plywood, HDF
Tablica 4. Optimalne vrijednosti P, v i E za bukovu furnirsku ploču i HDF

Parameter *Parametar*	**Beech plywood** *Bukova furnirska ploča*	**HDF**
$P_{optimal}$ (W)	200-300	300-500
$v_{optimal}$ (mm/s)	10-15	5-10
$E_{optimal}$ computed (MJ/m^2)	133	200-667
$E_{optimal}$ Figures 4-5 (MJ/m^2)	107	187-667

tell which *P, v* values are the best. This graph is qualitative. For finding optimal values of *P, v* and *E*, data must be processed "point by point".

3.4 Optimization of *P*, v and *E* values for agglomerates used
3.4. Optimizacija vrijednosti *P*, v i *E* za ispitivane drvne materijale

As mentioned above, the condition of optimal cut is where WKR is closest to 1 and minimum WKL and WKU values are reached as listed in Table 4 for both measured and predicted data.

From Table 4, the following can be concluded:

- For beech plywood, optimal values of *P* are between 200 and 300 W and for HDF between 300 and 500 W.
- Optimal feed rate *v* changes from material to material but feed rates higher than 20 mm·s^{-1} are not proper for any material.
- The lowest feed rates are optimal for HDF.
- The optimal value of *v* for beech plywood is higher than for HDF.
- In terms of quality, it can be said that for more dense materials lower *v* is optimal.
- It can be concluded that HDF needs significantly higher energy density to reach optimal quality of cut, versus plywood material.
- Compared optimal values of *E* obtained point-by-point and those obtained from the dependence of WKR vs *E* are in good agreement. It should be mentioned here that *E* values used in Figures 4 to 5 were discrete and point-by-point continuous.

In the final part of experimental results, we compare optimal values of *P*, *v* and *E*, obtained from the results on the same laser apparatus to highlight differences between studied materials and density of materials. For comparison of approaches, Figure 6 shows the graph of optimal *P* versus optimal *v* for different materials and for different cutting directions performed by the same laser machine with the same interval of used *P, v* values.

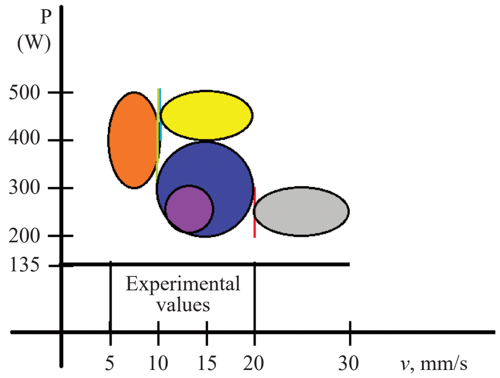


Figure 6 Optimal *P*, *v* values of different wood materials and different cutting directions
Slika 6. Optimalne *P* i *v* vrijednosti za različite drvne materijale i različite smjerove rezanja

For easy comparison of materials and densities, Table 5 and Figure 6 show density, denomination of materials together with the used color and cutting direction ($\perp$ across fibers direction and $\parallel$ in fibers direction).

From Figure 6 and Table 5, it can be concluded that optimal laser power values are obtained outside of experimental values. Also, it follows that except spruce cut across fibers, optimal feed rates are within the used *v* values. Furthermore, materials with higher densities have optimal feed rates lower than less dense materials. From Figure 6, it follows that optimal laser power for beech plywood is less than for massive beech. Almost all more dense materials have higher values of optimal laser powers.

Thus, wooden materials with higher density, got higher optimal powers (*P*) and lower optimal feed rates (*v*), which at same diameter of beam on the upper surface led to the increase of optimal energy densities *E*. However optimal values of *P*, *v* and *E* for which kerf is symmetric, and kerf widths are minimal, cannot be justified only versus density as many other parameters affect the laser cutting of wooden materials as anisotropy of wood, homogeneity of wood, microstructure of wood and many others.

Table 5 Wooden materials used in Figure 6
Tablica 5. Drvni materijali prikazani na slici 6.

Material *Materijal*	**HDF**	**Beech plywood** *bukova furnirska ploča*	**Beech$_{\perp}$** *bukovina$_{\perp}$*	**Beech$_{\parallel}$** *bukovina$_{\parallel}$*	**Oak$_{\perp}$** *hrastovina$_{\perp}$*	**Oak$_{\parallel}$** *hrastovina$_{\parallel}$*	**Spruce$_{\perp}$** *smrekovina$_{\perp}$*	**Spruce$_{\parallel}$** *smrekovina$_{\parallel}$*
Colour *Boja*	Orange *narančasta*	Purple *ljubičasta*	Blue line *plava linija*	Green line *zelena linija*	Blue *plava*	Yellow *žuta*	Grey *siva*	Red line *crvena linija*
Density, kg/m^3 *Gustoća,* kg/m^3	800-1040	700-900	697	697	764	764	400	400
Cutting direction *Smjer rezanja*	-	-		90° 0°	90°	0°	90°	0°

4 CONCLUSIONS
4. ZAKLJUČAK

Based on the analysis of experimental measurements and the subsequent predictions generated by artificial neural networks (ANN) as detailed in the tables, the following conclusions can be drawn:

- The ANN models demonstrate high predictive accuracy, with correlation coefficients exceeding 97 % and maximum MAPE values of 6.2 %, indicating their effectiveness in estimating the influence of laser power (*P*) and feed rate (*v*) on the kerf widths (WKU, WKL) and the kerf width ratio (WKR).
- All optimal models are multilayer perceptron (MLP) type, featuring 2 input neurons *P, v* and 3 output neurons representing WKU, WKL, and WKR using BFGS Quasi-Newton training method.
- The optimal value of *P* for beech plywood is lower than for HDF.
- It is further seen that the optimal value of *v* changes from material to material, with higher wood density corresponding to a better performance at lower values of *v*.
- The optimal energy density *E*, like for solid wood, increases with increasing wood density.
- Dependences on WKU, WKL and WKR for both measurement and predicted data are in good agreement with the trends obtained by many other authors.
- The identified optimal values of P, v for different wood-based materials, can be effectively applied in practical settings to reduce the number of experimental tests required, thereby material consumption and energy expenditure during laser cutting process.

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5 REFERENCES
5. LITERATURA

1. Aniszewska, M.; Maciak, A.; Zychowicz, W.; Zowczak, W.; Muhlke, T.; Christoph, B.; Lamrini, S.; Sujecki, S., 2020: Infrared Laser Application to Wood Cutting. Materials, 13 (22): 5222. https://doi.org/10.3390/ma13225222
2. Barcikowski, S.; Ostendorf, A.; Bunte, J., 2004: Laser cutting of wood and wood composites – Evaluation of cut quality and comparison to conventional wood cutting techniques. In: Proceedings of the 1st Pacific International Conference on Laser Materials Processing, Micro, Nano and Ultrafast Fabrication. Melbourne, Australia.
3. Barcikowski, S.; Koch, G.; Odermatt, J., 2006: Characterisation and modification of the heat affected zone during laser material processing of wood and wood composites. Holz als Roh und Werkstoff, 64: 94-103. https://doi.org/10.1007/s00107-005-0028-1
4. Barnekov, V. G.; McMillin, C. W.; Huber, H. A., 1986: Factors influencing laser cutting of wood. Forests Products Journal, 36: 55-58.
5. Barnekov, V. G.; Huber, H. A.; McMillin, C. V., 1989: Laser machining wood composites. Forests Products Journal, 39: 76-78.
6. Basar, G.; Der, O., 2025: Multi-objective optimization of process parameters for laser cutting polyethylene using fuzzy AHP-based MCDM methods. Proceedings of the Institution of Mechanical Engineers. Part E: Journal of Process Mechanical Engineering, 239 (4): 2295-2309. https://doi.org/10.1177/09544089251319202
7. Basar, G.; Der, O.; Guvenc, M. A., 2025: AI-powered hybrid metaheuristic optimization for predicting surface roughness and kerf width in CO_2 laser cutting of 3D-printed PLA-CF composites. Journal of Thermoplastic Composite Materials, 38 (7): 2688-2717. https://doi.org/10.1177/08927057251344183
8. Bedelean, B.; Ispas, M.; Racasan, S., 2023: Applying the artificial neural network and response surface methodology to optimize the drilling process of plywood. Applied Sciences, 13 (20): 11343. https://doi.org/10.3390/app132011343
9. Corleto, R.; Gaff, M.; Sethy, A. K.; Kelkar, B. U.; Nemeth, R.; Ditommaso, G.; Kamboj, G.; Todaro, L.; Rezaei, F., 2025: Effects of CO_2 laser parameters on quality of laser cut beech wood (*Fagus sylvatica* L.) surface and extent of heat affect zone. Journal of the Indian Academy of Wood Science, 22: 67-77. https://doi.org/10.1007/s13196-024-00361-2
10. Der, O.; Ordu, M.; Basar, G., 2024: Optimization of cutting parameters in manufacturing of polymeric materials for flexible two-phase thermal management systems. Materials Testing, 66 (10): 1700-1719. https://doi.org/10.1515/mt-2024-0127
11. Der, O., 2025: Multi-output prediction and optimization of CO_2 laser cutting quality in FFF-printed ASA thermoplastics using machine learning approaches. Polymers, 17 (14): 1910. https://doi.org/10.3390/polym17141910
12. Eltawahni, H. A.; Olabi, A. G.; Benyounis, K. Y., 2011: Investigating the CO_2 laser cutting parameters of MDF wood composite material. Optics and Laser Technology, 43 (3): 648-659. https://doi.org/10.1016/j.optlastec.2010.09.006
13. Eltawahni, H. A.; Rossini, N. S.; Dassisti, M.; Alrashed, K.; Aldaham, T. A.; Benyounis, K. Y.; Olabi, A. G., 2013: Evaluation and optimization of laser cutting parameters for plywood materials. Optics and Laser Engineering, 51 (9): 1029-1043. https://doi.org/10.1016/j.optlaseng.2013.02.019
14. Hernández-Castaneda, J. C.; Sezer, H. K.; Lin, L., 2011: The effect of moisture content in fibre laser cutting of pine wood. Optics and Lasers in Engineering, 49 (9-10): 1139-1152. https://doi.org/10.1016/j.optlaseng.2011.05.008
15. Keles, O.; Oner, U., 2010: A study of the laser cutting process: Influence of laser power and feed rate on cut quality. Lasers in Engineering, 20 (5): 319-327.
16. Lazov, L.; Narica, P.; Valiniks, J.; Pacejs, A.; Deneva, H.; Klavins, D., 2017: Optimization of CO_2 laser parameters for wood cutting. In: Environment. Technology. Resources. Proceedings of the International Scientific and

Practical Conference, vol. 3, 168-173. https://doi.org/10.17770/etr2017vol3.2624
17. Lum, K. C. P.; Ng, S. L.; Black, I., 2000: CO_2 laser cutting of MDF: 1. Determination of process parameter settings. Optics & Laser Technology, 32 (1): 67-76. https://doi.org/10.1016/S0030-3992(00)00020-7
18. Lum, K. C. P.; Ng, S. L.; Black, I., 2000: CO_2 laser cutting of MDF: 2. Estimation of power distribution. Optics & Laser Technology, 32 (1): 77-87. https://doi.org/10.1016/S0030-3992(00)00021-9
19. Martínez-Conde, A.; Krenke, T.; Frybort, S.; Muller, U., 2017: Review: Comparative analysis of CO_2 laser and conventional sawing for cutting of lumber and wood-based materials. Wood Science and Technology, 51: 943-966. https://doi.org/10.1007/s00226-017-0914-9
20. Nath, S.; Waugh, D.; Ormondroyd, G.; Spear, M.; Pitman, A.; Curling, S.; Mason, P., 2020: Laser incising of wood: A Review. Lasers in Engineering, 45 (4-6): 381-403.
21. Nukman, Y.; Saiful, R. I.; Azuddin, M.; Aznijar, A.-Y., 2008: Selected malaysian wood CO_2 – Laser cutting parameters and cut quality. American Journal of Applied Sciences, 5 (8): 990-996. https://doi.org/10.3844/ajassp.2008.990.996
22. Özşahin, Ş.; Singer, H., 2019: Development of an artificial neural network model to minimize power consumption in the milling of heat-treated and untreated wood. Kastamonu University Journal of Forestry Faculty, 19 (3): 317-328. https://doi.org/10.17475/kastorman.662699
23. Pikuma, B.; Lapshovs, N.; Pavlovs, I.; Katkovskis, R.; Adijans, I.; Lazov, L., 2019: Investigation of the influence of laser beam parameters on the plywood laser cut geometric characteristics. In: РАДИАЦИОННАТА БЕЗОПАСНОСТ В СЪВРЕМЕННИЯ СВЯТ, Rezekne, Latvia. https://doi.org/10.34660/INF.2023.93.48.039
24. Ready, J. F.; Farson, D. F.; Feeley, T., 2001: LIA Handbook of Laser Materials Processing. Springer Verlag, Berlin, Heidelberg.
25. Ružiak, I.; Igaz, R.; Kubovský, I.; Gajtanska, M.; Jankech, A., 2022: Prediction of the effect of CO_2 laser cutting conditions on spruce wood cut characteristics using an artificial neural network. Applied Sciences, 12 (22): 11355. https://doi.org/10.3390/app122211355
26. Ružiak, I.; Igaz, R.; Kubovský, I.; Tudor, E. M.; Gajtanska, M.; Jankech, A., 2024: ANN prediction of laser power, feed rate and number of cut annual rings and their influence on selected cutting characteristics of spruce wood for CO_2 laser processing. Materials, 17 (13): 3333 https://doi.org/10.3390/ma17133333
27. Ružiak, I.; Krišťák, Ľ.; Adijans, I.; Kubovský, I.; Richvalská, J.; Štefančin, L.; Gajtanska, M.; Tudor, E. M.; Todaro, L., 2025: Enhancing CO_2 laser cutting efficiency for diverse wood species using artificial neural networks. Forests, 16 (6): 881. https://doi.org/10.3390/f16060881
28. Tiryaki, S.; Malkocoglu, A.; Özsahin, S., 2014: Using artificial neural networks for modeling surface roughness of wood in machining process. Construction and Building Materials, 66: 329-335. https://doi.org/10.1016/j.conbuildmat.2014.05.098
29. Tiryaki, S.; Malkocoglu, A.; Özsahin, S., 2016: Artificial neural network modeling to predict optimum power consumption in wood machining. Drewno, 59 (196): 109-125. https://doi.org/10.12841/wood.1644-3985.140.08
30. Tiryaki, S., Özşahin, Ş.; Aydın, A., 2017: Employing artificial neural networks for minimizing surface roughness and power consumption in abrasive machining of wood. European Journal of Wood and Wood Products, 75: 347-358. https://doi.org/10.1007/s00107-016-1050-1
31. Xu, Y.; Wang, B.; Shen, Y., 2017: Study on laser cutting technology of bamboo. Wood Research, 62: 645-658.
32. Yung, K. Ch.; Choy, H. S.; Xiao, T.; Cai, Z., 2021: UV laser cutting of beech plywood. The International Journal of Advanced Manufacturing Technology, 112: 925-947. https://doi.org/10.1007/s00170-020-06376-6
33. Zhou, B. H.; Mahdavian, S. M., 2004: Experimental and theoretical analyses of cutting nonmetallic materials by low power CO_2-laser. Journal of Materials Processing Technology, 146 (2): 188-192. https://doi.org/10.1016/j.jmatprotec.2003.10.017

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Combustion and Mechanical Properties of Wood Impregnated with Aqueous Solutions of Various Ammonium and Phosphate-Based Commercial Fertilizers

Gorivost i mehanička svojstva drva impregniranoga vodenim otopinama različitih komercijalnih gnojiva na bazi amonijaka i fosfata

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ABSTRACT • *This study evaluates the combustion and mechanical behavior of Oriental beech (Fagus orientalis L.) wood impregnated with aqueous solutions of various commercial fertilizers–specifically calcium ammonium nitrate (CAN), triple superphosphate (TSP), and their 1:1 weight-based mixture (CAN+TSP). These fertilizers were selected for their known flame-inhibiting potential due to their ammonium and phosphorus content. Ammonium dihydrogen phosphate (ADF), a widely accepted reference fire retardant, was included for comparison. Specimens were treated with 3 %, 6 %, and 9 % aqueous solutions of fertilizers and ADF and subjected to combustion testing based on ASTM E69, including measurements of mass loss, temperature, CO emissions, time to extinction, and collapse. Mechanical performance was assessed by determining modulus of rupture (MOR) and compression strength parallel to the grain (CSPG) in accordance with TS and ISO standards. The results showed that 9 % solution of ADF yielded the most effective fire-retardant performance, with substantial reductions in mass loss and combustion temperature. In contrast, CAN treatments showed minimal improvement in flammability behavior. Mechanical degradation was evident at higher concentrations across all formulations, though 6 % solution of ADF and 3 % solution of CAN retained mechanical performance closest to untreated wood. These findings suggest that phosphate-rich fertilizers, especially ADF and TSP, may offer a viable and economical alternative to traditional fire retardants for wood, provided that impregnation concentration is carefully optimized to preserve mechanical integrity.*

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KEYWORDS: *wood impregnation; combustion; mechanical properties; ammonium dihydrogen phosphate (ADF); calcium ammonium nitrate (CAN); triple superphosphate (TSP)*

SAŽETAK • *U istraživanju su procijenjeni gorivost i mehanička svojstva drva kavkaske bukovine (Fagus orientalis L.) impregnirane vodenim otopinama različitih komercijalnih gnojiva – kalcij-amonijeva nitrata (CAN), trostrukog superfosfata (TSP) i njihove mješavine (CAN + TSP) u težinskom omjeru 1:1. Ta su gnojiva odabrana zbog svoga poznatog potencijala inhibicije plamena jer sadržavaju amonijak i fosfor. Za usporedbu rezultata u istraživanju je upotrijebljen amonijev dihidrogenfosfat (ADF) kao široko prihvaćeni referentni usporivač gorenja. Uzorci su tretirani 3-postotnim, 6-postotnim i 9-postotnim vodenim otopinama gnojiva i ADF-om te je ispitana njihova gorivost na temelju ASTM E69, uključujući mjerenja gubitka mase, temperature, emisije CO, vremena do trenutka gašenja i kolapsa. Mehanička su svojstva procijenjena određivanjem modula loma (MOR) i čvrstoće na tlak paralelno s vlakancima (CSPG), u skladu s TS i ISO standardima. Rezultati su pokazali da je 9-postotna otopina ADF-a najučinkovitije usporila gorenje, uz znatno smanjenje gubitka mase uzoraka i temperature izgaranja. Nasuprot tome, tretmani CAN-om rezultirali su minimalnim poboljšanjem u smislu smanjenja gorivosti. Mehaničko propadanje drva bilo je vidljivo pri višim koncentracijama svih formulacija, iako su primjenom 6-postotne otopine ADF-a i 3-postotne otopine CAN-a mehanička svojstva uzoraka zadržana najbližima netretiranom drvu. Ti rezultati pokazuju da gnojiva bogata fosfatima, posebno ADF i TSP, mogu biti održiva i ekonomična alternativa tradicionalnim usporivačima gorenja za drvo, uz uvjet da se koncentracija impregnacije pažljivo optimizira kako bi se očuvao mehanički integritet drva.*

KLJUČNE RIJEČI: *impregnacija drva; gorivost; mehanička svojstva; amonijev dihidrogenfosfat (ADF); kalcij-amonijev nitrat (CAN); trostruki superfosfat (TSP)*

1 INTRODUCTION
1. UVOD

Wood is a widely used natural material in both structural and non-structural applications within the fields of architecture, interior design, and civil engineering due to its favorable properties such as renewability, lightness, processability, aesthetic appeal, and thermal insulation (Reinprecht, 2016). Its use spans from structural systems to furniture and interior cladding in both residential and commercial environments (Baysal, 2011). However, despite these advantages, wood remains highly susceptible to biological and abiological degradation, particularly in humid environments or under elevated temperatures, which necessitates the application of protective treatments to enhance durability and safety (Yona *et al.,* 2021).

One of the most critical vulnerabilities of wood is its flammability. When exposed to heat, wood undergoes pyrolysis and produces combustible gases, tars, and smoke, which pose significant risks in fire scenarios (Lowden and Hull, 2013). In particular, smoke generation not only reduces visibility but also leads to suffocation hazards, especially in evacuation routes such as corridors and stairwells (Östman, 2006). Therefore, various fire-retardant treatments have been developed to reduce the spread of flames, lower heat release rates, and inhibit smoke production (Park and Baek, 2015; Lu *et al.,* 2020). Among these, inorganic salts such as ammonium sulfate, borates, and phosphates have shown promise due to their charring ability and flame inhibition (Le Van and Winandy, 1990; Atar *et al.,* 2004). However, issues such as leaching, corrosiveness, and ecological impact limit their widespread use (Wu *et al.,* 2021).

In recent years, ammonium and phosphate-based agricultural fertilizers have gained attention as low-cost alternatives for wood fire-retardant applications. These compounds are commonly available, water-soluble, and environmentally less aggressive compared to traditional chemicals (Baysal, 2011). Specifically, ammonium dihydrogen phosphate (ADF), calcium ammonium nitrate (CAN), and triple superphosphate (TSP) are known to contain fire-inhibiting elements such as ammonium and phosphorus, which facilitate char formation and limit thermal decomposition (Di Blasi *et al.,* 2008; Kol *et al.,* 2010). Studies have shown that wood impregnated with such fertilizers can exhibit improved resistance to combustion, with reduced mass loss and lower combustion temperatures (Gaff *et al.,* 2019; Lubloy *et al.,* 2021). However, the fire-retardant performance of these fertilizers varies by concentration and wood species, and limited research has compared them directly with standard fire-retardant chemicals such as ADF.

Beyond fire safety, a major consideration in the application of impregnating agents is their impact on the mechanical performance of wood. Water-soluble salt-based treatments can potentially compromise strength properties such as modulus of rupture (MOR) and compression strength parallel to the grain (CSPG) due to chemical interactions with lignocellulosic components (Winandy, 1988; Mourant *et al.,* 2008). High pH levels and ion concentrations in salt solutions can lead to degradation of wood polymers, resulting in cell wall weakening, microstructural damage, and increased brittleness of wood (Borůvka *et al.,* 2016). Several studies have reported that impregnated wood specimens exhibit decreased bending strength and dimensional stability, particularly under high-temperature curing or prolonged exposure (Furuno *et al.,* 1992; Tomak *et al.,* 2012).

In addition to the widespread use of conventional salts, recent research has explored hybrid and bio-based formulations as emerging alternatives in wood fire protection. For instance, Ellis and Rowel (1989) demonstrated that oligomer phosphonates combined with diisocyanates can form durable fire-retardant coatings with minimal leaching. Similarly, Gašparík *et al.* (2017) found that thermal modification followed by fire-retardant treatment significantly reduced peak heat release rates in oak specimens. Moreover, Adetayo and Dahunsi (2019) reported that tropical hardwoods impregnated with low-cost local salts showed considerable resistance to structural collapse during fire tests. These developments align with growing interest in low-toxicity, environmentally friendly fire retardants that maintain mechanical integrity. Listyanto *et al.* (2020) further emphasized that combinations of borax and boric acid can yield synergistic improvements in fire resistance, even in hardwoods like mahogany. Meanwhile, Chanpirak *et al.* (2018) introduced microwave-assisted impregnation as a promising method to enhance the penetration of sulfur-containing ammonium salts in teak wood, demonstrating both improved retention and combustion performance. As techniques evolve, integrating fire performance with sustainability and material compatibility continues to be a critical research direction.

Given these challenges, this study aims to evaluate the fire-retardant and mechanical properties of Oriental beech (*Fagus orientalis* L.) wood impregnated with aqueous solutions of CAN, TSP, and their 1:1 mixture (CAN+TSP). ADF was included as a reference compound to benchmark performance. The main objectives are (1) to assess whether these commercial fertilizers can provide comparable fire-retardant performance to conventional chemicals, and (2) to examine their effects on the mechanical strength of wood. The findings of this research are expected to contribute to the development of low-cost, environmentally conscious, and structurally viable fire-retardant wood treatments suitable for applications in architectural interiors and beyond.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

In this study, three different fertilizer-based aqueous solutions were utilized for wood impregnation: calcium ammonium nitrate (CAN), triple superphosphate (TSP), and a 1:1 (by weight) mixture of both (referred to as CAN+TSP). These fertilizers were sourced from various commercial agrochemical suppliers located in the Muğla region of Turkey. The chemical ammonium dihydrogen phosphate (ADF), a widely used reference fire retardant, was also included in the experiments to provide a comparative benchmark.

Furthermore, prior research suggests that water-soluble salt-based impregnating agents may adversely affect the mechanical properties of treated wood. Therefore, alongside flammability tests, mechanical characterization including modulus of rupture (MOR) and compression strength parallel to the grain (CSPG) was conducted to evaluate any potential degradation caused by the impregnation treatments.

Oriental beech (*Fagus orientalis* L.) wood was used as the substrate in all tests, and test specimens were prepared in accordance with relevant ASTM and TS ISO standards.

2.1 Impregnation method
2.1. Metoda impregnacije

According to ASTM D1413-07e1 (2016) standard, Oriental beech specimens were impregnated with 3 %, 6 %, and 9 % aqueous solutions of fertilizers. In this study, a vacuum desiccator was used for impregnation and connected to a vacuum pump via a vacuum trap. Before adding the solution to the chamber, a vacuum was applied at 101.325 Pa for 30 minutes, followed by an additional diffusion under vacuum at 101.325 Pa for 30 minutes.

After impregnation, retention amounts were calculated using Eq. 1:

$$Retention = \frac{G \cdot C}{V} \cdot 1000 \text{ (kg/m}^3\text{)} \qquad (1)$$

Where;

$G = T_2 - T_1$ (g),

T_1 – Dry mass of Oriental beech specimens before impregnation (g),

T_2 – Mass of Oriental beech specimens after impregnation (g),

C – Percentage concentration of solution

V – Volume of specimens (cm^3).

2.2 Modulus of rupture (*MOR*)
2.2. Modul loma (*MOR*)

The modulus of rupture of wood specimens was performed according to ISO 13061-3 (2014). Wood specimens had been conditioned at 20 °C and 60 % RH for two weeks prior to testing. In this test, specimen dimensions were prepared as 20 mm × 20 mm × 360 mm (R×T×L). A total of 130 specimens were prepared, 10 specimens from each group. The *MOR* of wood specimens treated with chemicals were calculated using Eq. 2:

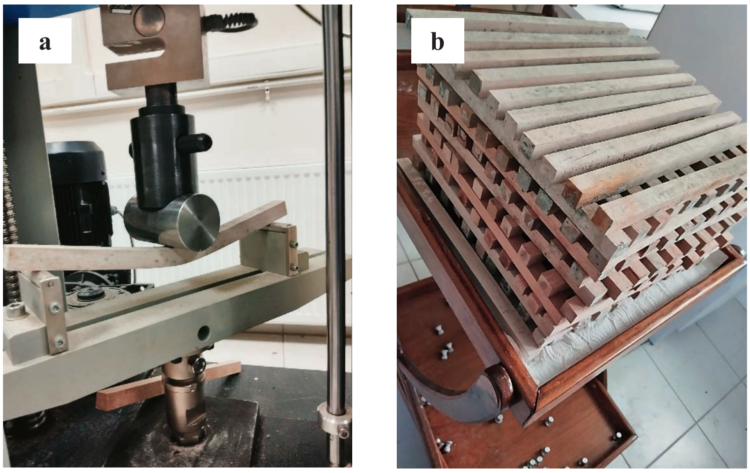

Figure 1 a) Three-point bending test setup; b) test specimens for *MOR* evaluation
Slika 1. a) Postav za ispitivanje savijanja u tri točke; b) uzorci za ispitivanje radi procjene *MOR*-a

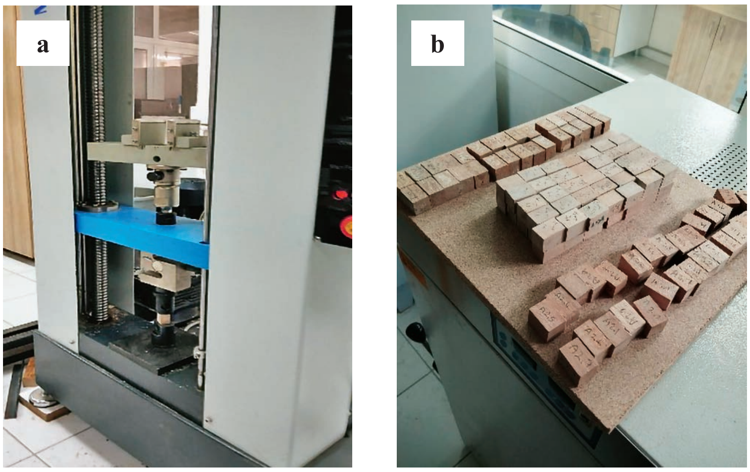

Figure 2 a) Compression strength test setup; b) CSPG wood specimens
Slika 2. a) Postav za ispitivanje tlačne čvrstoće; b) uzorci drva za ispitivanje čvrstoće na tlak paralelno s vlakancima

$$MOR = \frac{3 \cdot P \cdot I}{2 \cdot b \cdot h^2} \quad (\text{N/mm}^2) \qquad (2)$$

Where;
P – maximum load (N),
I – span (mm),
b – width of specimen (mm),
h – thickness of specimen (mm),
Y – deflection (mm).

The test setup and representative specimens used in the *MOR* measurements are shown in Figure 1.

2.3 Compression strength parallel to the grain (*CSPG*)
2.3. Čvrstoća na tlak paralelno s vlakancima (*CSPG*)

A universal testing machine (Marastek, Istanbul, Turkey) with a 4000 N load capacity was used to perform the *CSPG* test in compliance with ISO 13061-17 (2017). The testing procedure, which was controlled by software version M_tst_v17, employed a constant loading rate of 6 mm/min. All specimens were conditioned at 20 °C and 65 % relative humidity for 2 weeks before *CSPG* test. In this test, specimen dimensions were prepared as 20 mm × 20 mm × 30 mm (R×T×L). A total of 130 specimens were prepared, 10 specimens from each group. *CSPG* were calculated using Eq. 3:

$$CSPG = \frac{P}{a \cdot b} \quad (\text{N/mm}^2) \qquad (3)$$

Where;
P – load at break (N),
a, *b* – specimen cross-section dimensions (mm).

The test setup and representative specimens used in the compression strength measurements are shown in Figure 2.

2.4 Combustion test method
2.4. Metoda ispitivanja gorivosti

The combustion characteristics of the impregnated wood specimens were evaluated in accordance with ASTM E69-02 (2002), standard test method for combustion characteristics of large pieces of wood. Test specimens with dimensions of 9 mm × 19 mm × 1019 mm were vertically positioned inside a steel combustion tube equipped with a gas burner, simulating real fire exposure for the initial four minutes of testing. The combustion behavior was observed after the ignition phase and the removal of the flame source. A calibrated Testo 340 flue gas analyzer (Testo SE & Co. KGaA, Lenzkirch, Germany) was used to quantify the concentration of carbon monoxide (CO) in the combustion gases.

Measurements of temperature (°C) and carbon monoxide (CO) were recorded at 30-second intervals until the complete extinction of visible flames and structural collapse of the specimen. In addition, the time to flame extinction and time to collapse were manually recorded using a stopwatch.

To evaluate the flame-retardant effectiveness of the applied chemicals, key indicators such as mass loss, combustion duration, peak temperature, and CO emissions were analyzed. Weight loss due to combustion was calculated using Eq. 4:

$$R\ (\%) = \frac{M_a - M_b}{M_b} \cdot 100 \qquad (4)$$

Where;
M_b – Dry mass of test specimen before impregnation (g),
M_a – Dry mass of test specimen after impregnation (g).

All tests were conducted under identical ventilation and environmental conditions to ensure consistency. The test setup and representative specimens are illustrated in Figure 3.

2.5 Statistical analysis
2.5. Statistička analiza

Variance analysis was used to determine the statistical differences between the data collected for the study, which were examined using the statistical package SPSS program at a 95 % confidence level. The factors between which the discrepancies existed were identified using the Duncan test.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Results of modulus of rupture
3.1. Rezultati ispitivanja modula loma

MOR test results (Table 1) revealed statistically significant differences between the control and treatment samples. The untreated control sample exhibited the highest *MOR* (110.221 N/mm^2), establishing a reference for mechanical integrity. Among the treated specimens, ADF of 3 % (94.246 N/mm^2) and CAN of 3 % (95.750 N/mm^2) demonstrated values closest to the control and were classified in homogeneity group B, indicating that low-concentration impregnation had a relatively limited impact on *MOR*.

However, as the impregnation concentrations increased, a progressive decline in *MOR* values was observed. For instance, CAN of 6 % and CAN of 9 % decreased to 79.878 N/mm^2 and 74.935 N/mm^2, respectively. A similar trend was evident in the TSP group, with TSP of 9 % falling to 79.907 N/mm^2. These results suggest a concentration-dependent weakening of the wood matrix, likely due to the disruption of lignocellulosic structures by high levels of water-soluble salts. Such treatments can alter fiber adhesion and microfibril arrangement, leading to mechanical degradation (Bořůvka *et al.,* 2016; Mourant *et al.,* 2008). Baysal *et al.,* (2013) also reported that wood specimens treated with waterborne chemicals such as boron compounds exhibited a reduction in mechanical properties, including MOR.

Among all formulations, ADF of 6 % maintained a relatively high *MOR* value (92.418 N/mm^2) with the lowest coefficient of variation (2.454 %), indicating consistent performance and suggesting that phosphate-based compounds, when used at moderate levels, may ensure effective penetration without significantly com-

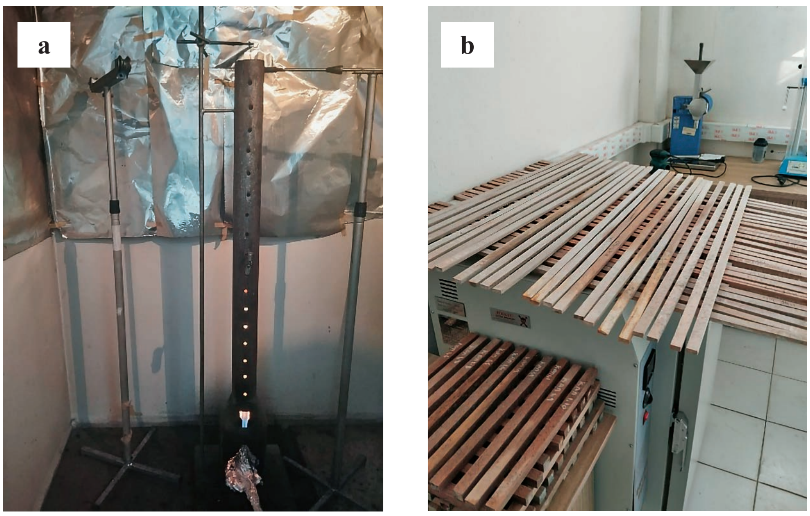

Figure 3 a) Vertical combustion test setup; b) flammability test wood specimens
Slika 3. a) Postav vertikalnog testa gorivosti; b) uzorci drva za ispitivanje gorivosti

Table 1 *MOR* values
Tablica 1. Vrijednosti modula loma

Chemicals *Kemikalije*	**Concentrations, %** *Koncentracija, %*	**Retention value, kg/m³** *Retencija,* kg/m³	***MOR*, N/mm²**	**Standard deviation** *Standardna devijacija*	**Coefficient of variation** *Koeficijent varijacije*	**Homogeneity group** *Homogenost skupina*
Control	-	-	110.221	13.657	12.390	A
ADF	3	12.48	94.246	11.948	12.677	B
ADF	6	23.69	92.418	2.268	2.454	BC
ADF	9	33.53	84.232	5.520	6.553	C
CAN	3	12.97	95.750	13.096	13.677	B
CAN	6	27.93	79.878	4.267	5.341	CD
CAN	9	41.73	74.935	6.685	8.921	D
TSP	3	11.56	90.546	10.746	11.868	BC
TSP	6	27.26	84.127	20.286	24.113	C
TSP	9	32.97	79.907	4.195	5.249	CD
CAN+TSP	3	12.46	83.161	11.515	13.846	CD
CAN+TSP	6	20.87	80.485	5.108	6.346	CD
CAN+TSP	9	45.06	75.430	6.553	8.687	D

ADF – Ammonium dihydrogen phosphate, CAN – calcium ammonium nitrate, TSP – Triple superphosphate
ADF – *amonijev dihidrogenfosfat,* CAN – *kalcij-amonijev nitrat,* TSP – *trostruki superfosfat*

promising structural cohesion (Kol *et al.*, 2010). In contrast, TSP of 6 %, despite a comparable MOR value (84.127 N/mm²), exhibited the highest coefficient of variation (24.113 %), indicating inconsistent distribution or retention. This inconsistency is likely due to the high solubility and potential leaching behavior of phosphate salts during drying, a phenomenon also highlighted by Tomak *et al*. (2012).

Mixture groups (K+T1) also followed similar trends, with increasing concentrations resulting in lower *MOR* values and moderate coefficient of variation. The K+T1 of 9 % group, with 75.430 N/mm² was placed in homogeneity group D, further confirming the negative impact of high impregnation levels.

Overall, the findings emphasize that high concentrations of CAN and TSP significantly reduce *MOR* of Oriental beech, while moderate ADF treatments, particularly at 6 % concentration, maintain mechanical performance within acceptable limits. The data reinforce the importance of optimizing the impregnation concentration to achieve a balance between fire-retardant efficacy and mechanical reliability.

3.2 Compression strength parallel to the grain (*CSPG*) results
3.2. Rezultati ispitivanja čvrstoće na tlak paralelno s vlakancima

CSPG results (Table 2) revealed statistically significant differences between the control and treated samples. The control sample exhibited the highest average compression strength (57.073 N/mm²), serving as the benchmark for untreated wood. Among the treated specimens, TSP of 3 % (44.080 N/mm²) achieved the highest *CSPG* and was classified in homogeneity group B, suggesting that phosphate-based impregnation at this concentration can maintain a satisfactory level of mechanical integrity.

In contrast, higher concentrations of ADF and CAN resulted in a marked reduction in compression strength. ADF of 9 % (30.395 N/mm²) and CAN of 9 % (30.867 N/mm²) were placed in the CD group, indicating substantial mechanical degradation. These findings align with previous studies reporting that excessive salt retention may disrupt the wood microstructure through osmotic stress and chemical interaction with lignin and hemicellulose, ultimately compromising load-bearing capacity (Mourant *et al.,* 2008; Baysal *et al.,* 2013; Borůvka *et al.,* 2016).

Intermediate values were observed in CAN of 3 %, TSP of 3 %, and CAN+TSP of 3 %, ranging between 39.498 – 44.080 N/mm². Although statistically lower than the control, these treatments may be considered structurally acceptable for non-load-bearing or interior architectural applications. The performance of TSP of 3 %, in particular, supports the notion that phosphate-based treatments, when properly dosed, are less detrimental to the compressive behavior of wood (Kol *et al.,* 2010).

These outcomes confirm a concentration-dependent mechanical impact, where excessive retention leads to internal stress and weakening. This effect was more severe in ADF and CAN treatments, suggesting a need for controlled formulation.

Overall, the results highlight a clear trade-off between fire retardancy and mechanical performance. While high ADF concentration offers superior flame resistance (as discussed in Section 3.3), they may not be suitable for structural components.

Table 2 *CSPG* values
Tablica 2. Vrijednosti čvrstoće na tlak paralelno s vlakancima

Chemicals *Kemikalije*	**Concentrations, %** *Koncentracija, %*	**Retention value, kg/m³** *Retencija,* kg/m³	***CSPG*, N/mm²**	**Standard deviation** *Standardna devijacija*	**Coefficient of variation** *Koeficijent varijacije*	**Homogeneity group** *Homogenost skupina*
Control	-	-	57.073	5.202	9.114	A
ADF	3	13.12	37.387	1.655	4.426	C
ADF	6	25.72	36.048	2.467	6.843	C
ADF	9	48.45	30.395	1.781	5.859	CD
CAN	3	15.03	39.498	5.447	13.790	BC
CAN	6	32.13	33.201	2.187	6.587	C
CAN	9	44.91	30.867	3.703	11.996	CD
TSP	3	11.52	44.080	5.313	12.053	B
TSP	6	29.95	37.343	3.048	8.162	BC
TSP	9	44.34	39.471	3.142	7.960	BC
CAN+TSP	3	14.22	41.728	5.936	14.225	B
CAN+TSP	6	26.19	38.496	4.796	12.458	BC
CAN+TSP	9	43.58	34.681	4.703	13.560	C

ADF – Ammonium dihydrogen phosphate, CAN – calcium ammonium nitrate, TSP – Triple superphosphate
ADF – *amonijev dihidrogenfosfat*, CAN – *kalcij-amonijev nitrat*, TSP – *trostruki superfosfat*

3.3 Combustion results
3.3. Rezultati ispitivanja gorivosti

3.3.1 Retention amounts
3.3.1. Retencija

Table 3 summarizes the retention values (kg/m³) of the fertilizer-based impregnation solutions applied to wood. Retention amount is a key indicator of how much active compound remains within the wood after treatment and directly influences the fire-retardant efficiency and potential mechanical impacts of the process.

As expected, retention values increased proportionally with solution concentration across all treatment samples, confirming the effectiveness and consistency of the applied vacuum-pressure impregnation method. The highest retention was recorded in the CAN+TSP of 9 % concentration group (50.26 kg/m³), followed by ADF of 9 % (48.33 kg/m³), and CAN of 9 % concentration (46.12 kg/m³). The lowest value was observed in ADF of 3 % concentration (13.60 kg/m³). These results align with previous studies showing that phosphate- and nitrate-based compounds, due to their high-water solubility and ionic structure, penetrate wood tissues efficiently (Kartal *et al.,* 2009; Kol *et al.,* 2010).

However, while high retention enhances fire resistance by increasing the availability of fire-retardant chemicals in the wood matrix, it may also result in mechanical degradation. As shown in previous sections, samples with high retention values – particularly ADF at 9 % and CAN at 9 % – exhibited notable reductions in both *MOR* and *CSPG*. This supports the existing evidence that high salt concentrations can disrupt cell wall integrity, alter lignocellulosic bonding, and increase brittleness, especially at elevated impregnation levels (Borůvka *et al.,* 2016; Mourant *et al.,* 2008).

In summary, retention values are essential for predicting both combustion resistance and mechanical impact in impregnated wood. The findings suggest that optimal fire-retardant performance requires a balanced concentration: one that ensures effective retention without compromising mechanical integrity. Further research may focus on hybrid systems or controlled-release formulations that optimize this balance for practical applications.

3.3.2 Mass losses after combustion
3.3.2. Gubitak mase izmjeren nakon gorenja

As shown in Table 4, the control sample exhibited the highest mass loss (92.73 %), reflecting the natural flammability of untreated wood. In contrast, the ADF of 9 % concentration recorded the lowest mass loss (38.05 %), followed by ADF of 6 % (69.28 %), and ADF of 3 % (73.04 %), indicating a clear dose-depend-

Table 3 Retention amounts of impregnation chemicals
Tablica 3. Retencija impregnacijskih kemikalija

Chemicals *Kemikalije*	**Concentrations, %** *Koncentracija, %*	**Retention**, **kg/m³** *Retencija,* kg/m³
TSP	3	15.30
TSP	6	37.21
TSP	9	43.03
CAN	3	15.99
CAN	6	36.32
CAN	9	46.12
ADF	3	13.60
ADF	6	25.38
ADF	9	48.33
CAN+TSP	3	15.03
CAN+TSP	6	27.10
CAN+TSP	9	50.26

Table 4 Mass losses data of impregnated wood specimens
Tablica 4. Podatci o gubitku mase impregniranih uzoraka drva

Chemicals *Kemikalije*	**Concentration, %** *Koncentracija, %*	**Mass loss, %** *Gubitak mase, %*	**Std. Dev.**	**Min.**	**Max.**	**Homogeneity group** *Homogenost skupina*
Control	-	92.73	2.59	89.37	95.68	H
TSP	3	77.99	1.32	76.63	79.44	DE
TSP	6	77.58	1.05	76.64	79.09	DE
TSP	9	74.28	1.70	72.83	76.45	CD
CAN	3	88.98	1.68	86.85	90.92	H
CAN	6	88.80	1.43	86.84	89.84	H
CAN	9	90.30	1.37	88.78	91.88	H
ADF	3	73.04	2.05	71.09	75.59	C
ADF	6	69.28	3.96	64.59	73.30	B
ADF	9	38.05	5.67	29.76	42.35	A
CAN+TSP	3	82.03	2.11	80.01	84.55	G
CAN+TSP	6	79.02	3.43	75.38	83.02	EF
CAN+TSP	9	79.70	1.59	77.50	81.26	FG

Table 5 Results measured during combustion
Tablica 5. Rezultati izmjereni tijekom gorenja

Chemicals *Kemikalije*	**Concentration, %** *Koncentracija, %*	**Time to collapse, min** *Vrijeme do kolapsa,* min	**Time to fade out, min** *Vrijeme do kraja gorenja,* min	**Temperature, °C** *Temperatura,* °C			**CO, ppm**		
		Mean (std. dev.)	Mean (std. dev.)	Mean	Max.	Min.	Mean	Max.	Min.
Control	-	4.39 (0.17)	5.28 (0.71)	117.86	166.70	52.50	42.65	82.00	13.00
TSP	3	3.57 (0.37)	4.33 (0.26)	125.92	155.40	110.70	9.41	21.00	3.00
TSP	6	3.50 (0.36)	4.78 (0.50)	114.90	161.40	49.30	12.06	51.00	3.00
TSP	9	3.38 (0.15)	4.63 (0.43)	104.33	123.70	84.10	12.19	26.00	2.00
CAN	3	3.63 (0.55)	4.38 (0.19)	105.44	154.70	34.00	36.30	70.00	6.00
CAN	6	3.21 (0.17)	3.67 (0.25)	106.99	155.30	34.30	37.38	63.00	20.00
CAN	9	2.86 (0.39)	4.22 (0.16)	129.71	151.50	109.90	52.65	90.00	24.00
ADF	3	4.26 (0.46)	5.21 (0.58)	88.70	116.50	66.70	44.55	98.00	13.00
ADF	6	4.31 (0.18)	5.00 (0.46)	90.59	116.80	74.00	32.90	92.00	7.00
ADF	9	3.85 (0.24)	3.86 (0.25)	58.82	85.40	38.80	20.71	39.00	5.00
CAN+TSP	3	3.44 (0.40)	4.02 (0.31)	127.53	147.90	108.40	19.26	59.00	5.00
CAN+TSP	6	3.90 (0.40)	4.49 (0.34)	112.29	148.00	25.60	20.18	73.00	4.00
CAN+TSP	9	4.18 (0.21)	4.88 (0.86)	98.13	153.90	20.90	17.23	59.00	3.00

ent flame-retardant effect of ammonium dihydrogen phosphate. These results align with previous findings that phosphate-based treatments enhance char formation and suppress volatile release, thereby reducing combustion (Di Blasi *et al.,* 2008; Gaff *et al.,* 2019).

Among other treatments, TSP of 9 % concentration showed moderate effectiveness (74.28 %), while CAN at 9 % remained close to the control (90.30 %), suggesting that nitrate-based compounds lack sufficient charring capacity and may even contribute oxidizing effects during combustion (Wu *et al.,* 2021). The CAN+TSP combinations showed intermediate mass losses (79.02–82.03 %), indicating limited synergistic behavior between nitrate and phosphate compounds.

3.3.3 Thermal and gas emission behavior
3.3.3. Emisija topline i plinova

In addition to mass loss, fire performance was evaluated based on extinction time, collapse time, combustion temperature, and carbon monoxide (CO) release (Table 5).

The ADF of 9 % concentration group demonstrated the shortest extinction time (3.86 min) and lowest average combustion temperature (58.82 °C), confirming its superior fire suppression capability through endothermic decomposition and char layer formation (Lowden and Hull, 2013). In contrast, CAN+TSP of 3 % exhibited the highest combustion temperature (127.53 °C), indicating limited heat suppression.

Regarding CO emissions, TSP of 3 % concentration released the lowest amount (9.41 ppm), while ADF of 3 % showed the highest (44.55 ppm). However, CO levels dropped substantially at higher ADF concentrations, with ADF of 9 % emitting only 20.71 ppm, consistent with improved gas-phase suppression. This trend supports findings that higher phosphorus content improves combustion stability (Gaff *et al.,* 2019).

3.3.4 Overall evaluation of fire-retardant effectiveness
3.3.4. Ukupna procjena učinkovitosti usporivača gorenja

Among all treatments, ADF at 9 % concentration provided the most comprehensive fire-retardant performance, significantly reducing mass loss, combustion temperature, and toxic gas emission, while ensuring fast flame extinction. In comparison, TSP treatments, especially at higher concentration, offered moderate protection with better mechanical preservation (as discussed earlier). CAN-based and CAN+TSP combinations showed limited flame-retardant capacity, underlining the importance of chemical composition as well as concentration in fire safety optimization.

4 CONCLUSIONS
4. ZAKLJUČAK

This study evaluated the effects of various commercial fertilizer-based aqueous impregnation solutions – namely calcium ammonium nitrate (CAN), triple superphosphate (TSP), their 1:1 mixture (CAN+TSP), and a reference chemical (ammonium dihydrogen phosphate, ADF) – on the fire-retardant and mechanical properties of Oriental beech (*Fagus orientalis* L.) wood.

The experimental results demonstrated that:

ADF of 9 % concentration showed the most effective flame-retardant behavior, significantly reducing mass loss, combustion temperature, and extinction time.

CAN treatments, across all concentrations, provided negligible fire-retardant performance and led to substantial mechanical degradation at higher concentrations.

The combination of CAN and TSP (CAN+TSP) showed intermediate fire behavior but did not provide clear synergistic advantages over individual formulations.

Modulus of rupture (MOR) and compression strength parallel to the grain (CSPG) were both adversely impacted mechanically by all high-concentration treatments. The formulations containing 6 % ADF and 3 % CAN had the least negative effects on the mechanical characteristics.

These findings suggest that phosphate-based compounds, particularly ADF and to some extent TSP, may serve as cost-effective and partially sustainable fire-retardant alternatives, provided their concentrations are carefully optimized. However, a trade-off remains between fire protection and mechanical performance, highlighting the need for tailored formulations depending on the intended end-use of the treated wood – structural or non-structural.

Further research should focus on the long-term durability, leaching resistance, and environmental impacts of these fertilizer-based treatments, as well as the development of hybrid or encapsulated systems to improve performance without compromising mechanical integrity.

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5 REFERENCES
5. LITERATURA

1. Adetayo, O. A.; Dahunsi, B. I. O., 2019: Fire resistance properties of some selected tropical timber species from South-western Nigeria after fire exposure. Selected Scientific Papers – Journal of Civil Engineering, 14 (2): 61-72. https://doi.org/10.1515/sspjce-2019-0018
2. Atar, M.; Keskin, H.; Yavuzcan, H. G., 2004: Varnish layer hardness of oriental beech (*Fagus orientalis* Lipsky) wood as effected by impregnation and color bleaching. Journal of Coatings Technology and Research, 1 (3): 219-225.
3. Baysal, E., 2011: Combustion properties of calabrian pine impregnated with aqueous solutions of commercial fertilizers. African Journal of Biotechnology, 10 (82): 19255-19260. https://doi.org/10.5897/AJB11.3054
4. Baysal, E.; Yilmaz, M.; Culha, F., 2013: Some mechanical properties of wood impregnated with environmentally-friendly boron and copper based chemicals. Wood Research, 58 (3): 495-504.
5. Borůvka, V.; Ziedler, A.; Doubek, S., 2016: Impact of silicon-based chemicals on selected physical and mechanical properties of wood. Wood Research, 61 (4): 513-524.
6. Chanpirak, A.; Samphakdee, A.; Wangna, S.; Weerachipichasgul, W., 2018: Effectiveness of microwave-soaking assisted impregnation of teak wood (*Tectona grandis* Linn. f) with sulfur-containing ammonium salt as fire retardant. Journal of Engineering Science and Technology, 13 (8): 2405-2420.
7. Di Blasi, C.; Branca, C.; Galgano, A., 2008: Thermal and catalytic decomposition of wood impregnated with sulphur and phosphorus containing ammonium salts. Polymer Degradation and Stability, 93 (2): 335-346. https://doi.org/10.1016/j.polymdegradstab.2007.12.003
8. Ellis, W. D.; Rowel, R. M., 1989: Flame-retardant treatment of wood with a diisocyanate and an oligomer phosphonate. Wood and Fiber Science, 21 (4): 367-375.
9. Furuno, T.; Shimada, K.; Uehara, T.; Jodai, S., 1992: Combinations of wood and silicate II. Wood-mineral composites using water glass and reactants of barium chloride, boric acid, and borax, and their properties. Mokuzai Gakkaishi, 38 (5): 448-457.

10. Gaff, M.; Kačík, F.; Gašparík, M.; Todaro, L.; Jones, D.; Corleto, R.; Čekovská, H., 2019: The Effect of Synthetic and Natural Fire-Retardants on Burning and Chemical Characteristics of Thermally Modified Teak (*Tectona grandis* L. f.) wood. Construction and Building Materials, 200: 551-558. https://doi.org/10.1016/j.conbuildmat.2018.12.10
11. Gašparík, M.; Osvaldová, L. M.; Čekovská, H.; Potůček, D., 2017: Flammability characteristics of thermally modified oak wood treated with a fire retardant. BioResources, 12 (4): 8451-8467.
12. Kartal, S. N.; Green III., F.; Clausen, C. A., 2009: Do the unique properties of nanometals affect leachability or efficacy against fungi and termites? International Biodeterioration and Biodegradation, 63 (4): 490-495. https://doi.org/10.1016/j.ibiod.2009.01.007
13. Kol, H. S.; Uysal, B.; Kurt, Ş.; Ozcan, C., 2010: Thermal conductivity of oak impregnated with some chemicals and finished. BioResources, 5(2): 545-555.
14. Le Van, S. L., Winandy, J. E., 1990: Effects of fire retardant treatments on wood strentgh: A rewiew. Wood Fiber Science, 22 (1): 113-131.
15. Listyanto, T.; Pratama, A. A.; Ando, K.; Hattori, N., 2020: Improving fire resistance of mahogany (*Swietenia macrophylla*) wood impregnated with mixture of borax and boric acid. Wood Research, 11 (2): 48-52. https://doi.org/10.51850/wrj.2020.11.2.48-52
16. Lowden, L. A.; Hull, T. R., 2013: Flammability behaviour of wood and a review of the methods for its reduction. Fire Science Reviews, 2(4): 1-19. https://doi.org/10.1186/2193-0414-2-4
17. Lu, J.; Jiang, P.; Chen, Z.; Li, L. 2020: Characteristic analysis of flame retardant particleboard using three methods of combustion performance evaluation. Journal of Forestry Engineering, 5 (1): 28-34. https://doi.org/10.13360/j.issn.2096-1359.201911023
18. Lubloy, E.; Takács, L. G.; Enczel, D. I.; Cimer, Z., 2021: Examination of the effect of fire retardant materials on timber. Journal of Structural Fire Engineering, 12 (4): 429-445. https://doi.org/10.1108/JSFE-11-2020-0036
19. Mourant, D.; Yang, D. Q.; Riedl, B.; Roy, C., 2008: Mechanical properties of wood treated with PF-pyrolytic oil resins. Holz als Roh- und Werkstoff, 66 (3):163-171. https://doi.org/10.1007/s00107-007-0221-5
20. Östman, B., 2006: Flammability of wood products. In: Flammability Testing of Materials Used in Construction, Transport and Mining. CRC Press LLC, US, pp 65-89. https://doi.org/10.1533/9781845691042.1.65
21. Park, S. H.; Baek, E. S., 2015: A Study on the combustion characteristics of wood according to flame resistant treatment. Fire Science and Engineering, 29 (1): 12-18. https://doi.org/10.7731/KIFSE.2015.29.1.012
22. Reinprecht, L., 2016: Wood deterioration, protection and maintenance. Wiley Blackwell, Wiley, UK.
23. Tomak, E. D.; Baysal, E.; Peker, H., 2012: The effect of some wood preservatives on the thermal degradation of Scots pine. Thermochimica Acta, 547: 76-82. https://doi.org/10.1016/j.tca.2012.08.007
24. Winandy, J. E., 1988: Effects of treatment and redrying on mechanical properties of wood. In: Proceedings of conference on wood protection and the use of treated wood in construction. Memphis, TN, Oct 28-30, 1987, by Forest Prod. Res. Soc., Madison, WI. pp 54-62.
25. Wu, Z.; Deng, X.; Luo, Z.; Zhang, B.; Xi, X.; Yu, L.; Li, L., 2021: Improvements in fire resistance, decay resistance, anti-mold property and bonding performance in plywood treated with manganese chloride, phosphoric acid, boric acid and ammonium chloride. Coatings, 11: 399. https:// doi.org/10.3390/coatings11040399
26. Yona, A. M. C.; Žigon, J.; Matjaž, P.; Petrič, M., 2021: Potentials of silicate-based formulations for wood protection and improvement of mechanical properties: A review. Wood Science and Technology, 55 (4): 887-918. https://doi.org/10.1007/s00226-021-01290-w
27. ***ASTM International, 2017: ASTM E69-02: Standard Test Method for Combustion Characteristics of Large Pieces of Wood. West Conshohocken, PA: ASTM International. https://doi.org/10.1520/E0069-02
28. ***ASTM International, 2007: ASTM D1413-07e1: Standard Test Method for Wood Preservatives by Laboratory Soil-Block Cultures. West Conshohocken, PA: ASTM International. https://doi.org/10.1520/D1413-07E01
29. ***ISO 13061-3, 2014: *Physical and mechanical properties of wood – Test methods for small clear wood specimens. Part 3: Determination of ultimate strength in static bending.* International Organization for Standardization.
30. ***ISO 13061-17, 2017: *Physical and mechanical properties of wood – Test methods for small clear wood specimens. Part 17: Determination of ultimate stress in compression parallel to grain.* International Organization for Standardization.

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Evaluation of Four Lesser-Known Indonesian Hardwood Species for Paper Pulp Production Based on Fiber Quality and Specific Gravity

Evaluacija četiriju manje poznatih indonezijskih vrsta drva listača za proizvodnju papirne pulpe na temelju kvalitete vlakana i specifične gustoće

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ABSTRACT • *The effort to ensure raw material sustainability in the paper pulp industry needs to focus on finding substitutes for wood species. Raw materials for making paper pulp can be obtained from all species of wood, but they must meet specific criteria. We analyzed the specific gravity and maceration preparations of four lesser-known hardwood species that grow in West Sulawesi as potential raw materials for the paper pulp industry. The study indicated that three lesser-known hardwood species (palado, kambelu, and kanduruan) were potentially useful as raw material for pulp paper making.*

KEYWORDS: *fiber quality; specific gravity; lesser-known hardwoods; West Sulawesi*

SAŽETAK • *Napori usmjereni na osiguranje održivosti sirovina za pripremu papirne pulpe moraju se usredotočiti na pronalaženje zamjena za trenutačno upotrebljavane vrste drva. Svaka vrsta drva može biti sirovina za izradu papirne pulpe, ali mora ispunjavati određene kriterije. U radu je analizirana specifična gustoća i priprema macerata četiriju manje poznatih vrsta drva listača koje rastu u Zapadnom Sulawesiju kao potencijalne sirovine za pripremu papirne pulpe. Studija je pokazala da se tri manje poznate vrste drva listača (palado, kambelu, and kanduruan) mogu potencijalno iskorištavati kao sirovina za pripremu papirne pulpe.*

KLJUČNE RIJEČI: *kvaliteta vlakana; specifična gustoća; manje poznate vrste drva listača; Zapadni Sulawesi*

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1 INTRODUCTION
1. UVOD

The Southeast Asian Plant Resources Book categorizes wood species in Southeast Asia as major, minor, lesser-known, and least-known wood species. Due to intensive exploitation, the supply of commercial wood (major and minor wood species) is continuously declining and becoming scarcer. The increasing demand for wood from natural forests, as raw material for paper, can threaten forest sustainability. Today, the forest area is decreasing, but the global need for paper raw materials continues to increase (Deniz *et al.,* 2017). According to Jepri *et al*. (2016), the increasing of raw materials for the paper industry exceeded 100 million tons per year, and wood as a main paper industry raw material was obtained from hardwood and softwood (Bahri, 2015; Gülsoy and Şimşir, 2018).

The raw materials for making paper pulp in Indonesia commonly come from monoculture crops such as acacia, pine, albizia, and eucalyptus. Nowadays, there are some new raw materials used for pulp paper making. Some wood species are estimated to have good properties for making paper pulp other than acacia and pine (Sable *et al*., 2012). According to Jepri *et al.* (2016), the production of paper pulp from palm oil trunks is according to established standards. Industrial-scale pulp production using banana trunks has met standards with a cellulose content above 80 % (Bahri, 2015). On the other hand, harvesting monoculture crops is generally done by clear-cutting, resulting in forest damage. Taking into account the morphological characteristics of fruit tree wood left over from pruning and/or removal of orchards, as well as the pulp yields obtained in the laboratory, it has been noted that kiwi (Yaman and Gencer, 2005), white mulberry (Gençer *et al*., 2013), hazelnut (Gençer and Özgül, 2016), cherry (Gençer and Gül Türkmen, 2016), wild dogwood (Gençer and Aksoy, 2017) and avocado (Altunışık Bülbül and Gençer, 2021a) wood bear similarities to hardwoods used in industrial pulp production. While the current industrial use of fruit tree wood for pulp production may present some challenges, these resources should be considered to promote sustainability and reduce pressure on forests for wood production (Altunışık Bülbül and Gençer, 2021b).

Many lesser-known wood species are underutilized, despite their ecological abundance and potential as raw materials for paper pulp. Unfortunately, the suitability information of those species as raw material for pulp paper making is still lacking. According to Marbun *et al*. (2023), the decreasing availability of commercial woods may be substituted by lesser-known wood species. Unfortunately, in promoting their usage, most wood species lack essential information about their properties, and the paper and pulp industries, which use wood as raw material, do not yet have knowledge of the study. A study of physical and mechanical properties of some lesser-known wood species had been done in India, Nigeria, Bangladesh, Malaysia, and Indonesia (Hedge, 2019; Areo *et al*., 2021; Chowdhury *et al*., 2017; Hamdan *et al*., 2020; Siam *et al*., 2022; Damayanti *et al*., 2019; Marbun *et al*., 2019). A study on the properties of lesser-known wood species as pulp paper raw material needs to be done to substitute raw material from commercial wood species. Sama-sama (*Pouteria firma* Baehni), Palado (*Aglaia* sp.), Kambelu (*Buxus rolfie* Vidal), and Kanduruan (*Phoebe cuneata* Blume) are underutilized lesser-known wood species, many of which are growing in Sulawesi, Indonesia. To produce high-quality products from wood raw material, the exact information on wood species properties is needed (Wahyudi *et al*., 2014). In general, the use of wood is based on its basic properties (Hastuti *et al*., 2017), and these properties are varied among species, influencing commercial value and predicting how to precisely process the wood (Hidayat *et al*., 2017; Purusatama *et al*., 2018; Riki *et al*., 2019). The objectives of this study were (1) to determine the specific gravity of four lesser-known hardwood species from West Sulawesi, (2) to analyze their fiber dimensions and derived indices, and (3) to assess their potential suitability for pulp and paper production.

The process of fiber separation in pulp and paper pulping is conducted through mechanical, chemical, or semi-chemical means (Bahri, 2015). In producing high-quality products from wood raw material, the exact information on wood species properties is needed (Wahyudi *et al*., 2014). The search for alternative wood species is needed for paper pulp raw material. This study aims to evaluate the specific gravity and fiber characteristics of four lesser-known hardwood species from West Sulawesi to determine their suitability as alternative raw materials for paper pulp production. It is hoped that this study can provide information on some wood species that have potential as alternative raw materials for pulp paper making.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

Research materials were collected from natural forests in West Sulawesi, Indonesia, with the geographical coordinates 2°38’50.82” N, 121°5’47.53.71 E. Confirmation of tree species names was based on herbarium tests. Four of the lesser-known hardwood species, i.e., sama-sama (*Pouteria firma* Baehni), palado (*Aglaia* sp.), kambelu (*Buxus rolfie* Vidal), and kanduruan (*Phoebe cuneata* Blume) were taken from a height of 1.30 m above ground level (chest height) or 30 cm above the buttress. Wood samples were shaped discs (5 cm in thickness) of each tree species collected from one mature tree, which was representative of multiple locations. Discs of wood samples were collected from the base, middle, and top of a standing tree with a diameter ranging from 40 to 45 cm. For specific gravity and maceration measurements, each wood species was divided into three parts, i.e., one part near the bark and the others in the middle and near the pith.

2.2 Methods
2.2. Metode

2.2.1 Specific gravity measurement
2.2.1. Mjerenje specifične gustoće

We used a total of 24 test samples (three replications) measuring 2 cm × 2 cm × 1 cm from four wood species to measure the specific gravity of wood, based on Hedge (2019). The specific gravity of wood is measured based on the comparison between the specific gravity of wood and the specific gravity of water at a temperature of 4 °C. The volume of air-dry wood in water is based on Kasmudjo (2012). The calculation of specific gravity is based on the weight of oven-dry wood (103 ± 2) °C and duration until constant weight. Equation for specific gravity is as follows:

$$SG = W / (1+ M/100)\ V,$$

Where SG – specific gravity; W – weight of air-dry wood (kg); M – moisture content of wood (%); V – volume of wood in water (cm^3). The classification of the specific gravity of wood was carried out based on the IAWA criteria (Wheeler *et al*., 2008).

2.2.2 Measurement of fiber dimensions
2.2.2. Mjerenje dimenzije vlakana

The wood samples of each species were obtained from the bottom, middle, and top of the tree. The maceration process was performed on wood pieces from four different directions on each disc, utilizing a modified version of the Franklin method (Rulliaty, 2014). The maceration was conducted by heating matchstick-sized pieces in a test tube that contained a 1:1 hydrogen peroxide solution with a glacial acetic acid solution.

The fibers were then washed using distilled water and immediately stained with safranin solution (for coloration: qualitative). After that, the fibers were covered with a cover glass for measuring. From this macerated material, 25 measurements of fiber length, fiber diameter, and fiber lumen diameter for each wood species were observed using an Olympus microscope CX 23LED. To calculate the thickness of the fiber wall, the formula (a-b)/2 is used, where a – fiber diameter and b – fiber lumen diameter. In order to categorize the quality class of wood fiber, the following properties were determined: the derived values of fiber dimension, namely the runkel ratio, felting power, muhlsteph ratio, flexibility ratio, and coefficient of rigidity, (Marbun *et al*., 2023). Fiber quality criteria are determined based on Abdurrahman *et al.* (2020) to obtain wood fiber quality. The fiber length dimension is measured with the help of a microscope with a magnification of 100x, while for measuring the fiber diameter and lumen, a magnification of 400x is used.

2.2.3 Data analysis
2.2.3. Analiza podataka

The measuring yield values were analyzed descriptively after obtaining the average yield from three replications. The calculation of the average fiber dimension uses the MINITAB 14 program.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Specific gravity
3.1. Specifična gustoća

Sama-sama, palado, kambelu, and kanduruan each have an *SG* of less than 0.7 (Table 1).

According to IAWA criteria (Wheeler *et al*., 2008), the specific gravity (*SG*) is low if wood has an *SG* of < 0.40, moderate if it has an *SG* of 0.40-0.75, and high if it has an *SG* of > 0.75 (Wheeler *et al*., 2008). The variables that affect pulp cooking are age, moisture content, fiber dimensions, and specific gravity (Gallichsen and Paulapuro, 2000). The high pulp yield is produced by woods that have a high specific gravity; however, the woods with high specific gravity in the pulping process necessitate more chemical solvents. According to Carrillo *et al*. (2011), the quality of the final product for pulp paper depends on the specific gravity of wood. The fiber content of wood is important for pulp and paper making, and wood with a specific gravity of 0.55-0.65 is preferred (Wahyudi, 2013). According to Hedge (2019), the yield of pulp in a unit volume is influenced by the specific gravity of different wood species, and it will affect the pulp produced in the process of pulping (Haroen, 2016). The specific gravity also indirectly affects the yield of paper production. The gruffness and

Table 1 Specific gravity of four lesser-known hardwoods species
Tablica 1. Specifična gustoća četiriju manje poznatih vrsta drva listača

Species of wood *Vrsta drva*	**Specific gravity** *Specifična gustoća*	**Categorization** *Kategorizacija*
Sama-sama (*P. firma*)	0.60	Moderate
Palado (*Aglaia sp.*)	0.48	Moderate
Kambelu (*B. rolfie*)	0.62	Moderate
Kanduruan (*P. cuneata*)	0.63	Moderate

the spreading of fibers in pulp are also affected by specific gravity, and they are significant parameters for conformity use of pulp (Kasmudjo, 2012).

The wood requirement to produce one ton of pulp is called the specific wood consumption (*SWC*). *SWC* is affected by the specific gravity of wood, which significantly affects costs of production (Magaton *et al*., 2009). According to Kasmudjo (2012), the specific gravity as a pulp raw material is between 0.35 and 0.65; however, wood with a specific gravity of 0.40 to 0.60 can produce pulp and paper optimally. The conditions of more severe cooking in pulp processing happen at high specific gravity because more chemical components of the wood are degraded (Indrawan *et al*., 2015). The excellent pulp sheet physical properties, such as tear index, breaking length, crack index, and folding resistance, are obtained from wood with a specific gravity of less than 0.70, except that the high specific gravity results in a lower pulp maturity level (high Kappa/Permanganate number), and the pulp sheet has lower physical properties (Haroen, 2006).

3.2 Fiber dimensions and quality
3.2. Dimenzije i kvaliteta vlakana

The fiber dimensions, such as fiber length, fiber diameter, and fiber wall thickness, have variation between wood species, and they determine wood quality as raw material for pulp and paper (Gallichsen and Paulapuro, 2000; Listya and Supartini, 2017). The quality of the wood used in pulp production positively affects pulp yield, ease of cooking and sheet formation in paper production (Kasmudjo, 2012; Haroen, 2006). A strong felting power will be produced if the fiber wall is long and thin because the fiber wall will be flattened easily (Lempang and Asdar, 2012). The fiber dimension measurement of wood species is available in Table 2 below.

The dimensions of the fiber and its derivatives will influence the properties of the pulp product (Syafii and Siregar, 2016), with the length of the fiber being the main determinant factor (Hedge, 2019). The wood species must have a long fiber for raw material for paper pulp (Wahyudi, 2013). According to Kasmudjo (2012), the fiber length of hardwood species ranges from 800 to 1,500 µm, fiber diameter ranges from 8.0 to 60.0 µm, and thickness from 2.0 to 10.0 µm. Based on IAWA criteria (Wheeler *et al.,* 2008), the fiber length of sama-sama and palado was short to long (900-1,600 µm), and of kambelu and kanduruan very long (> 1,600 µm). Based on the criteria of fiber quality of Indonesian hardwood for pulp and paper raw materials (Abdurachman *et al*., 2020), the fiber length of all species in this research is classified as short-to-long. Paper strength, such as index of tear, index of tensile, and index of folding, is influenced by fiber length (Istikowati *et al*., 2019; Rizqiani *et al*., 2019). The tear resistance of the paper is higher if the fiber is longer (Walia, 2013). The crease resistance of the paper and the tensile strength are affected by fiber length (Rizqiani *et al*., 2019). The fiber length is an important factor in bonding between fibers because the tear strength of the paper will increase if the fiber is long (Syafii and Siregar, 2016).

The cell wall thickness of sama-sama, kambelu, and kanduruan wood is classified as very thin, whereas palado is thin to thick. According to Tutus *et al*. (2010) and Kassim *et al*. (2016), there is a complex relationship between fiber dimensions that can influence the physical properties of pulp paper. The long fibers can produce strong weaving power as the walls of thin fiber are easily flattened in milling (Kassim *et al*., 2016). Fiber quality of wood species in this research is presented in Table 3.

Fiber dimensions and their derivatives are important wood properties for estimating pulp paper products. The comparison/ratio between twice the fiber wall thickness and the lumen diameter is a derivative of the fiber dimensions called the Runkel ratio. The best value of the Runkel ratio is fibers with low Runkel. The low Runkel ratio means the that fibers have thin walls and wide lumen diameters, which are easily flattened, and that the fibers have high tensile strength and breaking strength (Wahyudi, 2013; Syafii and Siregar, 2016; Akgul and Tozluoglu, 2009). High Runkel ratio values lead to reduced tensile strength and breaking strength in pulp sheets. The thick-walled and small diameter of fibers can maintain the shape of the pipe in milling. Kambelu and Kanduruan have a very low Runkel ratio (< 0.25), Palado has a low Runkel ratio (0.25-0.50), and Sama-sama has a high Runkel ratio (0.51-0.75).

Table 2 Fiber dimensions of four lesser-known hardwoods species
Tablica 2. Dimenzije vlakana četiriju manje poznatih vrsta drva listača

Wood species *Vrsta drva*	**Fiber dimensions** / *Dimenzije vlakana,* mm			
	Length of fiber *Duljina vlakana*	**Diameter of fiber** *Promjer vlakana*	**Diameter of fiber lumen** *Promjer lumena vlakana*	**Thickness of fiber wall** *Debljina stijenke vlakana*
Sama-sama (*P. firma*)	1,138	16.63	10.83	2.90
Palado (*Aglaia sp.*)	1,132	25.61	17.39	4.11
Kambelu (*B. rolfie*)	1,934	39.17	34.00	2.49
Kanduruan (*P. cuneata*)	1,777	36.00	31.36	2.32

Table 3 Fiber quality and dimension derivative values of four lesser-known hardwoods species
Tablica 3. Kvaliteta vlakana i vrijednosti izvedenih dimenzija za četiri manje poznate vrste drva listača

Species of wood/ Scoring *Vrsta drva/bodovanje*	**Length of fiber, µm** *Duljina vlakana,* mm	**Derivative value**					**Total score** *Ukupni rezultat*	**Fiber quality** *Kvaliteta vlakana*
		Runkel ratio *Runkelov omjer*	**Felting power** *Brzina filcanja*	**Muhlsteph ratio, %** *Muhlstephov omjer, %*	**Flexibility ratio** *Omjer fleksibilnosti*	**Coeffisient of rigidity** *Koeficijent krutosti*		
Sama-sama (*P. firma*)	1,138	0.54	68.43	57.59	0.65	0.17		
Score	50	50	50	75	75	50	350	III
Palado (*Aglaia sp*)	1,132	0.47	44.20	53.89	0.68	0.16		
Score	50	75	50	75	75	50	375	II
Kambelu (*B. rolfie*)	1,934	0.15	49.39	23.77	0.87	0.06		
Score	75	100	50	100	100	100	525	I
Kanduruan (*P. cuneata*)	1,777	0.15	49.37	24.12	0.87	0.06		
Score / *Rezultat*	75	100	50	100	100	100	525	I

The four wood species have a low felting power (40-70). According to Akgul and Tozluoglu (2009), the value of the felting power of hardwoods is between 40 and 60. The higher the felting power value, the more flexible and the higher the tear strength of fibers produced because the tear will be divided into larger areas (Syafii and Siregar, 2016).

Pulp strength is influenced by the multistep ratio, which reflects the value of the pulp sheet density. Muhlsteph ratios of kambelu and kanduruan are classified as very low (< 30%), and low (30-60%) for sama-sama and palado. The fiber wall is thin, making the fiber more compatible for paper pulp making (Akgul and Tozluoglu, 2009). It is stated that a lower Muhlsteph ratio results in higher density and strength pulp sheets. In contrast, a high Muhlsteph ratio results in low-density pulp sheets, so the pulp sheet is weaker.

The flexibility ratio is the ratio between the lumen diameter and the fiber diameter. The fiber that has high flexibility is the fiber that has a thin wall, with the result that it is easily deformed (Syafii and Siregar, 2016; Akgul and Tozluoglu, 2009). The change of the fiber shape causes the fiber to be more flexible in contact among the fiber surfaces, so the fiber bonds are better in sheets of pulp products that make a good strength of pulp. Sama-sama and palado have high flexibility ratios (0.60 to 0.80), and kambelu and kanduruan have very high flexibility ratios (>0.80). The low-flexibility fiber has a diameter with a narrow lumen, so it can produce thicker sheets of pulp and paper, uneven paper surfaces, and lower breaking strength.

The ratio between fiber wall thickness and fiber diameter is called the coefficient of rigidity. Sama-sama and palado have high coefficients of rigidity (0.15-0.20), whereas kambelu and kanduruan have very low coefficients of rigidity (<0.10). The tensile strength of paper is inversely proportional to the rigidity coefficient value. The lower the coefficient of rigidity, the higher the tensile strength of the paper produced (Syafii and Siregar, 2016; Akgul and Tozluoglu, 2009).

3.3 Potential use of paper pulp
3.3. Potencijalna primjena papirne pulpe

Specific gravity of sama-sama, palado, kambelu, and kanduruan is between 0.48 and 0.63. Such specific gravity is classified as moderate. As well known, mangium (*Acacia mangium*) is a wood species that is commonly used for paper pulp products. According to Arsad (2011), mangium (*Acacia mangium*) from South Kalimantan has a specific gravity of 0.6. The four wood species in this research have different specific gravity each. The specific gravity of palado is 0.48; it is lower than that of mangium. Sama-sama, kambelu, and kanduruan each have relatively the same specific gravity as mangium, namely 0.60, 0.62, and 0.63.

Fiber length of Kambelu and Kanduruan is 1,934 µm and 1,777 µm, and such fibers are classified as very long fibers. Fiber length of sama-sama and palado is 1,138 µm and 1,132 µm, and such fibers are classified as long fibers. The fibers of these four species are longer than the fibers of mangum (1,019 µm) researched by Mulyawati (2013).

The Runkel ratio of these four hardwoods varies from 0.15 to 0.54. According to Syafii and Siregar (2016), these Runkel ratios are classified as very low to moderate. The Runkel ratio of *Acacia mangium* is between these values (0.41). The Runkel ratios of kambelu (0.15) and kanduruan (0.15) are categorized as very low and lower than the Runkel ratio of A. mangium. Wood species with a long fiber and a low Runkel value can be obtained from wood species that have a specific gravity of 0.55 to 0.65, and such wood species are a proper raw material for pulp paper making (Wahyudi, 2013).

Table 3 presents the scores for fiber quality based on derivative values, which are classified into three ranges: classes I to III. The fibers in classes I to II have short to very long fibers, narrow to very wide lumen diameters, and very thin to thick walls. These fibers will range from difficult to relatively easy to flatten during milling, and the fiber bond will be sufficiently strong. The fibers classified in class II will exhibit low to high levels of cracking, tearing, and tensile strength. Of the four species of lesser-known hardwood studied, only three are potentially useful as raw material for pulp paper making, namely palado, kambelu, and kanduruan, with kambelu and kanduruan being more appropriate as raw material for pulp paper making because these two species not only have higher specific gravity but also good fiber quality.

4 CONCLUSIONS
4. ZAKLJUČAK

This research offers the first systematic fiber-quality assessment of four lesser-known Indonesian hardwood species, i.e., Sama-sama (*Pouteria firma* Baehni), Palado (*Aglaia* sp.), Kambelu (*Buxus rolfie* Vidal), and Kanduruan (*Phoebe cuneata* Blume), with specific gravity that is appropriate as raw material for pulp paper making. However, based on the analysis of fiber quality and dimension derivative value, only Palado, Kambelu, and Kanduruan have potential as raw material for paper pulp. Kambelu and Kanduruan were identified as the most promising species, referring specifically to their advantageous fiber properties–such as long fiber length (1,934 and 1,777 mm), low Runkel ratio (< 0.25), and moderate specific gravity (0.60–0.63), which together indicate high pulpability and strong bonding potential and make their specific gravity appropriate as raw material for pulp paper making. This paper has some limitations in pulping testing, meaning that further research is required. It is necessary to conduct pilot pulping experiments, analyze the chemical composition, and evaluate the paper strength.

5 REFERENCES
5. LITERATURA

1. Abdurachman; Akbar, A.; Santoso, A.; Ismanto, A.; Salim, A. G.; Andianto; Wibowo, A.; Soka, A.; Hidayat, A.; Sukmana, A.; Widarti, A.; Utari, A. D., 2020: Indonesian Forestry Vademecum. Jakarta: Kementerian Lingkungan Hidup dan Kehutanan (in Indonesian).
2. Akgul, M.; Tozluoglu, A., 2009: Some chemical and morphological properties of juvenile woods from beech (*Fagus orientalis* L.) and pine (*Pinus nigra* A.) plantations. Trends in Applied Sciences Research, 4 (2): 116-125.
3. Altunışık Bülbül, G.; Gençer, A., 2021a: Determination of some chemical and morphological properties of avocado wood and researching its suitability for pulp production. Journal of Bartin Faculty of Forestry, 23 (1): 95-103.
4. Altunışık Bülbül, G.; Gençer, A., 2021b: Determination of ideal cooking conditions for pulp production from avocado wood (*Persea americana* Mill.) by kraft method. Drvna industrija, 72 (4): 411-416. https://doi.org/10.5552/drvind.2021.2048
5. Areo, O. S., 2021: Wood properties and natural durability of *Artocarpus altilis* (Parkinson Ex F. A. Zorn) Fosberg. PhD Thesis, University of Ibadan, Ibadan.
6. Arsad, E., 2011: Physical properties and mechanical strength of acacia mangium wood (*Acacia mangium* Willd.) from industrial forest plantations in South Kalimantan. Jurnal Riset Industri Hasil Hutan, 3 (1): 20-23 (in Indonesian). https://doi.org/10.24111/jrihh.v3i1.1184
7. Bahri, S., 2015: Making pulp from banana stems. Urnal Teknologi Kimia Unimal, 4 (2): 36-50 (in Indonesian).
8. Chowdhury, P.; Hossain, M. K.; Hossain, M. A.; Dutta, S.; Ray, T. K., 2017: Status, wood properties and probable uses of lesser-used species recorded from Sitapahar Reserve Forest of Bangladesh. Indian Forester, 1439 (2): 1241-1248.
9. Carrillo, A.; Garza, M.; Nañez, M. J.; Garza, F.; Foroughbakhch, R.; Sandoval, S., 2011: Physical and mechanical wood properties of 14 timber species from Northeast Mexico. Annals of Forest Science, 68 (4): 675-678. https://doi.org/10.1007/s13595-011-0083-1
10. Damayanti, R.; Dewi, L. M., 2019: Wood anatomy and fiber quality of the least-known timbers belonging to Actinidiaceae from Indonesia. Wood Research Journal, 10 (2): 33-38. https://doi.org/10.51850/wrj.2019.10.2.33-38
11. Deniz, I.; Okan, O. T.; Serdar, B.; Sahin, H. I., 2017: Kraft and modified kraft pulping of bamboo (*Phyllostachys Bambusoides*). Drewno, 60 (200): 79-94.
12. Gençer, A.; Aksoy, H., 2017: Paper production from wild dogwood (*Cornus australis* L.) and the effect of bark on paper properties. Artvin Coruh University Journal of Forestry Faculty, 18 (2): 186-191.
13. Gençer, A.; Özgül, U., 2016: Utilization of common hazelnut (*Corylus avellana* L.) prunings for pulp production. Drvna industrija, 67 (2): 157-162. https://doi.org/10.5552/drind.2016.1529
14. Gençer, A.; Şirin, G.; Gül, H.; Özgül, U., 2013: Determination of the product conditions of pulp and paper from white mulberry (*Morus alba* L.) by kraft method. Journal of Bartin Faculty of Forestry, 15 (1): 63-68.
15. Gülsoy, S. K.; Şimşir, S., 2018: Chemical composition, fiber morphology and kraft pulping of bracken stalks (*Pteridium aquilinum* (L.) Kuhn). Drvna industrija, 69 (1): 23-33. https://doi.org/10.5552/drind.2018.1725
16. Gallichsen, J.; Paulapuro, H., 2000: Papermaking Science and Technology. Helsinki: Finland Papet Oy.
17. Hamdan, H.; Nordahlia, S. S.; Anwar, U. M. K.; Iskandar, M. M.; Omar, M. K. M.; Tumirah, K., 2020: Anatomical, physical and mechanical properties of four pioneer species in Malaysia. Journal of Wood Science, 66 (59): 1-9. https://doi.org/10.1186/s10086-020-01905-z
18. Hedge, N., 2019: Physical and mechanical properties of lesser-known timber species of Mizoram. PhD Thesis, Mizoram University, Aizawl.
19. Hastuti, N.; Efiyanti, E.; Pari, G.; Saepuloh; Setiawan, D., 2017: Chemical components and potential uses of five lesser-known wood species from West Java. Jurnal Penelitian Hasil Hutan, 35 (1): 15-27 (in Indonesian). https://doi.org/10.20886/jphh.2017.35.1.1-13
20. Hidayat, W.; Kim, Y. K.; Jeon, W. S.; Lee, J. H.; Kim, A. R.; Kim, N., 2017: Qualitative and quantitative anatomical characteristics of four tropical wood species from Moluccas, Indonesia. Journal of the Korean Wood Science and Technology, 45 (4): 369-381. https://doi.org/10.5658/WOOD.2017.45.4.369

21. Haroen, W. K., 2006: Variability of tropical broadleaf wood density in terms of fiber, chemical and sulfate pulp characteristics. Jurnal Ilmu dan Teknologi Kayu Tropis, 4 (2): 71-76 (in Indonesian). https://doi.org/10.51850/jitkt.v4i2.281.g254
22. Istikowati, W. T.; Sutya, B.; Sunardi; Ishiguri, F.; Yokota, S., 2019: Anatomical characteristics of terap, medang and balik angin wood from secondary forests in South Kalimantan, Indonesia. Jurnal Hutan Tropis, 7 (2): 172-180 (in Indonesian).
23. Indrawan, D. A.; Efiyanti, L.; Tampubolon, R. M.; Roliadi, H., 2015: Making pulp for wrapping paper from alternative fiber materials. Jurnal Penelitian Hasil Hutan, 33 (4): 283-302 (in Indonesian). https://doi.org/10.20886/jphh.2015.33.4.283-302
24. Jepri, H. C.; Hamzah, F.; Sulaeman, R., 2016: The paper quality of stem palm pulp. Jurnal Online Mahasiswa Fakultas Pertanian Universitas Riau, 3 (2): 1-2 (in Indonesian).
25. Kassim, A. S. M.; Aripin, A. M.; Ishak, N.; Hairom, N. H. H.; Fauzi, N. A.; Razali, N. F.; Zainulabidin, M. H., 2016: Potential of cogon grass (*Imperata cylindrica*) as an alternative fiber in the paper-based industry. ARPN Journal of Engineering and Applied Sciences, 11 (4): 2681-2686.
26. Kasmudjo, 2012: Forest Products Technology. Yogyakarta: Cakrawala Media (in Indonesian).
27. Listya, M. D.; Supartini, S., 2017: Anatomical and Chemical Properties of Keruing Wood from Labanan Research Forest, East Kalimantan. Jurnal Ilmu dan Teknologi Kayu Tropis, 15 (2): 97-109.
28. Lempang, M.; Asdar, M., 2012: Some basic properties and uses of three lesser-known species of wood originating from natural forests in Sulawesi. Jurnal Penelitian Kehutanan Wallacea, 30 (1): 27-39 (in Indonesian). https://doi.org/10.18330/jwallacea.2017.vol6iss2pp157-167
29. Marbun, S. D., Astutiputri, V. F.; Damayanti, R.; Hadisunarso; Trisatya, D. R.; Djarwanto, 2023: Anatomical investigation of five genera of the least-known timber of *Apocynaceae* and their potential utilization. Indonesian Journal of Forestry Research, 10 (1): 75-90. https://doi.org/10.59465/ijfr.2023.10.1.75-90
30. Marbun, S. D.; Wahyudi, I.; Suryana, J.; Nawawi, D. S., 2019: Anatomical structures and fiber quality of four lesser-used wood species grown in Indonesia. Journal of the Korean Wood Science and Technology, 47 (5): 617-632. https://doi.org/10.5658/WOOD.2019.47.5.617
31. Mulyawati, I., 2013: Characteristics of MFA (Microfibril Angle) and fiber at three ages of mangium wood (*Acacia mangium* Willd.). Undergraduate Thesis, Institut Pertanian Bogor, Bogor (IDN) (in Indonesian).
32. Magaton, A. D.; Colodette, J. L.; Gouvêa, A. D. F.; Gomide, J. L.; Gumuet, M. C. D. S.; Pedrazzi, C., 2009: Eucalyptus Wood Quality and its Impact on Kraft Pulp Production and Use. TAPPI Journal, 8 (8): 32-39. https://doi.org/10.32964/TJ8.8.32
33. Purusatama, B. D.; Kim, Y.; Jeon, W. S.; Lee, J.; Kim, A.; Kim, N., 2018: Qualitative anatomical characteristics of compression wood, lateral wood and opposite wood in a stem of *Ginkgo biloba* L. Journal of the Korean Wood Science and Technology, 46 (2): 125-131. https://doi.org/10.5658/WOOD.2018.46.2.12
34. Riki, J. T. B.; Sotannde, O. A.; Oluwadare, A. O., 2019: Anatomical and chemical properties of wood and their practical implications in pulp and paper production: a review. Journal of Research in Forestry, Wildlife and Environment, 11 (3): 358-368.
35. Rizqiani, K. D.; Aprianis, Y.; Junaedi, A., 2019: The potential of three species of Sumatran peat wood as raw materials for pulp and paper. Jurnal Ilmu dan Teknologi Kayu Tropis, 1 (2): 112-121 (in Indonesian). https://doi.org/10.51850/jitkt.v17i2.192
36. Rulliaty, S., 2014: Identification and fiber quality of five species of local wood from West Java and Banten. Jurnal Penelitian Hasil Hutan, 32 (4): 297-312 (in Indonesian). https://doi.org/10.20886/jphh
37. Siam, N. A.; Lipeh, S.; Uyup, M. K. A.; Juhari, M. A. A. A.; Talip, N.; Amri, C. N. A. C.; Abdullah, N. A., 2022: Anatomical and physical properties of three lesser-known timber species from Malaysia. BioResources, 17 (1): 1090-1105. https://doi.org/10.15376/biores.17.1.1090-1105
38. Syafii, W.; Siregar, I. Z., 2016: Chemical properties and dimensions of mangium wood fiber (*Acacia mangium* Willd.). Jurnal Ilmu dan Teknologi Kayu Tropis, 4 (1): 28-32 (in Indonesian).
39. Sable, I.; Grinfelds, U.; Jansons, A.; Vikele, L.; Irbe, I.; Verovkins, A.; Treimanis, A., 2012: Comparison of the properties of wood and pulp fibers from Lodgepole pine (*Pinus contarta*) and Scots pine (*Pinus sylvestris*). BioRecources, 7 (2): 1771-1783.
40. Tutus, A.; Ates, S.; Deniz, I., 2010: Pulp and paper production from spruce wood with kraft and modified kraft methods. African Journal of Biotechnology, 9 (11): 1648-1654.
41. Wahyudi; Makrus M.; Susilo, A. E., 2014: The machining properties of two underutilized speciess of wood from West Papua. Jurnal Ilmu dan Teknologi Kayu Tropis, 2 (1): 78-81 (in Indonesian).
42. Wahyudi, I., 2013: The relationship between the anatomical structure of wood and the properties of wood, its uses and processing. Bogor (IDN): Institut Pertanian Bogor (in Indonesian).
43. Walia, Y. K., 2013: Chemical and physical analysis of *Morus nigra* (black mulberry) for its pulpability. Asian Journal of Advanced Basic Sciences, 1 (1): 40-44.
44. Wheeler, E. A.; Baas, P.; Gasson, E., 2008: IAWA list of microscopic features for hardwood identification. IAWA Bulletin, n. s., 10 (3): 219-332.
45. Yaman, B.; Gencer, A., 2005: Fiber morphology of kiwi (*Actinidia deliciosa* (A. Chev.) C. F. Liang & A. R. Ferguson) grown in Trabzon. Turkish Journal of Forestry, 6 (2): 149-155 (in Turkish).

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Effect of Nail Models and Diameters on Withdrawal Strength of a Tropical Hardwood: A Preliminary Study

Utjecaj modela i promjera čavala na izvlačnu silu u tropskome tvrdom drvu: preliminarno istraživanje

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ABSTRACT • *Nails are a simple and viable solution to connect sections of wooden structures. Although they are the oldest and most traditional connection elements, there is a considerable knowledge gap concerning the use of larger sized, threaded nails, in tropical hardwoods. The objective of this study was to evaluate the effect of different nail models and diameters on the withdrawal strength of Allantoma decandra wood and verify the efficiency of the existing prediction equations of nail withdrawal. Withdrawal tests were carried out using three nail models (smooth, helical, and annular), of two different diameters (2.8 mm and 3.5 mm). For each combination, ten A. decandra wood specimens were used. Four nails were inserted 32 mm into each wood specimen and then withdrawn using a universal testing machine with a 600 kN capacity, according to the procedures of ASTM D143 (2014). The nail model was the most relevant factor in this study, having a direct influence on withdrawal strength. Annular nails presented the highest strength values, followed by helical and smooth nails. The nail diameter had no significant effect on the maximum load result. The equations for withdrawal strength prediction demonstrated considerable accuracy regarding the experimentally obtained data, being important tools to anticipate the behavior of wooden structures.*

KEYWORDS: *nail models; tropical wood; nail diameter; prediction models*

SAŽETAK • *Čavli su jednostavno i održivo rješenje za spajanje dijelova drvnih konstrukcija. Iako su najstariji i najtradicionalniji spojni elementi, postoji velik nedostatak znanja o upotrebi većih, navojnih čavala u tropskim tvrdim vrstama drva. Cilj ove studije bio je procijeniti utjecaj različitih modela i promjera čavala na izvlačnu silu u drvu Allantoma decandra i provjeriti učinkovitost postojećih jednadžbi predviđanja te sile. Ispitivanja izvlačenja provedena su s tri modela čavala (glatkima, spiralnima i prstenastim) dvaju različitih promjera (2,8 i 3,5 mm). Za svaku kombinaciju provedeno je istraživanje na deset uzoraka drva A. decandra. Četiri čavla umetnuta su 32 mm duboko u svaki uzorak drva, a zatim izvučena uz pomoć univerzalnoga ispitnog stroja kapaciteta 600 kN, prema postupcima opisanima normom ASTM D143 (2014). Model čavla bio je najrelevantniji čimbenik u ovom*

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istraživanju i izravno je utjecao na izvlačnu silu. Prstenasti čavli pokazali su najveće vrijednosti izvlačne sile, a zatim su slijedili spiralni i glatki čavli. Promjer čavala nije znatnije utjecao na rezultate izvlačne sile. Jednadžbe za predviđanje izvlačne sile pokazale su prilično veliku točnost s obzirom na eksperimentalno dobivene podatke, što ih čini važnim alatima za predviđanje ponašanja drvnih konstrukcija.

KLJUČNE RIJEČI: *modeli čavala; tropske vrste drva; promjer čavla; modeli predviđanja*

1 INTRODUCTION
1. UVOD

The strength and stability of any structure depend primarily on the connections between its parts. A great advantage of wood as a structural material is the ease with which sections can be joined using a range of different elements (Rammer, 2021). Among these, nails are the oldest and most traditional connection elements (De Paula *et al*., 1988; Ruan *et al.,* 2021). Unlike other connectors such as screws and adhesives, nails are low cost, do not require specific infrastructure to be used, and can be inserted into wood manually or using pneumatic nail guns. Furthermore, they are a simple and viable solution for making connections between sections of wood with low adhesion capacity, especially tropical hardwoods with high density or high presence of extractives (Hosseinzadeh *et al.,* 2022). Recently developed, the nail cross-laminated timber (NCLT) is a kind of engineered wood products that can be used for structural purpose, whose bear capacity and strength mainly relies on the nail withdrawal strength. Further information regarding NCLT can be found in Hosseinzadeh *et al.* (2022) and Pang *et al.* (2017).

Nail withdrawal strength is directly related to the tree species, wood density, nail diameter and insertion depth (Rammer and Zelinka, 2004; Mahdavifar *et al.*, 2018; Kim, 2021). The most used nails are the smooth-shank nails, which resist withdrawal forces due to the friction force between the wood fibers and the nail shaft. Friction forces have their maximum point immediately after nail insertion, but over time, the wood fibers relax with a consequent loss of withdrawal strength (Rammer, 2001). This effect may be increased if the wood is exposed to constant drying and soaking processes (Rammer and Mendez, 2008). Gahagan and Scholten (1938) recorded a 57 % decrease in nail withdrawal strength 105 days after the nails were driven into the wood specimens.

Over time, different sizes and shapes of nails were tested with the aim of improving performance and withdrawal strength (Theilen *et al.,* 1998). The application of helical or annular threads, by compression, onto the nail shafts is one of the developed technologies (Wills *et al.,* 1996; Luszcki *et al.,* 2013). Helical nails were originally developed to facilitate the insertion in high-density woods. Their threads are typically aligned at angles between 30° and 70° to the axis and therefore tend to rotate during insertion (like screws), causing less damage to the adjacent wood fibers (Rammer *et al.,* 2001). On the other hand, annular nails were developed with the specific purpose of increasing their withdrawal strength, and their threads are aligned perpendicular to the axis, at angles of approximately 90° (Skulteti *et al.,* 1997).

Unlike smooth-shank nails, which resist withdrawal merely by the friction forces between the wood fibers and the shaft, threaded nails also have mechanical strength, as during their insertion the wood fibers enchase between the crests of the threads (Luszcki *et al.,* 2013). To withdraw a helical or annular nail, it is necessary to tear the wood fibers, which requires a greater force than that of smooth-shank nails of the same dimensions (Skulteti *et al.,* 1997; Rammer *et al.,* 2001; Skulteti *et al.,* 2013). Threaded nails are ideal for situations of extreme load and adverse moisture conditions, as the relaxation and contractions of the fibers have less effect on their strength (Wills *et al.,* 1996; Rammer *et al.,* 2001). On the other hand, the presence of threads on the nail shaft requires 15 % more energy for insertion into wood (Ogurinde *et al.,* 2019). Furthermore, the deformations applied to create the threads result in slightly smaller diameters compared to smooth-shank nails of the same size (Wills *et al.,* 1996).

Due to the recent increase of environmental awareness and the ability of wood to embed carbon, timber constructions have emerged worldwide as an alternative for mitigating climate change while acting as a limitless carbon sink (Wang *et al.,* 2021; Ahn *et al.,* 2021; Abdoli *et al.,* 2022). This resumption and appreciation of wooden buildings, which has been called the mass timber construction movement, is based on various wood engineered products and building technologies, such as glued laminated timber (glulam), cross laminated timber (CLT), wood-frame and post-frame, (Ahn *et al.,* 2021; Kim, 2021). Despite a high level of prefabrication of their components, all these techniques use and depend on metallic connection elements, such as nails. Most research has focused on smooth-shank nails, with small diameters, tested in coniferous wood species from temperate zones (Wills *et al.,* 1996).

Nowadays, available data regarding nail withdrawal strength for tropical hardwoods is still scarce. Specifically, in Brazil the first study was made by De Paula *et al.* (1988) who evaluated and the nail withdrawal strength of nine high density Amazonian tropical hardwoods. Recently, Ribeiro *et al.* (2018) determined only the screw withdrawal load for five hardwoods ranging from low to high density. Therefore, there is a considerable knowledge gap regarding the use of larger sized, threaded (helical and annular) nails in tropical hardwoods.

Furthermore, several authors and institutions developed model design equations to predict the withdrawal performance of smooth and threaded nails. The equations are based on wood density, nail diameter and depth of insertion, and while some authors developed exclusive equations for each nail model (Ehlbeck and Siebert, 1988; Rammer *et al.,* 2001), others suggest the use of the same equation for more multiple models (Blass and Uibel, 2007; AWC, 2018; Rammer, 2021). Although the equations were developed based on a restricted and specific dataset, they may be important tools to anticipate the behavior of wooden structures.

In this context, the objective of this study was to evaluate the effect of different nail models and diameters on the withdrawal strength of *Allantoma decandra* wood, and verify the efficiency of the existing prediction equations of nail withdrawal regarding the experimental results. *A. decandra,* which is native to the Amazon Forest, has no legal logging restrictions and has been explored in sustainable forest management projects (SFB, 2023).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Wood material and test setup
2.1. Drvni materijali i postavka ispitivanja

The tests were carried out utilizing wood specimens obtained from ten trees identified as *A. decandra* (Ducke) S. A. Mori, Y. Y. Huang & Prance. The specie belongs to the Lecythidaceae family, and its wood has a specific gravity of approximately 0.57 g/cm^3, which had been previously evaluated by Pimentel *et al.* (2021). The specimens were produced from clear wood (i.e., free from knots, cracks, frays, etc.) and were deposited in an acclimatization room with controlled temperature and humidity (20±3) °C and (65±1) %, until moisture content stabilization (±12 %). For theoretical testing purposes, the volume and mass of the specimens was also calculated at 0 % moisture content (oven dry).

Three nail models (smooth, helical, and annular) of two different diameters (2.8 mm and 3.5 mm) were tested, totalling six model/diameter combinations (Figure 1). To avoid material variation, all nails used in this study were produced by the same manufacturer (Gerdau S.A., Brazil). The withdrawal test was performed according to the procedures of ASTM D143 (2014). This way, for each combination, ten 50 mm × 50 mm × 150 mm (width, depth, and length) specimens were used. Two nails were driven on the radial face and two on the tangential face of the specimen, maintaining a minimum distance of 19 mm from the sides, 38 mm from the ends and 50 mm between the nails, while avoiding alignment. The nails were driven at right angles to the face of the specimen to a total penetration of 32 mm. All 240 nails (40 repetitions per combination) were withdrawn within a maximum one-hour period after insertion. A universal testing machine with a 600 kN capacity (Martins Campelo Testing Systems, Brazil) was used to carry out the tests at a speed rate of 2 mm/minute. Additionally, some physical and mechanical properties of the wood were also evaluated according to this same standard.

Figure 1 Nails used in withdrawal tests: smooth, helical, and annular with 2.8 mm and 3.5 mm of diameter, respectively
Slika 1. Čavli upotrijebljeni u testovima izvlačenja: glatki, spiralni i prstenasti, promjera 2,8 i 3,5 mm

2.2 Statistical and experimental analyses
2.2. Statističke i eksperimentalne analize

The experimental design consisted of six combinations of nail models and diameters. First of all, an analysis of variance (ANOVA) at 5 % significance was performed to evaluate the statistical difference between the maximum supported loads obtained by the radial and tangential faces. Next, a factor analysis of variance (Two-way ANOVA) at 5 % significance was performed to evaluate the most efficient model/diameter combination and the effect of each factor on the maximum supported loads. All analyses were executed using the IBM SPSS software. To verify the efficiency of the prediction equations of nail withdrawal presented by several authors (Table 1), the maximum loads for each nail model/diameter combination were calculated and then compared to the results obtained experimentally.

The American Wood Council (AWC, 2018) and the Forest Products Laboratory (Rammer, 2021) developed specific equations for smooth-shank and annular nails. Due to the absence of studies, both institutions suggest the use of smooth-shank nail equations to pre-

Table 1 Prediction equations of nail withdrawal strength
Tablica 1. Jednadžbe predviđanja izvlačne sile čavala

Nail shank model *Vrsta čavla*	Equation *Jednadžba*	Unit *Jedinica*	Authors *Autori*
Smooth *glatki*	$W = 1380\ G^{5/2}\ D\ L$	LB	AWC (2018)
	$W = 54{,}12\ G^{5/2}\ D\ L$	N	Rammer (2021)
Helical *spiralni*	$W = 36 \cdot 10^{-2}\ G^2\ D\ L$	N	Ehlbeck and Siebert (1988)
	$W = 29{,}6\ G^{1{,}28}\ D\ L$	N	Rammer *et al.* (2001)
	$W = 0{,}117\ D^{0{,}6}\ L\ G^{0{,}8}$	N	Blass and Uibel (2007)
	$W = 1380\ G^{5/2}\ D\ L$	N	AWC (2018)
	$W = 54{,}12\ G^{5/2}\ D\ L$	N	Rammer (2021)
Annular *prstenasti*	$W = 42{,}8\ G^{1.38}\ D\ L$	N	Rammer *et al.* (2001)
	$W = 0{,}117\ D^{0{,}6}\ L\ G^{0{,}8}$	N	Blass and Uibel (2007)
	$W = 1800\ G^2\ D\ L$	LB	AWC (2018)
	$W = 77{,}57\ G^2\ D\ L$	N	Rammer (2021)

**W* – maximum load; *G* – wood density; *D* – nail diameter; *L* – depth of insertion of the nail
**W – maksimalna sila; G – gustoća drva; D – promjer čavla; L – dubina umetanja čavla*

Table 2 Mean values and coefficients of variation (*CV*) of some physical and mechanical properties of *A. decandra* wood
Tablica 2. Srednje vrijednosti i koeficijenti varijacije (*CV*) nekih fizičkih i mehaničkih svojstava drva *A. decandra*

Property *Svojstvo*	Unit *Jedinica*	Mean value *Srednja vrijednost*	*CV*, %
ρ_{12}	g/cm^3	0.7	7.8
ε_1	%	5.4	11.2
ε_2	%	7.5	12.5
ΔV	%	12.8	11.3
AC	-	1.4	8.4
f_M	MPa	115.6	7.4
E_{M0}	MPa	13817.0	12.5
$f_{v,0}$	MPa	11.0	13.6
$f_{c,0}$	MPa	54.2	9.6
$f_{c,90}$	MPa	9.7	13.3

ρ_{12} – 12 % density; ε_1 – radial shrinkage; ε_2 – tangential shrinkage; ΔV – volumetric shrinkage; AC – anisotropic coefficient; f_M – bending strength; E_{M0} – bending stiffness; $f_{v,0}$ – shear strength; $f_{c,0}$ – parallel compression strength; $f_{c,90}$ – perpendicular compression strength
ρ_{12} – gustoća od 12 %; ε_1 – radijalno utezanje; ε_2 – tangentno utezanje; ΔV – volumno utezanje; AC – koeficijent anizotropnosti; f_M – čvrstoća na savijanje; E_{M0} – krutost pri savijanju; $f_{v,0}$ – smična čvrstoća; $f_{c,0}$ – čvrstoća na tlak paralelno s vlakancima; $f_{c,90}$ – čvrstoća na tlak okomito na vlakanca

dict the withdrawal strength of helical nails. Blass and Uibel (2007) developed a single equation for both helical and annular nails. The equations proposed by Rammer (2021) use wood specific gravity based on oven dry weight and 12 % moisture content volume. All other authors use specific gravity values based on oven dry weight and volume. The values predicted by the AWC equations represent the maximum strength load divided by five to adjust to test conditions, safety, and load duration.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Table 2 presents some physical and mechanical properties obtained for *A. decandra* wood. According to the values presented, the wood showed radial, tangential, and volumetric shrinkages of 5.4 %, 7.5 %, and 12.8 %, respectively. According to Melo and Camargos (2016), the value of 12.8 % classifies the wood as having medium shrinkage. The anisotropic coefficient (ratio between tangential and radial shrinkage) calculated was 1.4, which, according to Durlo and Marchiori (1992), classifies it as having excellent dimensional stability. As presented in Table 2, the average values of the mechanical properties obtained were similar to those found in the Tropical Woods Database (LPF, 2022) for *Allantoma lineata* and *Couratari guianensis*, the two most exploited species of the Lecythidaceae family in Brazil (SFB, 2022). By analogy, the same uses cited by Melo and Camargos (2016) for the aforementioned species can be indicated for *A. decandra* wood: light structural uses, furniture, frames, musical instruments, household utensils, boats, packaging, linings, tool handles, barrels, and cladding.

Table 3 shows the maximum withdrawal strength load and coefficient of variation obtained by the six model/diameter nail combinations tested on *A. decandra* wood. The maximum nail withdrawal strength loads were initially analyzed separating the data obtained by the radial and tangential faces. For all nail models and dimensions, the tangential faces showed

Table 3 Maximum withdrawal strength loads and coefficients of variation (*CV*) obtained by six model/diameter nail combinations tested on *A. decandra* wood
Tablica 3. Maksimalne sile izvlačenja i koeficijenti varijacije (*CV*) dobiveni za šest kombinacija modela i promjera čavala testiranih u drvu *A. decandra*

Model/Diameter *Model/promjer*	**Maximum load, N** *Najveća sila,* N	***CV*, %**
Smooth/*glatki* 2.8 mm	1039.70 a	15.7
Smooth/*glatki* 3.5 mm	1088.32 a	19.7
Helical/*spiralni* 2.8 mm	1330.10 b	26.8
Helical/*spiralni* 3.5 mm	1557.32 b	23.5
Annular/*prstenasti* 2.8 mm	2050.09 c	24.3
Annular/*prstenasti* 3.5 mm	2244.55 c	25.4

Means followed by the same letter do not differ statistically from each other at 5% significance.
Srednje vrijednosti iza kojih slijedi isto slovo statistički se međusobno ne razlikuju, uz 5 % značajnosti.

greater withdrawal strength than the radial faces, which can be explained by the higher number of dense parenchyma layers crossed by the nails (Taj *et al.,* 2009). In this direction, there is greater interaction between the wood tissues and the nails, resulting in greater withdrawal strength and consequently greater damage to the wood surface (Abdoli *et al.,* 2022). However, after applying ANOVA, no statistically significant difference was found between the results obtained for the radial and tangential faces. As this observation had already been made by other authors in similar experiments (Aytekin, 2008; Teng *et al.,* 2018), it was decided to analyze the data jointly, as shown in Table 3.

The scientific literature on nails indicates a positive correlation between diameter and withdrawal strength (Gehloff, 2011; Mahdavifar, 2018; Ceylan and Girgin, 2020; Li, 2021). In this study, the increase in nail diameter generated an increase of 5 %, 17 % and 9.5 % in withdrawal strength for smooth, helical, and annular nails, respectively. However, the two-way ANOVA analysis showed that only the models had a significant effect at a 95 % confidence ($P < 0.05$), with no statistically significant difference between the means of different diameters of the same nail model.

As expected, annular nails showed the highest withdrawal strength value (2147 N), followed by helical nail (1443 N), while smooth nails had the lowest value (1064 N). As mentioned previously, smooth-shank nails resist withdrawal forces due to the friction force between the wood fibers and the nail shaft, while threaded nails also have mechanical strength, as during their insertion the wood fibers enchase between the crests of the threads (Luszcki *et al.,* 2013). This way, to withdraw these kinds of nails, a greater force is required in order to additionally tear the wood fibers (Skulteti *et al.,* 1997; Rammer *et al.,* 2001).

In accordance with data found in literature (Blass and Uibel, 2004), helical nails showed a strength increase of approximately 30 % to 40 % (according to nail diameter). Annular nails presented the highest withdrawal strength, being approximately twice the value presented by smooth-shank nails of the same diameter. This result is consistent with data presented by Skulteti *et al.* (1997) and Rammer (2021).

The values determined for the coefficients of variation ranged between 15 % and 27 %. Despite being high, they are considered satisfactory for nail withdrawal tests as the manual insertion of the nails is subject to operator-caused variations. Nevertheless, the CV values presented lower variations than those obtained by Rammer *et al.* (2001) for the same three nail models: annular = 17 % to 32 %, helical = 12 % to 41 % and smooth = 22 % to 48 %. In addition to the maximum load values, the behavior of the different types of nails tested can also be explained through the curves formed by the displacement × load graphs (Figure 2) and wood failure modes (Figure 3).

According to Li *et al.* (2021), nail withdrawal causes various levels of stress at the interface between the threads and the wood components, leading to a combination of shear and traction of the fibers. Due to static friction, during the initial stage of the test, the smooth-shank nails present a linear behavior between displacement and load. After the maximum strength is reached, the static friction is overcome, and the graph shows a sudden drop. From this moment on, strength depends only on the dynamic friction, which continues losing strength until the nail is completely withdrawn. As the insertion of smooth-shank nails occurs exclusively by the separation of the wood fibers, their withdrawal occurs without causing major damage to the wood specimen (Figure 3A).

As mentioned by Rammer (2021), all the equations for nail-withdrawal resistance indicate that density has a great influence on the nail withdrawal strength, and therefore, denser wood species usually require higher withdrawal loads in comparison with lower density ones. Nevertheless, these lighter wood species should not be disqualified for uses requiring high resistance to withdrawal, since they do not suffer from cracks as expected for denser ones, which can be an opportunity for increasing the diameter, length, and number of the nails to counterbalance its lower nail withdrawal resistance. It is assumed that it can happen for any type of nail.

Although helical nails tend to rotate around their axis during insertion into wood, the rotating movement does not occur during withdrawal, and therefore, the

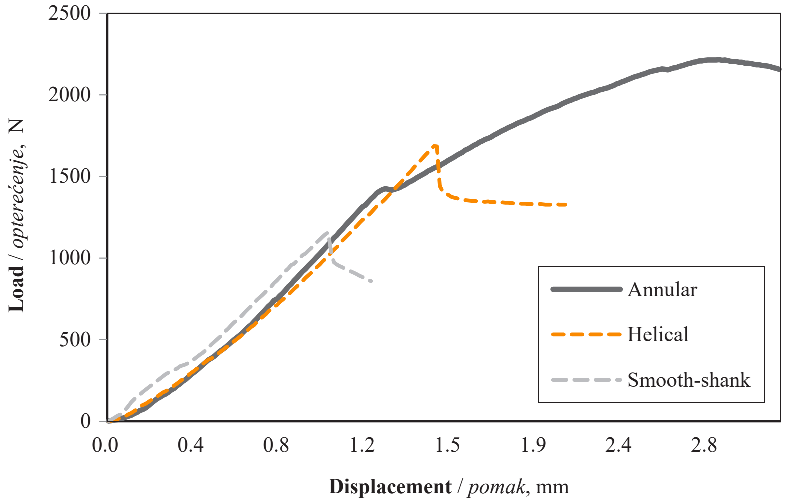

Figure 2 Typical displacement × load graphs for threaded and smooth-shank nails during withdrawal
Slika 2. Tipični grafovi pomaka i opterećenja za spiralne, prstenaste i glatke čavle tijekom izvlačenja

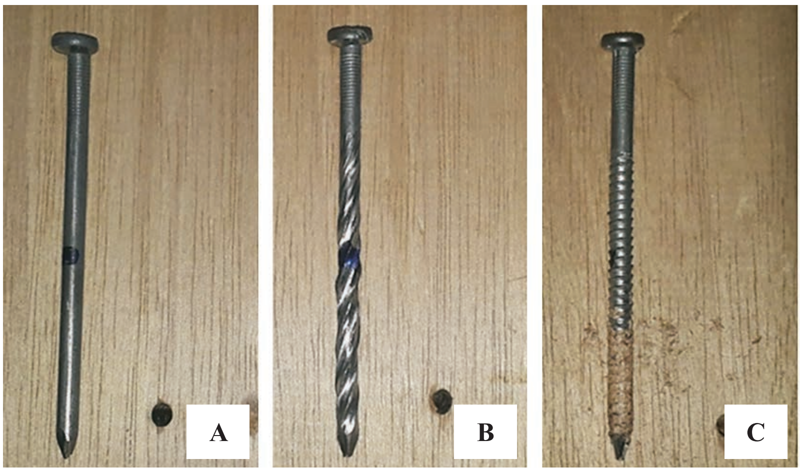

Figure 3 Typical modes of wood failure after nail withdrawal: A) smooth-shank nails cause minimal damage to the wood; B) helical nails withdraw small amounts of wood fibers; C) annular nails extract a column of wood fiber fragments adhered to its threads
Slika 3. Tipični načini loma drva nakon izvlačenja čavala: A) glatki čavli uzrokuju minimalna oštećenja drva; B) spiralni čavli izvlače male količine drvnih vlakana; C) prstenasti čavli izvlače stupac fragmenata drvnih vlakana prilijepljenih za njegove navoje

threads increase the friction surface of nails, ensuring prolonged strength, which allows higher maximum loads than smooth nails (Luszcki *et al.,* 2013). After reaching maximum load during the tests, helical nails present a sudden drop and then a tendency to stabilize. During this moment, the threads still exert dynamic friction against wood fibers, and the connection is still capable of resisting considerable load while the nail is detached from the wood. As can be seen in Figure 3B, the withdrawal of helical nails causes the tearing of small portions of wood fiber.

In general, annular nails exhibit initial linear elastic behavior, provided by the mechanical strength of the wood fibers lodged between the threads. As the fibers begin to tear, the graphs assume a non-linear (inelastic) behavior until they reach the maximum load values. After the peak, the load decreases quickly, as the wood fibers are cut, pulled out and brought to the surface in the form of a column of fragments adhered to the nail shaft (Figure 3C). From this moment on, strength is only due to friction, being similar to the behavior shown by smooth nails (Luszcki *et al.,* 2013; Ceylan *et al.,* 2019).

Based on the wood density of *A. decandra*, nail diameters and nail insertion depth, maximum loads of withdrawal strength for the six combinations model/diameter of nails were estimated using the equations found in the specialized literature (Table 4).

The AWC (2018) and Rammer's (2021) equations overestimated the maximum withdrawal loads of the 2.8 mm and 3.5 mm smooth nails by approximately 30 and 60 %, respectively. All the equations tested for

Table 4 Maximum load values (N) obtained experimentally and estimated by equations for each combination of nail model/diameter
Tablica 4. Maksimalne vrijednosti sile (N) dobivene eksperimentalno i procijenjene jednadžbama za svaku kombinaciju modela i promjera čavla

Nail models *Model čavla*	Experimental values, N *Eksperimentalne vrijednosti,* N	Ehlbeck and Siebert (1988)	Rammer *et al.* (2001)	Blass and Uibel (2007)	AWC (2018)	Rammer (2021)
Smooth *glatki* 2.8 mm	1040	-	-	-	1452	1359
					(+40 %)	(+31 %)
Smooth *glatki* 3.5 mm	1088	-	-	-	1815	1762
					(+67 %)	(+62 %)
Helical *spiralni* 2.8 mm	1330	1363	1528	1236	1452	1359
		(+2 %)	(+15 %)	(-6 %)	(+9 %)	(+2 %)
Helical *spiralni* 3.5 mm	1557	1704	1910	1413	1815	1762
		(+9 %)	(+23 %)	(-9 %)	(+17 %)	(+13 %)
Annular *prstenasti* 2.8 mm	2050	-	2116	1236	2344	2936
			(+3 %)	(-40 %)	(+14 %)	(+43 %)
Annular *prstenasti* 3.5 mm	2245	-	2645	1413	2941	3671
			(+18 %)	(-37 %)	(+31 %)	(+64 %)

The values in parentheses (%) refer to the difference between the estimated values and those observed experimentally.
Vrijednosti u zagradama (%) odnose se na razliku između procijenjenih i eksperimentalno dobivenih vrijednosti.

helical nails showed results close to those obtained experimentally, especially the equation by Blass and Uibel (2007), which underestimated the maximum load by 6 % for 2.8 mm nails and approximately 9 % for 3.5 mm nails. To predict the maximum strength load of annular nails, the most precise equation was that of Rammer *et al.* (2001), which overestimated the withdrawal strength by approximately 3 % and 18 % for 2.8 mm and 3.5 mm nails, respectively. It is important to note that, for structural project calculation, it is more appropriate to use equations that underestimate the strength values, increasing the project's safety margin, than the opposite. Therefore, the equation by Blass and Uibel (2007) can be considered the most suitable.

4 CONCLUSIONS
4. ZAKLJUČAK

In this study three nail models and two nail diameters were evaluated, and it was found that the nail model was the most relevant factor, having a direct influence on withdrawal strength, while the nail diameter had no significant effect. It was also found that there was no statistically significant difference between the results of withdrawal load for the radial and tangential faces. Annular nails presented the highest strength values, followed by helical and smooth nails. The five evaluated equations to predict the withdrawal strength demonstrated considerable accuracy regarding the experimentally obtained data, being important tools to anticipate the behavior of wooden structures. Nevertheless, the predictability was different between nail models, and the values of withdrawal strength for smooth and annular nails were overestimated, while for helical nails the models were more precise presenting a slight underestimation. It can be concluded that this tropical hardwood can be used for structural purposes or to manufacture forest products that need to be nailed.

5 REFERENCES
5. LITERATURA

1. Abdoli, F.; Rashidi, M.; Rostampour-Haftkhani, A.; Layeghi, M.; Ebrahimi, G., 2022: Withdrawal performance of nails and screws in cross-laminated Timber (CLT) made of poplar (*Populus alba*) and Fir (*Abies alba*). Polymers, 14 (15): 3129. https://doi.org/10.3390/polym14153129
2. Ahn, K. S.; Pang, S. J.; Oh, J. K., 2021: Prediction of withdrawal resistance of single screw on Korean wood products. Journal of the Korean Wood Science and Technology, 49 (1): 93-102. https://doi.org/10.5658/WOOD.2021.49.1.93
3. Aytekin, A., 2008: Determination of screw and nail withdrawal resistance of some important wood species. International Journal of Molecular Sciences, 9 (4): 626-637. https://doi.org/10.3390/ijms9040626
4. Blass, H. J.; Uibel, T., 2007: Tragfähigkeit von stiftförmigen Verbindungsmitteln in Brettsperrholz, Karlsruher Berichte zum Ingenieurholzbau, Karlsruhe, Germany.
5. Ceylan, A.; Girgin, Z. C., 2020: Comparisons on withdrawal resistance of resin and phosphate coated annular ring nails in CLT specimens. Construction and Building Materials, 238: 117742. https://doi.org/10.1016/j.conbuildmat.2019.117742
6. De Paula, E. M.; Rocha, J. S.; Nascimento, C. C. 1988: Extração de pregos em madeiras da Amazonia. Acta Amazonica, 18 (3-4): 243-253.

7. Durlo, M. A.; Marchiori, J. N. C., 1992: Tecnologia da madeira: retratibilidade. Série técnica, 10. Santa Maria: CEPEF/FATEC.
8. Ehlbeck, J.; Siebert, T. W., 1988: Axially loaded nails: Proposals for supplement to the CIB code, Int. Council Build. Res. Studies Documentation Working Commission W18A-Timber Struct. CIB-W18A/21-7-5, Universität Karlsruhe, Germany.
9. Gahagan, J. M.; Scholten, J. A., 1938: Resistance of Wood to the Withdrawal of Nails. USDA Forest Service, Forest Products Laboratory, Madison, WI.
10. Gehloff, M., 2011: Pull-Out Resistance of Self-Tapping Wood Screws with Continuous Thread. University of British Columbia: Vancouver, BC, Canada.
11. Hosseinzadeh, S.; Mohebby, B.; ElyasiI, M., 2022: Bending performances and rolling shear strength of nail-cross-laminated timber. Wood Material Science and Engineering, 17 (2): 113-120. https://doi.org/10.1080/17480272.2020.1800089
12. Kim, K., 2021: Predicting nail withdrawal resistance and bearing strength of cross-laminated timbers from mixed species. BioResources, 16 (2): 4027-4038.
13. Li, X.; Ashraf, M.; Subhani, M.; Ghabraie, K.; Li, H.; Kremer, P., 2021: Withdrawal resistance of self-tapping screws inserted on the narrow face of cross laminated timber made from Radiata Pine. Structures, 31: 1130-1140. https://doi.org/10.1016/j.istruc.2021.02.042
14. Luszcki, G. E.; Clapp, J. D.; Davids, W. G.; Lopez-Anido, R., 2013: Withdrawal capacity of plain, annular shank and helical shank nail fasteners in Spruce-Pine-Fir lumber. Forest Products Journal, 63 (5-6): 213-220.
15. Mahdavifar, V.; Sinha, A., Barbosa, A.; Muszynski, L.; Gupta, R., 2018: Lateral and withdrawal capacity of fasteners on hybrid cross-laminated timber panels. Journal of Materials in Civil Engineering, 30 (9): 04018226. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002432
16. Melo, J. E.; Camargos, J. A., 2016: A madeira e seus usos. Brasília: SFB/LPF/MMA, p. 228.
17. Ogurinde, O.; Gong, M.; Chui, Y. H.; Li, L., 2019: Flexural properties of downscaled dowel-type-fastener laminated timber. International Journal of Scientific Research in Multidisciplinary Studies, 5 (11): 98-104.
18. Pang, S. J.; Kim, K. M.; Park, S. H.; Lee, S. J., 2017: Bending behavior of nailed-jointed cross-laminated timber loaded perpendicular to plane. Journal of the Korean Wood Science and Technology, 45 (6): 728-736. https://doi.org/10.5658/WOOD.2017.45.6.728
19. Pimentel, T. S.; Wimmer, P.; Carvalho, H. R.; Roitman, L.; Del Menezzi, C. H. S., 2021: Resistência ao cisalhamento da linha de cola em madeiras tropicais amazônicas. Scientia Forestalis, 49 (132): e3753. https://doi.org/10.18671/scifor.v49n132.19
20. Rammer, D. R.; Winistorfer, S. G.; Bender, D. A., 2001: Withdrawal strength of threaded nails. Journal of Structural Engineering, 127 (4): 442-449. https://doi.org/10.1061/(ASCE)0733-9445(2001)127:4(442)
21. Rammer, D. R.; Zelinka, S. L., 2004: Review of end grain nail withdrawal research. Gen. Tech. Rep. FPL-GTR-151. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, p. 28.
22. Rammer, D. R.; Mendez, A. M., 2008: Withdrawal strength of bright and galvanized annularly threaded nails. Frame Building News, 59-67.
23. Rammer, D., 2021: Wood Handbook: Wood as an engineering material, Chapter 8 Fastenings Contents. General technical report FPL-GTR- 190, ed. R. J. Ross, U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.
24. Ribeiro, M. L.; Del Menezzi, C. H. S; Siqueira, M. L.; Melo, R. R., 2018: Effect of wood density and screw length on the withdrawal resistance of tropical wood. Nativa, 6 (4): 402-406. http://dx.doi.org/10.31413/nativa.v6i4.5638
25. Ruan, G.; Filz, I.; Günther, H.; Fink, G., 2021: Shear capacity of timber-to-timber connections using wooden nails. Wood Material Science and Engineering, 17 (1): 20-29. https://doi.org/10.1080/17480272.2021.1964595
26. Skulteti, M. J.; Bender, D. A.; Winstorfer, S. G.; Pollock, D. G., 1997: Withdrawal strength of ring-shank nails embedded in southern pine lumber. Transactions of the ASAE, 40 (2): 451-456.
27. Taj, M. A.; Najafi, S. K.; Ebrahimi, G., 2009: Withdrawal and lateral resistance of wood screw in beech, hornbeam and poplar. European Journal of Wood and Wood Products, 67 (1): 135-140. https://doi.org/10.1007/s00107-008-0294-9
28. Teng, Q.; Que, Z.; Li, Z.; Zhang, X., 2018: Effect of installed angle on the withdrawal capacity of self-tapping screws and nails. In: Proceedings of the World Conference of Timber Engineering, Seoul, Korea, 20-23 August.
29. Theilen, R. D.; Bender, D. A.; Pollock, D.; Winistorfer, S. G., 1998: Lateral resistance of ring-shank nail connections in southern pine lumber. Faculty publications – Department of Mechanical and Civil Engineering. Paper 32.
30. Wang, Y.; Lian, W.; Benjeddou, O., 2021: Experimental and numerical investigation on withdrawal connectors usage for lateral resistance of timber shear wall's structure. Journal of Building Engineering, 44: 103266. https://doi.org/10.1016/j.jobe.2021.103266
31. Wills, B. L.; Winistorfer, S. G.; Bender, D. A.; Pollock, D. G., 1996: Threaded-nail fasteners – Research and standardization needs. Transactions of the ASAE, 39 (2): 661-668.
32. ***American Society for Testing and Materials. ASTM D-143, 2000: Standard Test Methods for small clear specimens of timber. West Conshohocken.
33. ***American Wood Council (AWC), 2018: National Design Specification for Wood Construction with Commentary 2018 Edition. Leesburg, VA 20175.
34. ***Laboratório de Produtos Florestais – LPF – Banco de Dados de Madeiras Brasileiras. https://lpf.florestal.gov.br/pt-br/bd-madeiras-brasileiras (Accessed: Sep. 19, 2022).
35. ***Serviço Florestal Brasileiro – SFB, 2022: Sistema de Cadeia de Custódia.

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Fuelwood Production in the Form of Discs

Proizvodnja ogrjevnog drva u obliku diskova

SHORT NOTE
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ABSTRACT • *The proposed method comprises a small-scale production of fuelwood from felled and delimbed tree trunks in private households by slicing them into roundwood discs. The time consumption of this method was compared to that of the traditional method, which consists of cutting roundwood into log sections that are subsequently split into split billets. Production of fuelwood by the novel method was 2.2 times faster compared to the traditional method. The reason for the higher productivity of the novel method is the smaller number of operations. The application of this pioneering approach resulted in a 25 % lower fuelwood production cost, if compared to the commonly applied practice.*

KEYWORDS: *fuelwood production; chronometry; roundwood; fuelwood discs*

SAŽETAK • *Metoda predložena u priopćenju obuhvaća proizvodnju ogrjevnog drva u malom opsegu – od posječenih debala bez grana u privatnim kućanstvima piljenjem na diskove. Utrošak vremena za tu metodu uspoređen je s utroškom vremena tradicionalne metode koja obuhvaća piljenje oblovine na dijelove trupaca koji se potom cijepaju na cjepanice. Proizvodnja ogrjevnog drva novom metodom pokazala se 2,2 puta bržom od tradicionalne metode. Razlog veće produktivnosti nove metode jest manji broj operacija. Primjena tog pionirskog pristupa rezultirala je 25 % nižim troškovima proizvodnje ogrjevnog drva u usporedbi s troškovima u uobičajenoj praksi.*

KLJUČNE RIJEČI: *proizvodnja ogrjevnog drva; kronometrija; oblovina; diskovi ogrjevnog drva*

1 INTRODUCTION
1. UVOD

Nowadays wood as a fuel is an important energy source (Mydlarz and Wieruszewski, 2024; Anselmino *et al*., 2025; Bont *et al*., 2025). Wood can serve as a substitute for fossil fuels as an energy carrier (Schulze *et al*., 2022). To fulfil the ambitious task of reducing greenhouse gas emissions in Estonia, it is substantially significant to expand the application of fuelwood as a renewable energy source (Padari *et al*., 2023).

There are many technical solutions for producing fuelwood. The applications range from traditional methods where roundwood is sawn into log sections and split into billets with an axe afterwards, to more advanced semi-automatically operating technologies that perform both tasks simultaneously (Manzone and Spinelli, 2014). Technically more advanced solutions

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enable higher productivity (Lindroos, 2008) but are more expensive, requiring large production volumes to assure cost effectiveness (Kärhä and Jouhiaho, 2009). For example, a study conducted in Latvia revealed that cutting grey alder stand was faster with machine-cutting method but economically more effective when cut manually (Liepinš *et al*., 2015). According to Moradpour *et al*. (2016), optimization of wood cutting conditions can lead to the decrease of relevant cutting forces, which is ultimately related to the energy consumption.

Slicing roundwood into fuelwood discs on the felling site enables avoiding most of the lifting operations that are needed in the traditional split billet making with chainsaw and axe. The discs must be lifted only twice: first, when loading onto a vehicle, and second, when unloading from the vehicle to woodshed for drying. In traditional fuelwood production, where logs are cut into lengths suitable for splitting, the wood is typically lifted four times: first, when loading the logs onto the truck; second, when unloading them for splitting; third, when placing them onto the splitting block; and fourth, when stacking the split fuelwood. Each lifting operation adds time to the process. Additional time is also required during splitting, as sections of larger logs often need to be repositioned on the splitting block multiple times.

In the process of preparing small quantities of fuelwood, it is also important to consider the time required for loading and unloading the wood. Therefore, one of the objectives of this study was to investigate whether different preparation methods affect the speed of manual loading and unloading, as the shape of fuelwood pieces is different depending on the preparation method used.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

To determine whether cutting grey alder (*Alnus Incana* (L.) Moench) roundwood into fuelwood discs offers a time-saving advantage compared to the traditional method of sawing similar roundwood into billet-length sections and splitting them with an axe, a comparative chronometry experiment was conducted. The experiment was carried out at a forest felling site. For time measurement, sections of already felled and delimbed tree trunks (logs) were used.

To ensure comparable conditions for both test materials, the same chainsaw − a Stihl 023 with a power output of 1.9 kW and the width of the chainsaw chain of 7 mm − was used for cutting in both methods. The saw chain was sharpened in the same manner prior to applying each method. During the work process, no rapid dulling of the chain occurred; the chain did not come into contact with soil, metal, stones, or any other materials that could have significantly reduced its sharpness and remained sharp after processing the entire volume of roundwood.

To avoid contact between the saw chain and abrasive soil particles splashed onto the tree stems from the ground during rainfall, the stems used in the experiment were felled at least one meter above the root collar. The chainsaw air filter was cleaned before the start of the experiment, and its cleanliness was checked during each refuelling break to prevent any loss of engine power due to filter clogging during the test work. A special fuel for 2-stroke engines (*Aspen* 2) and chain oil (*Stihl ForestPlus*) were used in processing both woodlots in the chronometry test.

The quantities of fuelwood produced using both methods were similar in the experiment, but inevitably not identical, as the stems used varied in length and diameter. However, since the comparison focused on the time spent per unit of volume, the amounts of produced fuelwood did not need to be exactly the same. For both methods, long logs (stem sections) of similar diameter and length were selected. All the trees used in the experiment grew in close proximity within the same forest subcompartment and were of the same age and height. The proposed method involved sawing roundwood into 10 cm thick discs (Figure 1).

The traditional method consisted of sawing roundwood into 30 cm long log sections, splitting them into fuelwood billets on the same tree stump in the forest. 30 cm long log sections with a diameter greater than 20 cm were split into four billets (pieces), while those of 20 cm or less in diameter were split into two. All volume calculations were based on the solid volume of wood (without air gaps) and bark volume included. For all roundwood volume calculations, the following formula of truncated cone was used:

$$V=\pi/12\cdot(d_1^2+d_1\cdot d_2+d_2^2)\cdot L\cdot 1000 \quad (1)$$

Where V – volume in dm^3, d_1– diameter on bark measured from thinner end (m), d_2 – diameter on bark measured from thicker end (m), L – length of stem section or log section or distance between the ends (m).

In addition to analysing the time required for fuelwood preparation using the proposed and traditional methods, this study also examined the speed of loading in the case of these two studied methods. Manual loading was chosen as the most likely loading for small-scale forestry. For this purpose, additional chronometry experiments were conducted. At the beginning of chronometry tests for loading, both discs and split billets were initially heaped loosely on the ground, and after transport, both fuelwood types were not stacked in the woodshed when unloading. Instead, they were thrown through the shed door onto the shed floor into a loose pile. All the work operations, for both pro-

Figure 1 Grey alder stem cut into 10 cm thick discs with 1.9 kW Stihl 023
Slika 1. Deblo drva bijele johe raspiljeno na diskove debljine 10 cm pilom Stihl 023 snage 1,9 kW

posed and traditional methods were carried out by the same person having a chainsaw operator certificate. During the work operations, the weather was without precipitation, 1-6 degrees above zero degrees Celsius and with moderate wind. The efficiency of both methods was compared by applying prices to the spent work time and the consumed roundwood volume.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The comparative results of the chronometry tests are as follows. The average time required for the preparation of 10 cm-thick disc fuelwood (proposed method) was (2.1 ± 0.3) s/dm^3. For the traditional production of fuelwood billets by splitting 30 cm log sections with an axe, the relevant average time was (4.6 ± 1.9) s/dm^3. Comparison of time consumptions on loading and unloading fuelwood produced by proposed and traditional methods to and from a vehicle is given in Table 1.

When taking into account loading and unloading speeds from Table 1 and the production speed, the average of the proposed method is 1.0 s/dm^3. The corresponding value in the case of traditional method is 1.9 s/dm^3. Despite the finding that fuelwood production in the form of discs is approximately twice as fast, if compared to the traditional approach, a technical issue arises with discs of small diameter (estimated at less than 20 cm), which cannot be stacked as stably as billets. The reason is that discs under 20 cm in diameter do not interlock sufficiently to form a stable pile. Consequently, such discs must be heaped rather than stacked for storage and drying. An alternative approach is to store and dry the discs in mesh bags. The mesh bags can be stacked up. The effectiveness of drying billets in mesh bags has been previously demonstrated in a test (Pari *et al*., 2020).

In the loading test, it took 27 % more loading time in the case of split billets than in the case of discs. One possible explanation may be that when the 30 cm long stem part was sawn into 3 discs, each with thickness of 10 cm, the 30 cm long log section was split into 4 billets. Therefore, the number of split billets was one third higher than that of discs. To make the same number of split billets and discs, the log sections had to be split into three billets instead of four. It can be assumed that throwing more split billets than discs requires more time. Data presented in Table 2 shows that the cost for producing one m^3 of fuelwood is a quarter cheaper in case of discs despite of bigger roundwood losses to sawdust. The same relation is also valid after considering the labour cost of loading and unloading transportation vehicles. Purchase price of the roundwood was arbitrarily set to €25 per m^3 of solid volume including bark. Labour costs, incorporating tool amortisation as well as fuel and oil expenses, were arbitrarily set at €20 per hour.

Loading discs was supposedly faster because the discs were of the same thickness, and flat surfaces of discs were easier to grasp by hand compared to split billets that are in the form of sectors. When taken by hand, the sector-shaped split billets have always at least one sharp edge against the fingers. That is uncomfortable and may cause slower movements to reduce the acceleration pressure of the sharp edge to hand.

In the current work, species with relatively soft wood (grey alder) was used. Its absolutely dry specific gravity is 0.46 g/cm^3 (Miezite and Dreimanis, 2006). Tree species with higher absolutely dry specific gravity

Table 1 Time consumptions on loading and unloading fuelwood produced by proposed and traditional methods to and from a vehicle
Tablica 1. Utrošak vremena za utovar i istovar ogrjevnog drva proizvedenoga predloženom i tradicionalnom metodom

Method *Metoda*	**Volume of fuelwood, dm³** *Volumen ogrjevnog drva,* dm³	**Loading time, s** *Vrijeme utovara,* s	**Unloading time, s** *Vrijeme istovara,* s	**Loading speed, s/dm³** *Brzina utovara, s/dm³*	**Unloading speed, s/dm³** *Brzina istovara,* s/dm³
Proposed *predložena*	360	130	190	0.4	0.6
Traditional *tradicionalna*	290	190	220	0.5	0.7

Table 2 Comparison of estimated costs of production methods
Tablica 2. Usporedba procijenjenih troškova proizvodnih metoda

Production costs of 1 m³ solid volume of end product and their comparison *Troškovi proizvodnje 1 m³ cjelovitog volumena gotovog proizvoda i njihova usporedba*	**Discs** *Diskovi*	**Split billets** *Cjepanice*	**Unit** *Jedinica*
Labour cost with costs of fuel, oil, and amortisation *trošak rada s troškovima goriva, ulja i amortizacije*	12	26	€
The volume of roundwood needed to produce 1 m³ of end product *količina oblovine potrebne za proizvodnju 1 m³ gotovog proizvoda*	1.06	1.02	m³
Cost of roundwood *trošak oblovine*	27	26	€
Cost of roundwood lost as sawdust *trošak oblovine izgubljene u obliku piljevine*	1.5	0.5	€
Costs of roundwood, labour, fuel, oil and amortisation altogether *ukupni troškovi oblovine, rada, goriva, ulja i amortizacije*	41	54	€
Price difference between methods *razlika u cijeni među metodama*	-13	13	€
Price difference between methods in % *razlika u cijeni među metodama, %*		24	%
Labour cost for loading and unloading vehicle *trošak rada za utovar i istovar vozila*	5.0	7.7	€
Labour cost difference for loading and unloading vehicle *razlika u cijeni rada za utovar i istovar vozila*	-2.7	2.7	€
Labour cost difference for loading and unloading vehicle in % *razlika u cijeni rada za utovar i istovar vozila, %*		35	%
Total costs of all production and loading operations *ukupni troškovi svih proizvodnih i utovarnih operacija*	46	62	€
Cost difference of all production and loading operations *razlika u cijeni svih proizvodnih i utovarnih operacija*	-16	16	€
Cost difference of all production and loading operations in % *razlika u cijeni svih proizvodnih i utovarnih operacija, %*		26	%

like birch, ash, maple etc. need more energy for sawing and are therefore slower to process. In the future, additional tests with other fuelwood species will be conducted for comparison of the two methods.

4 CONCLUSIONS
4. ZAKLJUČAK

The cost for producing one m³ of fuelwood from grey alder roundwood in the form of discs is a quarter cheaper than the costs for producing traditional split billets.

Higher work speed is achieved mainly through omitting two time-consuming lifting operations when producing fuelwood from roundwood in the form of discs compared to the traditional manual production of split billets.

The work should be continued with other fuelwood species due to their different density.

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5 REFERENCES
5. LITERATURA

1. Anselmino, A.; Piedra-Jimenez, F.; Rodriguez, M. A.; Dondo, R. G.; Cóccola, M. E., 2025: Strategic optimization of short-rotation woody crops for bioenergy production. Biomass and Bioenergy, 195: 107686. https://doi.org/10.1016/j.biombioe.2025.107686
2. Bont, L. G.; Gemperle, F.; Perry, N. T.; Werder, M.; Schweier, J., 2025: Derivation of a nationwide wall-to-wall map of fuelwood potential. Journal of Cleaner Production, 494: 145010. https://doi.org/10.1016/j.jclepro.2025.145010
3. Kärhä, K.; Jouhiaho, A., 2009: Producing chopped firewood with firewood processors. Biomass and Bioenergy, 33 (9): 1300-1309. https://doi.org/10.1016/j.biombioe.2009.05.019
4. Liepinš, K.; Lazdinš, A.; Liepinš, J.; Prindulis, U., 2015: Productivity and cost-effectiveness of mechanized and motor-manual harvesting of grey alder (*Alnus incana* (L.) Moench.): a case study in Latvia. Small Scale Forestry, 14: 493-506. https://doi.org/10.1007/s11842-015-9302-1
5. Lindroos, O., 2008: The effects of increased mechanization on time consumption in small-scale firewood processing. Silva Fennica, 42 (5): 791-805. https://doi.org/10.14214/sf.227
6. Manzone, M.; Spinelli, R., 2014: Efficiency of small-scale firewood processing operations in Southern Europe. Fuel Processing Technology, 122: 58-63. https://doi.org/10.1016/j.fuproc.2014.01.025
7. Miezite, O.; Dreimanis, A., 2006: Investigations of Grey Alder (*Alnus Incana (L.) Moench*) Biomass. In: Proceedings of the 12th International Scientific Conference – Research for Rural Development 2006, Jelgava, Latvia, pp. 271-275.
8. Moradpour, P.; Scholz, F.; Doosthoseini, K.; Tarmian, A., 2016: Measurement of wood cutting forces during bandsawing using piezoelectric dynamometer. Drvna industrija, 67 (1): 79-84. https://doi.org/10.5552/drind.2016.1433
9. Mydlarz, K., Wieruszewski, M., 2024: The energy potential of firewood and by-products of round wood processing-Economic and technical aspects. Energies, 17 (19): 4797. https://doi.org/10.3390/en17194797
10. Padari, A.; Mitt, R.; Pärn, L.; Kurvits, V.; Kaasik, S.; Muiste, P., 2023: The impact of extra long-term storage of logging residues on fuel quality in Estonian conditions – a case study. Forestry Studies (Metsanduslikud Uurimused), 79 (1): 51-65. https://doi.org/10.2478/fsmu-2023-0012
11. Pari, L.; Rezaie, N.; Suardi, A.; Cetera, P.; Scarfone, A.; Bergonzoli, S., 2020: Medium rotation eucalyptus plant: a comparison of storage systems. Energies, Special Issue: Renewable Energy Production from Energy Crops and Agricultural Residues, 13 (11): 2915. https://doi.org/10.3390/en13112915
12. Schulze, E.; T., Bouriaud, O.; Irslinger, R.; Valentini, R., 2022: The role of wood harvest from sustainably managed forests in the carbon cycle. Annals of Forest Science, 79: 17. https://doi.org/10.1186/s13595-022-01127-x
13. Spinelli, R.; Magagnotti, N.; Lombardini, C.; Mihelič, M., 2021: A low-investment option for the integrated semi-mechanized harvesting of small-scale, short-rotation poplar plantations. Small-Scale Forestry, 20: 59-72. https://doi.org/10.1007/s11842-020-09456-3
14. Spinelli, R.; Lombardini, C.; Marchi, E.; Aminti, G., 2019: A low-investment technology for the simplified processing of energy wood from coppice forests. European Journal of Forest Research, 138: 31-41. https://doi.org/10.1007/s10342-018-1150-z

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Drvo gorskog javora
Acer pseudoplatanus L.

OPĆENITO O VRSTI

Acer pseudoplatanus L. vrsta je drva iz porodice *Aceraceae*. Trgovački su nazivi te vrste Bergahorn, Waldahorn, Falsche Platane (Njemačka); Érable (Francuska); Sycamore maple (Velika Britanija); Acero di montagna (Italija); Falso platano (Španjolska), javor klen (Češka, Slovačka). Gorski javor uglavnom raste u planinskim regijama južne, jugozapadne, zapadne, središnje i istočne Europe, s krajnjom istočnom granicom na Kaspijskome moru (Krabel i Wolf, 2023.).

Stabla dobro rastu u sjeni, posebice u svojoj juvenilnoj fazi, što objašnjava njihovo uspijevanje u već uspostavljenim šumama (Pasta i dr., 2016.). Javor je također jedna od najbrže rastućih listopadnih vrsta drveća ako se uzgaja na pogodnim staništima. Njegovo se drvo upotrebljava za tokarenje, izradu namještaja i stolarije, unutarnjih podova i glazbenih instrumenata. Brz rast i potencijalno visoke cijene drva čine ga ekonomski atraktivnim. Gorski je javor otporan na onečišćenja, a nije osjetljiv na nepovoljne klimatske uvjete izloženih mjesta, uključujući slane vjetrove i niske ljetne temperature. Uz dojmljiv i privlačan izgled, to ga čini popularnim izborom u smislu ukrasnog drveta u urbanim i obalnim područjima.

Gorski javor nije na popisu ugroženih vrsta međunarodne organizacija CITES, dok se prema IUCN vodi kao vrsta drveta najmanje zabrinjavajućeg opstanka.

RELEVANTNE SPOZNAJE O DRVU GORSKOG JAVORA

Drvo gorskog javora je bakuljavo, žućkastobijelo do bijelo, s blagim crvenkastim tonom u sirovom stanju, no poslije potamni (Wägenfuhr i Scheiber, 2026.). Tekstura drva može biti pravilno ravna, rebrasta, valovita, nalik na cvjetove i ikre, vrlo dekorativna. Drvo je prilično sjajno. Godovi su uočljivi, rastresito porozni. Pore nisu vidljive golim okom. Drvni su traci vrlo uski, ali svjetliji od okolnog staničja.

Pregled novijih istraživanja drva javora donosi spoznaje: a) o nasljeđivanju različitih abnormalnosti žice (Zobel i van Buijtenen, 1989.), b) o reakciji javora na povišene temperature povećanjem širine proizvedenih godova (Rothe i Hartl-Mayer, 2014.), c) o širini godova s većom prosječnom vrijednosti u zoni

GENERAL INFORMATION ON SPECIES

Acer pseudoplatanus L. is a wood species in the *Aceraceae* family. Common names are: Bergahorn, Waldahorn, Falsche Platane (Germany); Érable (France); Sycamore maple (Great Britain); Acero di montagna (Italy); Falso platano (Spain), clove maple (Czech Republic/Slovakia). Sycamore maple is native mainly to the mountainous regions of Southern, South-Western, Western, Central and Eastern Europe, with the extreme easterly limit at the Caspian Sea (Krabel and Wolf, 2023).

Trees grow well in shaded conditions, particulary in their juvenile stage and this explains their ability to succeed within established forests (Pasta *et al.,* 2016). Sycamore is also one of the fastest growing broadleaved species when grown on suitable sites. Its timber is used for turnery, furniture making, joinery, indoor flooring and musical instruments. Rapid growth and potentially high timber prices make it economically attractive. The sycamore maple is tolerant to pollution, exposed sites including salt winds and low summer temperatures. Together with its striking and attractive appearance, it becomes a popular choice as an ornamental tree in urban and coastal locations.

This wood species is not listed in the international organization CITES Appendices and is reported by the IUCN as being a species of least concern.

RELEVANT KNOWLEDGE ABOUT SYCAMORE MAPLE WOOD

The wood of the sycamore maple is with uncoloured heartwood, yellowish-white to white, with a slight reddish tone when fresh, later darkening (Wägenfuhr and Scheiber, 2026). The texture can be regular, flat, ribbed, wavy, flowery and speckled, very decorative. The lustre of wood is considerable. The rings are noticeable, diffuse porous. The pores are not visible to the naked eye. The wood rays are very narrow, but lighter in colour compared to the surrounding wood.

A review of recent research on sycamore maple wood provides knowledge on: (a) different grain abnormalities being inherited (Zobel and van Buijtenen, 1989); (b) sycamore responding to increased temperatures with an increase in annual ring widths (Rothe and Hartl-Mayer, 2014); (c) annual ring width having a od 1. do 30. goda (Sedlar i dr., 2019.), d) o potvrđenoj vezi između vrijednosti fizičkih parametara i akustičnih i elastičnih svojstava javorova drva za izradu glazbala (Dinulica i dr., 2023.), e) o rasponu gustoće drva ovisno o uvjetima rasta, vlazi i starosti stabla (Vacek i dr., 2026.).

Napomena: podatci o tehničkim i tehnološkim svojstvima drva gorskog javora dostupni su na web stranicama navedenima u literaturi na kraju teksta.

ZNAČENJE GORSKOG JAVORA I ISTRAŽIVANJA TE VRSTE U HRVATSKOJ

Prema EUFORGEN-u, gorski javor treba promicati kao drvni resurs jer ima velik potencijal za iskorištavanje u šumarstvu unatoč tome što ga na plodnim tlima obično nadmašuje bukva (Rusanen i Myking, 2003.). Gorski javor ima poželjna svojstva drva, tolerantan je prema nizu stanišnih uvjeta i mogao bi se rabiti kao zamjena za obični jasen (*Fraxinus excelsior* L.), kojemu prijeti izumiranje. Programi uzgoja gorskog javora već su pokrenuti (Neophytou, Konnert i Fussi, 2019.).

Unutar ekološke mreže Natura 2000 gorski se javor, uz bukvu i jelu, pronalazi na planinskim lokalitetima, točnije na dijelovima Dinare (Gorski kotar, Lika i Velebit) te u sredogorskim šumama, posebice u ilirskim bukovim šumama kao jednim od najvažnijih Natura 2000 šumskih staništa u Hrvatskoj (Martinić i dr., 2009.). Uz europsku bukvu (*Fagus sylvatica* L.), spominje se kao prikladna vrsta za obnovu složenih planinskih šuma iako su mlada stabla osjetljiva na klimatski stres, kao i na biotičke štetnike (Balcar i dr., 2011.) Osim toga, drvo gorskog javora ima visoku ekonomsku i ekološku vrijednost te bi njegova široka rasprostranjenost pridonijela i vrijednosti gospodarstva (Hein i dr., 2009.). Slijedom navedenoga, obnove planinskih šuma gorskim javorom i bukvom imaju znatnu gospodarsku važnost (Nebe i dr., 1997.).

Prema istraživanju javnog nadmetanja i postupka prodaje drvne sirovine u Republici Hrvatskoj te usporedno sa slovenskim tržištem u 2022. godini, u obje je zemlje najvrednija prodana vrsta na nadmetanju bio gorski javor (Landekić i dr., 2024.).

U Hrvatskoj je o prirastu gorskog javora u usporedbi s običnom bukvom rano pisao Tomaševski (1960.), već 1960-ih godina. Isti autor govori o njegovu uzgojnom značenju, ali ističe da mu se ne pridaje dovoljna, a ni posebna pozornost kakvu zaslužuje.

Svojstva drva gorskog javora nedovoljno su ispitivana u svijetu, a u Hrvatskoj nisu postojali mjerodavni rezultati za materijal autohtonog podrijetla i obilježja rasta. Sedlar je (2014.) proveo detaljno istraživanje fizikalnih i mehaničkih svojstava drva gorskog javora s Medvednice i utjecaj tih parametara na

higher average value in the zone from the 1st to the 30th annual ring (Sedlar *et al.,* 2019); (d) confirmed link between the values of the physical parameters and the acoustic and elastic properties of sycamore maple wood for music instruments (Dinulica *et al.,* 2023); (e) the range of wood density depending on growth conditions, moisture and tree age (Vacek *et al.,* 2026).

Note: data on technical and technological properties of sycamore maple wood are available on web pages listed in the literature section.

IMPORTANCE OF SYCAMORE MAPLE AND ITS RESEARCH IN CROATIA

According to EUFORGEN, sycamore maple should be promoted as a timber resource as it has significant potential for use in forestry despite it typically being outcompeted by beech on fertile soils (Rusanen and Myking, 2003). Sycamore maple has desirable wood properties, it is tolerant to a range of site conditions and could be used to replace common ash (*Fraxinus excelsior* L.), which is under threat from ash dieback. Breeding programmes for the species have already been initiated (Neophytou, Konnert, and Fussi, 2019).

Through the Natura 2000 ecological network, sycamore maple is found alongside beech and fir in mountainous locations, more precisely in parts of Dinara (Gorski Kotar, Lika and Velebit) and in mid-mountain forests, especially in the Illyrian beech forests, as one of the most important Natura 2000 forest habitats in Croatia (Martinić *et al.*, 2009). It is mentioned as a good species for the restoration of complex mountain forests alongside European beech (*Fagus sylvatica* L.), although young trees are sensitive to climatic stress, as well as to biotic pests (Balcar *et al.,* 2011). In addition, sycamore maple wood has a potentially high economic and ecological value (Hein *et al.*, 2009). Consequently, the renewal of mountain forests with sycamore maple and beech is of significant economic importance (Nebe *et al.*, 1997).

According to the research on public tenders and the process of selling wood raw materials in the Republic of Croatia and compared to the Slovenian market in 2022, sycamore maple was the most valuable species sold at the tender in both countries (Landekić *et al.*, 2024).

In Croatia, Tomaševski (1960) wrote about the diameter increment of sycamore maple compared to common beech as early as in the 1960s. The same author speaks of its importance in cultivation but points out that it is not given sufficient or adequate attention.

The properties of sycamore maple wood have been insufficiently studied worldwide, and in Croatia there has been no relevant information on its autochthonous origin and growth characteristics. Sedlar (2014) tehnološka svojstva prerade njegova drva. Na Fakultetu šumarstva i drvne tehnologije Sveučilišta u Zagrebu u tijeku su istraživanja anatomskih svojstava drva gorskog javora iz istog izvora.

conducted a detailed study of the physical and mechanical properties of sycamore maple wood from Medvednica and their influence on the technological characteristics of processing. Research on the anatomical properties of sycamore maple wood from the same source is ongoing at the Faculty of Forestry and Wood Technology.

LITERATURA / *REFERENCES*

1. Balcar, V.; Kacálek, D.; Kuneš, I.; Dušek, D., 2011: Effect of soil liming on European beech (*Fagus sylvatica* L.) and sycamore maple (*Acer pseudoplatanus* L.) plantations. Folia Forestalia Polonica, series A, 53 (2), 85-92.
2. Dinulica, F.; Savin, A.; Stanciu, M. D., 2023: Physical and Acoustical Properties of Wavy Grain Sycamore Maple (*Acer pseudoplatanus* L.) Used for Musical Instruments. Forests, 14, 197. https://doi.org/10.3390/f14020197
3. Hein, S.; Collet, C.; Ammer, C.; Le Goff, N.; Skovsgaard, J. P.; Savill, P., 2009: A review of growth and stand dynamics of Acer pseudoplatanus L. in Europe: implications for silviculture. Forestry, 82 (4), 361-385.
4. Krabel, D.; Wolf, H., 2013: Sycamore maple (*Acer pseudoplatanus* L.). In: Pâques, L. E. (ed.), Forest tree breeding in Europe. Springer, Netherlands, 373-402.
5. Landekić, M.; Troha, J.; Bakarić, M., 2024: Studij slučaja javnih nadmetanja prodaje drvnih sortimenata 2022. godine u Hrvatskoj i Sloveniji. Šumarski list, 1-2: 71-82. https://doi.org/10.31298/sl.148.1-2.7
6. Martinić, I.; Landekić, M.; Bakarić, M.; Martinić, F., 2009: Bioraznolikost šuma u Nacionalnom parku Plitvička jezera. Priručnik, Nacionalni park Plitvička jezera.
7. Nebe, W.; Woydich, T.; Leube, F., 1997: Zur Ernährung und Düngung der Fichte mit Kalium, Kalium und Magnesium im Unterharz bei anhaltenden Immissionsbelastungen. Beiträge für Forstwirtschaft und Landschaftsökologie, 31 (1), 1-6.
8. Neophytou, C.; Konnert, M.; Fussi, B., 2019: Western and eastern post-glacial migration pathways shape the genetic structure of sycamore maple (*Acer pseudoplatanus* L.) in Germany. Forest Ecology and Management, 432, 83-93. https://10.1016/j.foreco.2018.09.016
9. Pasta, S.; de Rigo, D.; Caudullo, G., 2016. Acer pseudoplatanus in Europe: distribution, habitat, usage and threats. In: San-Miguel-Ayanz, J.; de Rigo, D.; Caudullo, G.; Houston Durrant, T.; Mauri, A. (eds.), European Atlas of Forest Tree Species. Publ. Off. EU, Luxembourg, pp. e01665a+
10. Rothe, A.; Hartl-Meier, C., 2014: Jahrringuntersuchungen an Bergahorn in Wäldern der Nördlichen Kalkalpen. LWF aktuell 100, S. 55-57.
11. Rusanen, M.; Myking, T., 2003: EUFORGEN Technical Guidelines for genetic conservation and use for sycamore (*Acer pseudoplatanus*). Maccarese, Italy, International Plant Genetic Resources Institute, 6 pp.
12. Sedlar, T., 2014: Utjecaj fizikalnih i mehaničkih svojstava gorske javorovine (*Acer pseudoplatanus* L.) s područja Medvednice na tehnološke karakteristike preradbe. Doktorska disertacija, Šumarski fakultet Sveučilišta u Zagrebu.
13. Sedlar, T.; Sinković, T.; Trajković, J.; Hasan, M.; Ištok, I.; Šefc, B., 2019: Physical Properties of Juvenile and Mature Sycamore Maple (*Acer pseudoplatanus* L.) Wood from Medvednica Region. Drvna industrija, 70 (1): 19-26. https://doi.org/10.5552/drvind.2019.1762
14. Tomaševski, S., 1960: Odnos prirasta gorskog javora i bukve u G. J. Ravna Gora. Šumarski list, 5-6, 166-173.
15. Vacek, Z.; Vacek, S.; Černý, J.; Cikor, J.; Kuběnka, M.; Gallo, J.; Trojan, V.; Lukáčik, I.; Štefančik, I.; Králičer, I., 2026: Sycamore maple (*Acer pseudoplatanus* L.) and global climate change: a new perspective for sustainable forestry. Frontiers in Forests and Global Change, 1-15. https://doi.org./10.3389/ffgc.2025.1731092
16. Wagenführ, R.; Scheiber, C., 2006: HOLZATLAS. VEB Fchbuchverlag, Leipzig, pp. 53-56.
17. Zobel, B. J.; van Buijetenen, J. P., 1989: Wood variation. Its causes and control. Springer-Verlag, Berlin, Heildeberg.
18. https://cites.org/eng/search?search_api_fulltext=ACER+PSEUDOPLATANUS (pristupljeno 26. siječnja 2026.).
19. https://www.iucnredlist.org/species/193856/125923004 (pristupljeno 26. siječnja 2026.).
20. https://www.wood-database.com/sycamore-maple/ (pristupljeno 26. siječnja 2026.).

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Web stranice

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