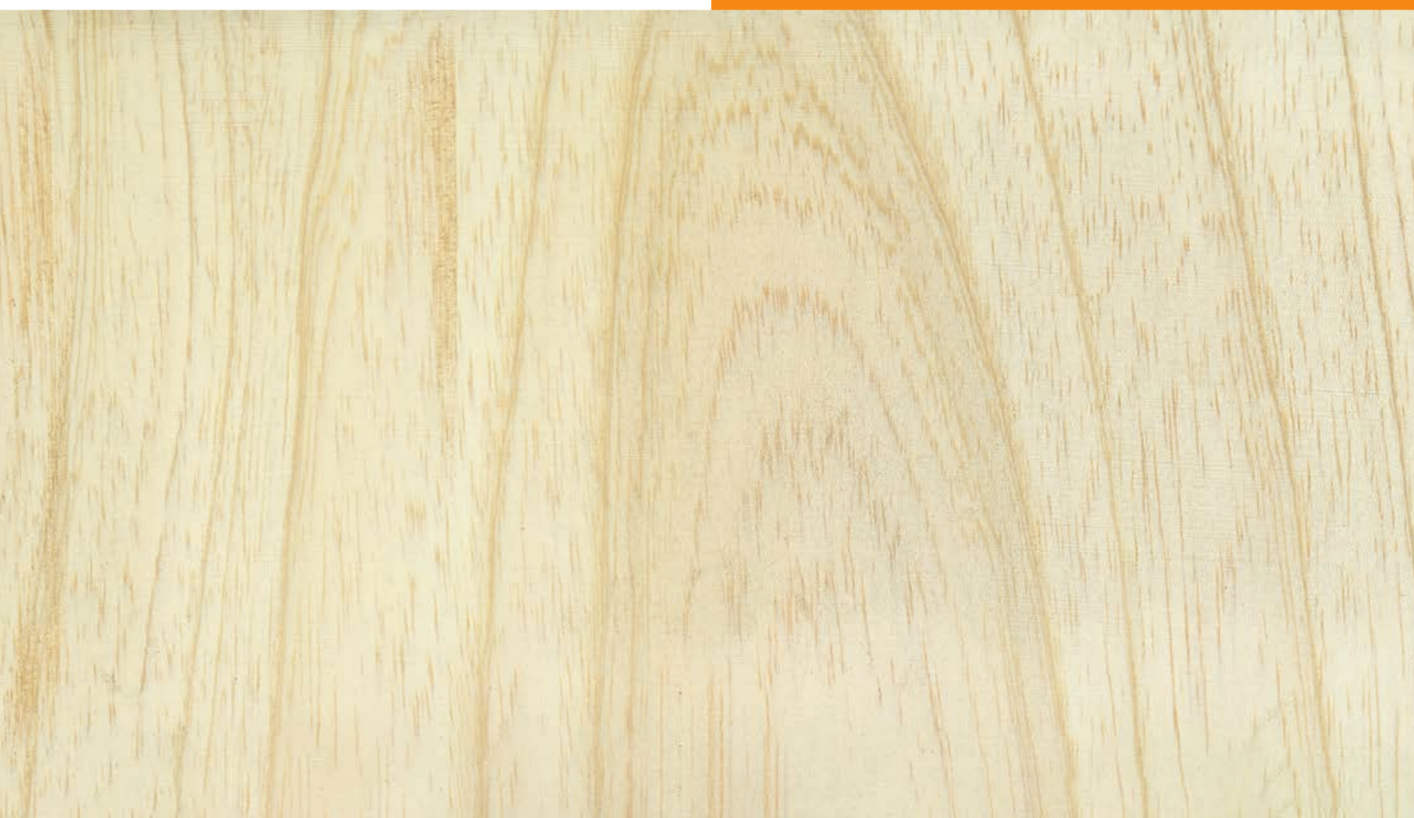




DRVNA INDUSTRIJA

SCIENTIFIC JOURNAL
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ZNANSTVENI ČASOPIS
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Acer pseudoplatanus L.

UDK 674.031.677.7
ISO: Drv. Ind.
CODEN: DRINAT
JCR: DRVNA IND
ISSN 0012-6772

3/26
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Znanstveni časopis iz područja drvne tehnologije

PUBLISHER AND EDITORIAL OFFICE

Izdavač i uredništvo

University of Zagreb

Faculty of Forestry and Wood Technology

Sveučilište u Zagrebu

Fakultet šumarstva i drvne tehnologije

www.sumfak.unizg.hr

CO-PUBLISHER / Suizdavač

Hrvatska komora inženjera šumarstva i drvne tehnologije

FOUNDER / Osnivač

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The journal is published quarterly and financially supported by the Ministry of Science and Education of the Republic of Croatia.

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Časopis izlazi četiri puta u godini uz financijsku potporu Ministarstva znanosti, obrazovanja i mladih Republike Hrvatske.

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CIRCULATION: 400 pieces

INDEXED IN: Science Citation Index Expanded, Scopus, CAB Abstracts, Compendex, Environment Index, Veterinary Science Database, Geobase, DOAJ, Hrčak, Open Policy Finder

MANUSCRIPTS ARE TO BE SUBMITTED by the link
<http://journal.sdewes.org/drvind>

CONTACT WITH THE EDITORIAL
e-mail: drvind@sumfak.unizg.hr

SUBSCRIPTION: Annual subscription is 55 EUR. For pupils, students and retired persons the subscription is 15 EUR. Subscription shall be paid to the IBAN HR0923600001101340148 with the indication "Drvna industrija".

PRINTED BY: DENONA d.o.o., Radnička cesta 206, Zagreb, www.denona.hr

DESIGN: Bernardić Studio

THE JOURNAL IS AVAILABLE ONLINE:
<https://drvnaindustrija.com>

COVER: Tangential section view of *Acer pseudoplatanus* L., xylothea of Institute for Wood Science, University of Zagreb Faculty of Forestry and Wood Technology

DRVNA INDUSTRIJA · VOL. 77, 3 ·
P. 261-384 · AUTUMN 2026 · ZAGREB
EDITORIAL COMPLETED 15. 09. 2026.

NAKLADA: 400 komada

ČASOPIS JE REFERIRAN U: Science Citation Index Expanded, Scopus, CAB Abstracts, Compendex, Environment Index, Veterinary Science Database, Geobase, DOAJ, Hrčak, Open Policy Finder

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PRETPLATA: Godišnja pretplata za pretplatnike u Hrvatskoj i inozemstvu iznosi 55 EUR. Za dake, studente i umirovljenike 15 EUR. Pretplata se plaća na IBAN HR0923600001101340148 s naznakom "Drvna industrija".

TISAK: DENONA d.o.o., Radnička cesta 206, Zagreb, www.denona.hr

DESIGN: Bernardić Studio

ČASOPIS JE DOSTUPAN NA INTERNETU: <https://drvnaindustrija.com>

NASLOVNICA: Tangentni presjek drva gorskog javora (*Acer pseudoplatanus* L.), ksiloteka Zavoda za znanost o drvu, Sveučilište u Zagrebu Fakultet šumarstva i drvene tehnologije

DRVNA INDUSTRIJA · VOL. 77, 3 ·
STR. 261-384 · JESEN 2026 · ZAGREB
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Milad Gorganli Davaji¹, Vahid Vaziri^{*2}, Loya Jamalirad³, Mehرداد Sedghi⁴

Investigating the Characteristics of Particleboards Produced from a Combination of Pine Tree Branches / Melamine Impregnated Paper Waste with Industrial Wood Particles in Different Amounts of Resin

Istraživanje obilježja iverice proizvedene od borovih grana i melaminom impregniranoga papirnog otpada u kombinaciji s industrijskim drvnim iverjem i različitim količinama ljepila

ORIGINAL SCIENTIFIC PAPER

Izvorni znanstveni rad

Received – prispjelo: 20. 10. 2025.

Accepted – prihvaćeno: 10. 4. 2026.

UDK: 674.812

<https://doi.org/10.5552/drvind.2026.0301>

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ABSTRACT • The properties of particleboards manufactured from pine tree branches /melamine impregnated paper waste with industrial wood particles were investigated. This research aims to reduce the amount of industrial wood particles and resin content. The proportions of industrial wood particles to an equal mixture of pine branches and melamine impregnated paper waste were 100: 0, 90:10, 80:20, 70:30 and urea-formaldehyde resin was used at two levels – 8 % and 10 %. A factorial test was used to statistically assess the board properties. According to the results, with increasing resin content, the physical and mechanical properties of the boards improved. With increasing the mixing ratio of pine branches and melamine impregnated paper waste up to 20 percent, the mechanical properties of the boards improved compared to the control sample (the boards containing 100 % industrial wood particles). The boards containing 90 % industrial wood particles and 8 % resin (mixture W90R8) as well as the boards containing 70 % industrial wood particles and 10 % resin (mixture W70R10) are recommended for the Type P1 boards. For the Type P2 boards, the boards containing 90 % industrial wood particles and 10 % resin (mixture W90R10) are recommended.

KEYWORDS: industrial wood particles; urea-formaldehyde resin; pine branches; melamine impregnated paper waste

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SAŽETAK • U radu su istražena svojstva iverice proizvedene od smjese borovih grana i otpadnog papira impregniranoga melaminom u kombinaciji s industrijskim drvnim iverjem. Ciljevi ovog istraživanja bili su smanjenje količine industrijskoga drvnog iverja i udjela smole. Omjeri drvnog iverja i smjese jednakih udjela borovih grana i otpadnog papira impregniranoga melaminom bili su 100:0, 90:10, 80:20, 70:30, a udio urea-formaldehidne smole iznosio je 8 % i 10 %. Za statističku procjenu svojstava ploče primijenjen je faktorski test. Prema rezultatima istraživanja, s povećanjem udjela smole poboljšala su se fizička i mehanička svojstva ploča. S povećanjem udjela smjese borovih grana i otpadnog papira impregniranoga melaminom do udjela od 20 % mehanička svojstva ploča poboljšala su se u usporedbi s kontrolnim uzorkom (ploče sa 100 % drvnog iverja). Glede ploča tipa P1 preporučuje se proizvodnja onih koje sadržavaju 90 % drvnog iverja i 8 % smole (smjesa W90R8), kao i ploča s udjelom 70 % drvnog iverja i 10 % smole (smjesa W70R10). Za ploče tipa P2 preporučuje se proizvodnja onih koje sadržavaju 90 % drvnog iverja i 10 % smole (smjesa W90R10).

KLJUČNE RIJEČI: drveno iverje; urea-formaldehidna smola; borove grane; melaminom impregniran otpadni papir

1 INTRODUCTION

1. UVOD

In 2020, 96.01 million cubic meters of particleboards were produced worldwide (Lee *et al.*, 2022). The cost of wood has increased significantly in recent years. Many researchers investigated the use of various wastes, such as recycled wood, tea leaves, fruits, as raw materials for particleboard production (Mostafalo *et al.*, 2019; Baharlouei *et al.*, 2020; Ebrahimi *et al.*, 2021). They determined that these wastes may be utilized to make particleboards. To protect the environment, wood products can be made from industrial waste, such as sawdust, bark, wood pulp, wastepaper fibers, and waste from sawmills and veneering. During the veneering process, the melamine impregnated paper production line produces a significant amount of waste that is burned to produce energy. Wood product waste can be recycled and reused in the manufacturing process (Babazadeh Lehi *et al.*, 2018). Nemli *et al.* (2003) investigated the use of kiwifruit pruning in the particleboard production. Incorporating kiwifruit branches into the board center layer was shown to improve the boards resistance above the minimum set by the European standard. However, the physical properties of the boards increased. According to Thomas *et al.* (2011), the veneer production process generates a large amount of melamine resin-impregnated paper waste, which can be used instead of adhesive to produce particleboards. The results demonstrated that using melamine-coated paper improved the board strength properties and reduced the quantity of urea-formaldehyde adhesive utilized. Varga *et al.* (2004) studied the usage of melamine-coated paper waste in particleboard production. The results showed that adding melamine-coated paper improved the strength properties of the boards and decreased the usage of urea-formaldehyde adhesive. Melamine-coated paper powder was used by Alpar and Winkler (2006) as a filler and adhesive in the production of particleboards. The findings revealed no appreciable variation between the boards made with urea-formaldehyde adhesive and melamine-coated paper powder.

Silva *et al.* (2012) used variable amounts of 6 mm long melamine veneer waste as a synthetic resin in the central layer of the particleboard. The findings revealed that boards with melamine veneer waste of 4 % and 8 % met the minimum standard criteria, while those with 12 % had lower strengths than the standard. The particleboard properties manufactured from waste leather and wastepaper were studied by Kibet *et al.* (2022). The two materials listed above were found to be suitable wood replacements for the production of particleboards.

Babazadeh Lehi *et al.* (2018) studied the replacement of urea formaldehyde adhesives with melamine wastepaper in the center of particleboard. In this research, melamine wastepaper was used in the core layer at four concentrations: 0, 20, 40, and 60 % of the dry weight of the resin used. The research found that while the boards resistance declined with higher wastepaper powder concentration, as required by the Iranian National Standard 9044, the strength of the boards remained within acceptable limits up to 40 % of the melamine wastepaper powder. Additionally, the physical properties of the board improved as the melamine wastepaper powder content increased. According to the research, using melamine wastepaper in particleboard manufacturing lowers the usage of urea-formaldehyde resin.

Latibari *et al.* (2013) investigated the possibility of using pine and sycamore waste and grape pruning in comparison to a combination of hardwoods in the production of particleboards. According to the results, pine wood boards had the greatest bending strength and modulus of elasticity because of their lower bulk density, while mixed hardwood chips had the highest internal bonding.

Wronk and Kowaluk (2022) investigated the possibility of using pine branches as a replacement material in the particleboard. The study showed that increasing the proportion of pine branches improved the boards' internal bonding and water absorption but reduced their bending strength and modulus of elasticity.

Basboga *et al.* (2016) studied the use of different types of melamine-saturated paper waste in particleboard production. Because of its economic and envi-

ronmental benefits, the aforementioned material can be used as a resin replacement in the production of particleboards, and the result showed that 15 % melamine paper provides the most significant resistance.

Due to the importance of alternative raw materials and waste, and the reduction of industrial wood consumption in boards production, the objective of this research is to substitute pine branches and melamine paper waste with industrial wood particles to produce particleboards with desirable physical and mechanical properties at different amounts of resin.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

2.1 Raw materials

2.1. Sirovine

Melamine-impregnated paper waste was taken from the coating line of the Northern Wood Industry Company and then ground into powder in a hammer mill. Industrial wood particles with a thickness of 0.8-1.5 mm (10-20 mesh) were obtained from the Northern Wood Industry Company, and pine tree branches (*Pinus*

brutia) from Gonbad Kavous city, and processed into wood chips using chipper and mechanical grinding. These particles were dried to a moisture content of 4 %.

2.2 Adhesive

2.2. Ljepilo

Urea-formaldehyde (UF) resin was used at two levels – 8 and 10 %. Table 1 lists the properties of UF resin. The ammonium chloride was used as hardener at 2 % of the weight of the resin.

2.3 Manufacture of particleboards

2.3. Proizvodnja iverice

The mixed proportion of industrial wood particles, melamine impregnated paper waste, and pine tree branches was selected at four levels: (100 %: 0 %: 0 %), (90 %: 5 %: 5 %), (80 %: 10 %: 10 %), and (70 %: 15 %: 15 %), respectively. UF resin was used at two levels – 8 % and 10 % of the dry weight of the raw materials.

2.4 Evaluation of board properties

2.4. Analiza svojstava ploče

The boards were cut according to EN 326-1:1994 after two weeks. Thickness swelling of boards was

Table 1 Properties of urea-formaldehyde resin

Tablica 1. Svojstva urea-formaldehidne smole

Density, kg/m ³ Gustoća, kg/m ³	Manufacturer Proizvođač	Viscosity, cP Viskoznost, cP	Gel time, s Vrijeme želiranja, s	pH	Solids, % Suha tvar, %
1270	Samed Mashhad	320	56	7	61

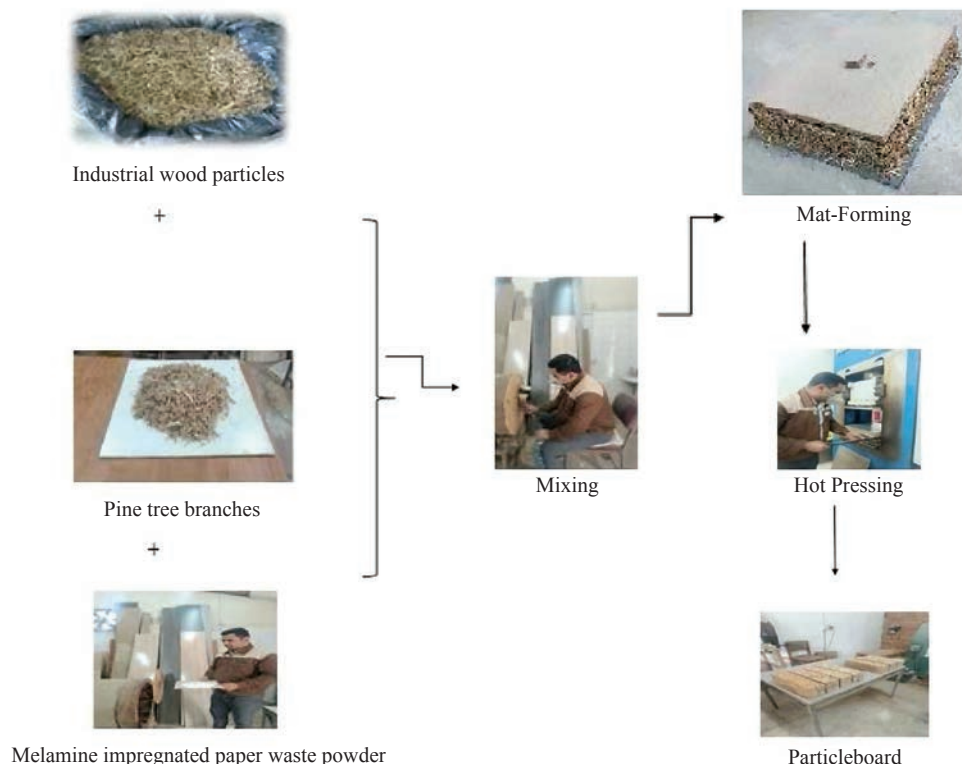


Figure 1 Production stages of particleboard

Slika 1. Faze proizvodnje iverice

Table 2 Combination of test samples**Tablica 2.** Kombinacije ispitnih uzoraka

Treatment code <i>Oznaka uzorka</i>	Particles for producing particleboard, % <i>Sirovina za proizvodnju iverice, %</i>			UF resin / UF smola	
	Industrial wood particles (W) <i>Drvno iverje (W)</i>	Pine tree branches <i>Borove grane</i>	Melamine-impregnated paper waste <i>Melaminom impregniran otpadni papir</i>	8 % (R8)	10 % (R10)
W100R8	100	0	0	8	-
W100R10	100	0	0	-	10
W90R8	90	5	5	8	-
W90R10	90	5	5	-	10
W80R8	80	10	10	8	-
W80R10	80	10	10	-	10
W70R8	70	15	15	8	-
W70R10	70	15	15	-	10

measured according to EN 317:1993, and the mechanical properties of boards according to EN 310:1993 and EN 319:1993. The results were compared with Type P1 board and Type P2 board according to EN 312:2010.

2.5 Data analysis

2.5. Analiza podataka

Factorial test was used for data analysis. Duncan's test at a 95 % confidence level was used to compare the means.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

3.1 Bending strength and modulus of elasticity

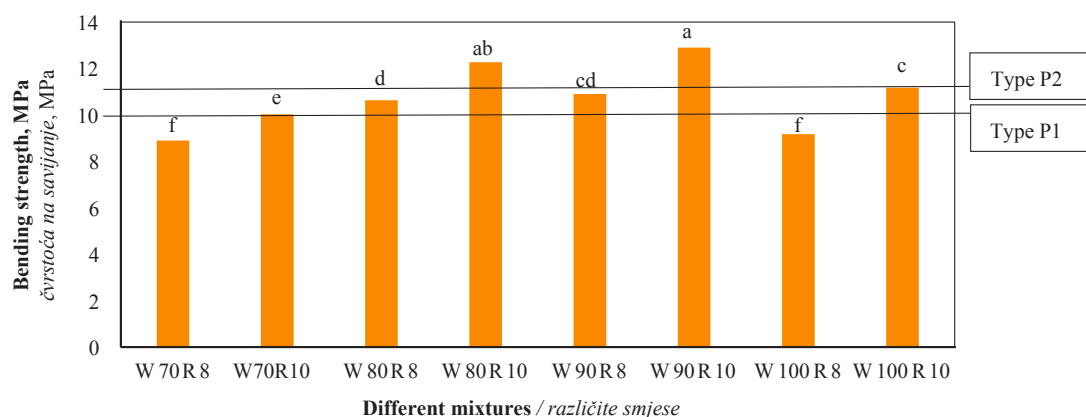
3.1. Čvrstoća na savijanje i modul elastičnosti

The results showed that different factors had a significant effect on the above mechanical properties at a 95 % confidence level (Table 3).

Table 3 Results of data analysis**Tablica 3.** Rezultati analize podataka

Parameter <i>Parametar</i>	Source of variance <i>Izvor varijance</i>	Degrees of freedom <i>Stupnjevi slobode</i>	Mean square <i>Srednji kvadrat</i>	F value	P Sig.
Bending strength <i>čvrstoća na savijanje</i>	Mixture / <i>smjesa</i>	3	7.599	4.368	0.020*
	Resin / <i>smola</i>	1	17.170	9.870	0.006**
	Mixture × Resin / <i>smjesa × smola</i>	3	0.253	0.145	0.031*
	Error / <i>pogreška</i>	16	1.740		
	Total / <i>ukupno</i>	23			
Modulus of elasticity <i>modul elastičnosti</i>	Mixture / <i>smjesa</i>	3	468252.642	7.139	0.003**
	Resin / <i>smola</i>	1	831904.370	12.684	0.003**
	Mixture × Resin / <i>smjesa × smola</i>	3	11772.305	0.179	0.039*
	Error / <i>pogreška</i>	16	65589.122		
	Total / <i>ukupno</i>	23			

*Significance at the level of 95 %, ** significance at the level of 99 % / *Značajno na razini od 95 %, **značajno na razini od 99 %

**Figure 2** The effect of different mixtures on boards bending strength**Slika 2.** Utjecaj različitih smjesa na čvrstoću ploča na savijanje

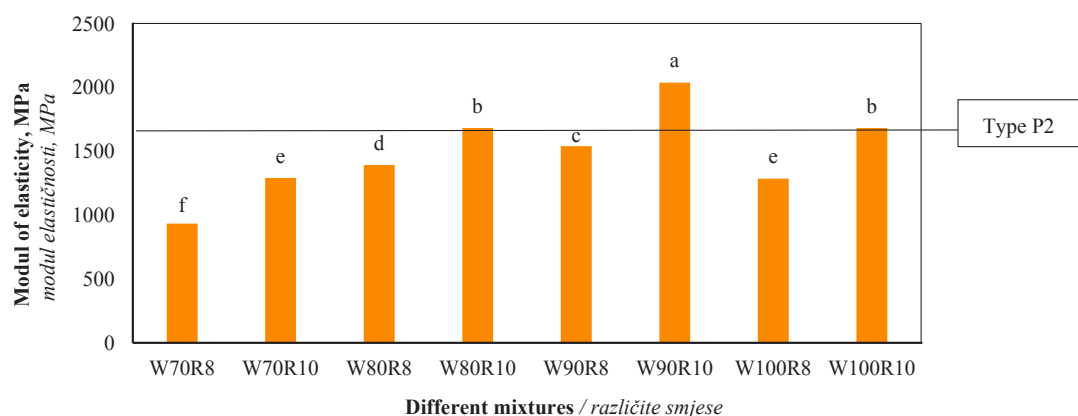


Figure 3 The effect of different mixtures on boards modulus of elasticity

Slika 3. Utjecaj različitih smjesa na modul elastičnosti ploča

Figures 2 and 3 show the effect of different mixtures on the bending strength and the modulus of elasticity of particleboards. The bending strength and the modulus of elasticity improved with increasing the amounts of UF resin and the mixture up to 80 %. As the density of pine wood is lower than that of industrial wood particles, which increases the compression coefficient, the bending strength and modulus of elasticity increase. At low content (up to 10 %), melamine impregnated paper waste acts as a filler, fills the inter-fiber voids, leading to improved strength (Bashoga *et al.* 2016). However, at higher contents (15 %), these wastes induce stress concentration, ultimately leading to a reduction in strengths. The maximum modulus of elasticity and bending strength values were achieved from a mixture of 90 % industrial wood particles and 10 % UF resin (mixture W90R10). The minimum bending strength and modulus of elasticity values were achieved in a mixture of 70 % industrial wood particles and 8 % UF resin (mixture W70R8). Figures 2 and 3 show that the mixtures of W100R10, W90R10, and W80R10 were comparable to the values required for Type P2 boards according to EN 312 (EN 2010). The

mixture of W90R8, W80R8, and W70R10 accomplished the requirements of EN 312 (EN 2010) for Type P1 boards.

3.2 Internal bonding strength

3.2. Čvrstoća na raslojavanje

The results showed that different factors had a significant effect on the internal bonding of the boards at a 95 % confidence level (Table 4).

Internal bonding value increased as resin content was increased from 8 wt% to 10 wt% (Figure 4). The maximum internal bonding values were achieved from a mixture of 90 % industrial wood particles and 10 % UF resin (mixture W90R10). Melamine paper waste functions as a filler in low amounts, while in greater amounts it has a high specific surface area. When the resin is applied in uniform amounts, it causes a decrease in the board internal adhesion. Figure 5 shows that mixtures of W100R10, W90R10 accomplished the requirements of EN 312 (EN 2010) for Type P2 (0.35 MPa), while mixtures of W80R10, W90R8, and W70R10 accomplished the requirements of EN 312 (EN 2010) for Type P1 boards (0.24 MPa).

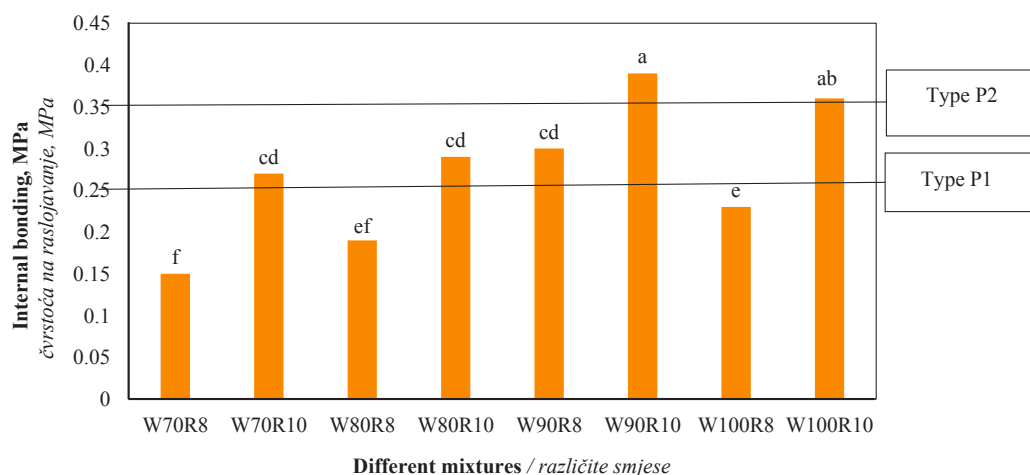


Figure 4 The effect of different mixtures on internal bonding

Slika 4. Utjecaj različitih smjesa na čvrstoću na raslojavanje

Table 4 Results of data analysis for board internal bonding strength**Tablica 4.** Rezultati analize podataka za čvrstoću ploča na raslojavanje

Parameter Parametar	Source of variance Izvor varijance	Degrees of freedom Stupnjevi slobode	Mean square Srednji kvadrat	F value	P Sig.
Internal bonding čvrstoća na raslojavanje	Mixture / smjesa	3	0.019	13.726	0.000**
	Resin / smola	1	0.070	50.298	0.000**
	Mixture × Resin / smjesa × smola	3	0.001	0.361	0.022*
	Error / pogreška	16	0.001		
	Total / ukupno	23			

*Significance at the level of 95 %, ** significance at the level of 99 % / *Značajno na razini od 95 %, **značajno na razini od 99 %

3.3 Water absorption and thickness swelling

3.3. Upijanje vode i debljinsko bubrenje

The results showed that different factors had a significant effect on water absorption (WA) and thickness swelling (TS) after 24 hours of immersion in water at a 95 % confidence level (Table 5).

The TS and WA values of boards decreased with increasing resin content and proportion of mixture (Figure 5), because the melamine impregnated paper waste is waterproof (Babazadeh Lehi *et al.*, 2018). The density of the boards was constant, which indicates that the amount of particles in the boards decreased when the

amount of the melamine paper waste was increased. Also, by increasing the amount of melamine paper waste, the amount of hydrophilic wood material decreased (Silva *et al.*, 2012). The minimum TS and WA values were obtained in a mixture of 70 % industrial wood particles and 10 % UF resin (mixture W70R10).

4 CONCLUSIONS

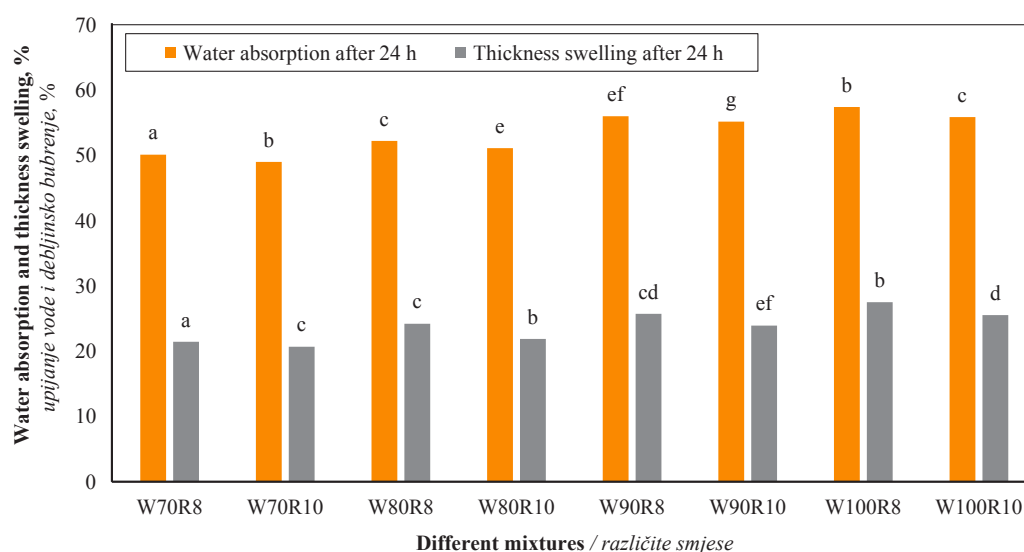
4. ZAKLJUČAK

The results showed that with increasing the resin content, the mechanical properties of the boards in-

Table 5 Results of variance analysis**Tablica 5.** Rezultati analize varijance

Parameter Parametar	Source of variance Izvor varijance	Degrees of freedom Stupnjevi slobode	Mean square Srednji kvadrat	F value	P Sig.
Water absorption after 24 h upijanje vode nakon 24 h	Mixture / smjesa	3	1461.200	13.537	0.000**
	Resin / smola	1	36.866	1.628	0.020*
	Mixture × Resin / smjesa × smola	3	162.156	0.028	0.023*
	Error / pogreška	16	1.297		
	Total / ukupno	23			
Thickness swelling after 24 h debljinsko bubrenje nakon 24 h	Mixture / smjesa	3	32.952	230.104	0.000**
	Resin / smola	1	17.665	123.352	0.000**
	Mixture × Resin / smjesa × smola	3	0.701	4.894	0.013*
	Error / pogreška	16	0.143		
	Total / ukupno	23			

*Significance at the level of 95 %, ** significance at the level of 99 % / *Značajno na razini od 95 %, **značajno na razini od 99 %

**Figure 5** The effect of different mixtures on board water absorption and thickness swelling**Slika 5.** Utjecaj različitih smjesa sirovine na upijanje vode i debljinsko bubrenje ploča

creased. Up to the level of 10 %, melamine-impregnated paper can act as a filler and improve the mechanical properties of boards; however, at higher contents (15 %), stress concentration results in a reduction in strength (Basboga *et al.*, 2016). With increasing the resin content and reducing the proportion of industrial wood particles, the physical properties of the boards decreased, as increasing the resin caused more fiber bonding and decreased water absorption. The amount of water absorption and thickness swelling of the boards decreased with reducing the proportion of industrial wood particles and increasing the amounts of pine wood, due to lower density and increased compression coefficient, and waterproofness of melamine paper waste.

According to the results obtained, boards containing 90 % industrial wood particles and 8 % resin (mixture W90R8) and boards containing 70 % and 80 % industrial wood particles and 10 % resin (mixture W70R10 and W80R10) can be used for general use (Type P1). In 10 % resin, the control sample (mixture W100R10) and 90 % industrial wood particles (mixture W90R10) can be used for interior fitments (Type P2). Considering that the aim is to reduce the amount of industrial wood particles and resin, boards containing 90 % industrial wood particles and 8 % resin (mixture W90R8) and boards containing 70 % industrial wood particles and 10 % resin (mixture W70R10) are recommended for Type P1 boards.

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Artificial Intelligence as a Tool for Marketing Communication and Innovation in Bedroom Furniture Production

Umjetna inteligencija kao alat za marketinšku komunikaciju i inovacije u proizvodnji namještaja za spavaće sobe

ORIGINAL SCIENTIFIC PAPER

Izvorni znanstveni rad

Received – prispjelo: 29. 1. 2026.

Accepted – prihvaćeno: 19. 4. 2026.

UDK: 630*88

<https://doi.org/10.5552/drind.2026.0332>

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ABSTRACT • *The study focuses on the impact of artificial intelligence (AI) on the creation of marketing communications in the furniture industry, specifically in the bedroom furniture segment, where research into consumer attitudes toward AI-generated content is still limited. The aim was to determine whether the method of creating marketing elements (AI vs. human) influences customer perception. The experiment involved the creation of a product name, advertising text, and visual presentation of a bedroom set by professional designers, students of marketing-oriented fields, and an AI system. The outputs were evaluated by Generation Z respondents. The data were analyzed using descriptive statistics and statistical hypothesis testing (Wilcoxon test). The results showed statistically significant differences between AI and professional processing. AI created visuals dominated in attractiveness and originality, while human proposals achieved better results in memorability and factual relevance of text advertising. The findings confirm that AI is a suitable support tool, but humans remain key in the area of visual and emotional communication.*

KEYWORDS: furniture; marketing communication; artificial intelligence; experiment

SAŽETAK • *U studiji se obrađuje utjecaj umjetne inteligencije (UI) na stvaranje marketinških komunikacija u industriji namještaja, posebice u segmentu namještaja za spavaće sobe, u kojemu je istraživanje stajališta potrošača prema sadržaju generiranom UI-jem još uvijek ograničeno. Cilj je bio utvrditi utječe li metoda stvaranja marketinških elemenata (UI – čovjek) na percepciju kupaca. Eksperiment je obuhvatio stvaranje naziva proizvoda, reklamnog teksta i vizualne prezentacije spavaćih soba od profesionalnih dizajnera, studenata marketinški orijentiranih područja i UI sustava. Izlazne rezultate procijenili su ispitanici generacije Z. Podatci su analizirani primjenom deskriptivne statistike i testiranjem statističkih hipoteza (Wilcoxonov test). Rezultati su pokazali statistički značajne razlike između UI i profesionalne obrade. Vizuali stvoreni UI-jem dominirali su po atraktivnosti i*

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originalnosti, dok su ljudski prijedlozi postigli bolje rezultate u pamtljivosti i činjeničnoj relevantnosti tekstualnog oglašavanja. Nalazi potvrđuju da je UI prikladan alat za potporu, ali ljudi ostaju ključni činitelj u području vizualne i emocionalne komunikacije.

KLJUČNE RIJEČI: namještaj; marketing; komunikacija; umjetna inteligencija; istraživanje

1 INTRODUCTION

1. UVOD

Artificial intelligence (AI) is increasingly applied across industries, driving innovation and technological progress (Zahra, 2023; Li *et al.*, 2024). In the furniture sector, AI accelerates design processes, and brings new opportunities for customer engagement, thereby improving the customer experience (Kariž *et al.*, 2024). Innovation and adaptability are key to creating value and meeting changing market needs (Rame *et al.*, 2023). Development is moving from intelligent and smart furniture to AI-based solutions, which increase production efficiency and product quality (Aboushall and Jalagat, 2024). AI is involved in the entire process from design to production and enables more personalized and sustainable solutions (Wang *et al.*, 2024; Faran, 2024), but it still does not replace the role of the designer, especially in the creative phase (Zahra, 2023). Kariž *et al.* (2024) present an overview of currently available solutions and new opportunities for the use of AI in the wood industry, pointing out its importance in marketing: It helps in the strategic planning of marketing activities and the sales process by providing insights derived from comprehensive market analyses. AI could help in creating marketing materials, communicating with customers, managing social networks and websites, analyzing competitors, predicting demand, etc.

It is evident that in today's environment, the use of artificial intelligence (AI) to improve the effectiveness of advertising campaigns is becoming increasingly important (Nesterenko and Olefirenko, 2023). According to Zhang and Hur (2025), the use of generative AI in marketing is growing along with industry interest in technology. The use of AI in advertising has significantly changed the way brands create and convey their marketing messages (Bui, 2025). According to Hermann and Puntoni (2024), generative AI significantly streamlines the preparation of marketing materials by enabling the rapid creation of personalized advertising texts and other communication outputs. According to Sicilia *et al.* (2025), artificial intelligence has opened up new space for creativity, which is reflected in its diverse use in creative advertising, especially in the generation of texts, images, music, voice, and sound. However, as claimed, for example by Kravets *et al.* (2025), it does not replace human editing but helps reduce the time and financial costs of their creation.

With the growing use of AI in creative advertising, it is important to evaluate its benefits and risks from the consumer's perspective (Sicilia *et al.*, 2025), as audience responses to AI-generated ads have not yet been sufficiently researched (Chen *et al.*, 2024) so that consumer responses to AI-generated advertising remain unclear. The study of Nesterenko and Olefirenko (2023) has shown statistically significant findings where those respondents liked the video created by AI more than that made by humans. Other studies indicate that ads in which the role of AI is apparent may increase online engagement but elicit more negative emotions and poorer ad ratings (Hanson *et al.*, 2025), while hybrid human-AI content with consumer engagement significantly influences brand perception and performs better (de Cicco *et al.*, 2025). These findings highlight the importance of transparency and maintaining the human element in AI-supported communication to preserve trust and authenticity (Kučinskis and Survilaitė, 2025).

Despite its rapid development, AI still has its limitations; it is strong at processing images but weaker at complex reasoning and contextual understanding (Maslej *et al.*, 2024; Chong, 2024). It also faces challenges such as a lack of implementation details, inappropriate usage of data sets, and unrealistic assumptions (Si *et al.*, 2024). Although AI can generate ideas, the role of humans remains crucial, as the successful use of AI depends on both technological and human factors, particularly the perceived usefulness of systems and a balanced approach to their implementation (Tursunbayeva *et al.*, 2024; Oliveira *et al.*, 2024; Rane *et al.*, 2024). To conclude, AI still has limitations in the areas of contextual understanding and complex reasoning (Maslej *et al.*, 2024; Chong, 2024), which is why the role of humans remains indispensable (Norton, 2023).

At the same time, however, research focused on consumer attitudes toward AI-generated marketing communications in the furniture industry, particularly in the bedroom furniture segment, remains limited. Therefore, in this study, an experiment is conducted to examine the attitudes toward AI generated marketing communication in furniture industry. The paper focuses exclusively on the results relating to the analyzed bedroom furniture set. Therefore, the research question is: Does the use of artificial intelligence in the development of marketing communication for a specific bedroom furniture set have an impact on customers?

The main aim of the study was to determine whether the use of artificial intelligence in the creation of marketing communication for a specific bedroom furniture set influences consumer perception.

Based on the stated research question, the following hypotheses were formulated:

Hypothesis H_0 – *There is not a statistically significant difference in respondents' evaluation of marketing communication created by artificial intelligence and marketing communication created by professional designers.*

Hypothesis H_1 – *There is a statistically significant difference in respondents' evaluation of marketing communication created by artificial intelligence and marketing communication created by professional designers.*

2 MATERIALS AND METHODS

2. MATERIJA I METODE

The focus of the paper was to compare the application of artificial intelligence, professional expertise, and human creativity in the creation of marketing communication.

The main research approach used in this study is the experimental research method. Three groups of subjects participated in the experimental research:

1. Professional – professional advertising designers from Decodom, a Slovak furniture manufacturer (2025);
2. Experts – graduates of study subjects focused on marketing and innovation management, who were selected based on their professional education and relevant knowledge of the subject matter;
3. AI – an artificial intelligence system provided by the Deeply.cz platform. The task for all participants was to design a product name and create a short advertising text for the Sklik text based on a visual presentation of a bedroom furniture set.

The professional proposal prepared by Decodom experts consisted of the product name, Sklik advertising text, and an original photograph of the analyzed bedroom furniture set. Sklik advertising was in the form of short text belonging to the chosen furniture product, which is a tool to display text and banner ads in search results (Netmarketer, 2025). Subsequently, a concept generated by artificial intelligence was created, which used the proposed product name and advertising text as input for the creation of the visual appearance of the bedroom furniture. The result of this process was two visual representations of the product, ten alternative names, and ten advertising texts, which served as experimental research material.

We designed the research tool as a questionnaire in which respondents rated selected characteristics on a

five-point Likert scale (1 – appropriate, 5 – inappropriate). The structure of the questions was based on a modified CRUSH model (Bergh, Behrer, 2012; Aaker, 2003) and focused on the following parameters: order, attractiveness, clarity, originality, emotional impact, credibility, memorability, and relevance to the product. The high level of internal consistency and reliability of the questionnaire was confirmed by Cronbach's alpha coefficient of 0.945. According to the methodology of Nunnally and Bernstein (1994), this result represents an excellent level of reliability, confirming that the items measure the concept under study consistently and that the data are suitable for further statistical analysis.

The selected bedroom furniture set was tested at the Technical University in Zvolen, with the experiment taking place in a simulated market environment. Respondents evaluated two visual versions of the product – one created by artificial intelligence and the other professionally processed by Decodom – along with the relevant marketing communications. The core group of respondents consisted of members of Generation Z. Given the experimental nature of the research, students of Economics and Management of Natural Resources were included in the research sample. The research sample consisted of fifteen students representing Generation Z as potential consumers, but also as future creators of creative marketing messages. This generation was also chosen because of its continuous contact with digital technologies and the online environment from an early age. This is the most technically sophisticated generation of all time (ConZoomer, 2023). The experiment was conducted during the summer semester of the 2024/2025 academic year.

Descriptive statistical methods were used to analyze the respondents' attitudes, specifically the arithmetic mean, median, and mode. The arithmetic mean was calculated as the ratio of the sum of the measured values to their number. The median divides the ordered set of values into two equal parts, each containing 50 % of the statistical units. The mode represents the value that occurs most frequently in the data set (Ostertagová, 2015). Given the use of a 5-point Likert scale (1 = appropriate, 5 = inappropriate), the focus was primarily on the median and mode in the interpretation.

Statistical hypothesis testing was used to verify the hypothesis, allowing for a comparison of respondents' attitudes towards marketing materials created by artificial intelligence and professional designers. A non-parametric Wilcoxon test was used to verify the existence of statistically significant differences in the perception of marketing outputs between artificial intelligence and professional creation. This test was chosen due to the ordinal nature of the data (Likert scale) and the small size of the research sample ($n=15$), which

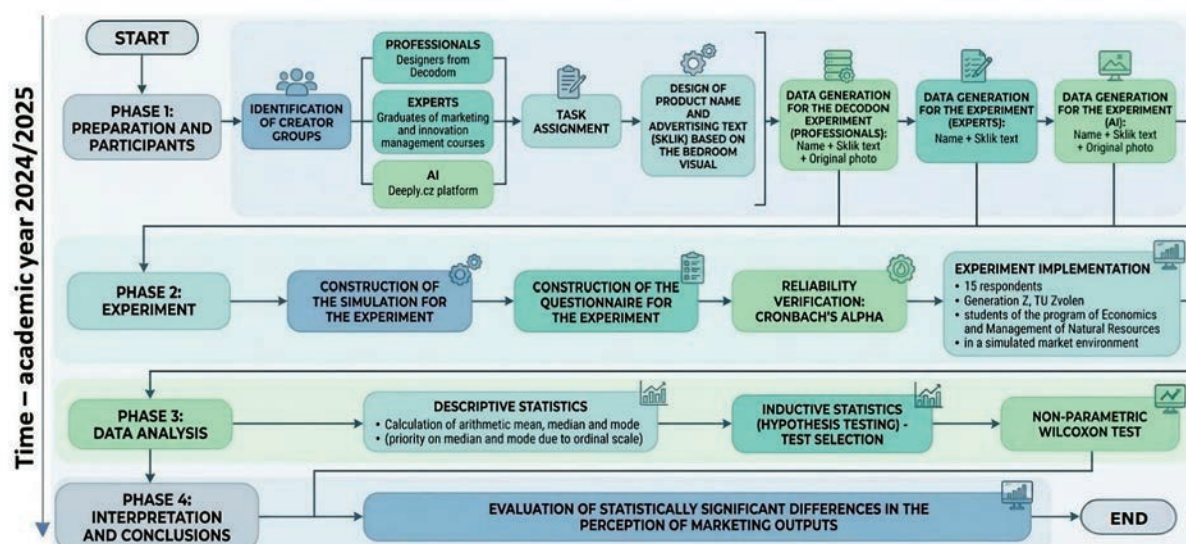


Figure 1 Research methodology
Slika 1. Metodologija istraživanja

is in line with methodological recommendations for this type of data (Okoye and Hosseini, 2024).

The entire methodological procedure is clearly depicted in Figure 1.

MS Excel, MS Word, Statistics SPSS 20 and Google functionalities were used for data analysis and evaluation.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

The present study provides a comprehensive experimental comparison of creative marketing outputs generated by three distinct groups: professional designers from Decodom, marketing and innovation graduates (experts), and the Deeply.cz AI platform (Table 1). Reflecting the 5-point Likert scale (1 = appropriate, 5 = inappropriate), the focus was primarily on the median and mode in the interpretation. Within the product naming task, AI emerged as the superior performer, securing the highest ratings for credibility (median 1, mode 1), attractiveness (median 2, mode 1) and comprehensibility (median 2, mode 1). Conversely, the professionally designed name was perceived as the least suitable, with medians at levels 3 and 4 (e.g. attractiveness: median 4, mode 4). Experts maintained a stable intermediate position with medians 2 and 3.

In Sklik advertising texts, AI dominated in comprehensibility (median 1, mode 1), originality (median 1, mode 1) and credibility (median 1, mode 1). Respondents considered the texts generated by AI to be highly suitable. In contrast, both professionals and experts recorded less favorable ratings in these categories (medians mostly 2 and 3). Paradoxically, AI underperformed significantly in memorability and relevance to the product, where it achieved a median of 4 (mode 4),

while humans (professionals and experts) achieved a median of 2 in these parameters. In the case of visuals – image proposals, AI again received the best rating. Respondents rated the AI visual as extremely suitable in attractiveness, clarity and originality (median 1 and mode 1 for all). The professionally created visual achieved less favorable results in these parameters (medians 2 and 3). The only parameter, where the professional design was perceived as comparable to AI, was emotional impact and relevance (median 1).

To verify the existence of statistically significant differences in the perception of marketing outputs between artificial intelligence and professional creation, a non-parametric Wilcoxon signed-rank test was used. The test results showed that the differences in the evaluation are statistically significant ($Z = -2.262$; $p = 0.024$). Since the achieved p-value was lower than the significance level ($\alpha = 0.05$), the null hypothesis of equal perception was rejected. Based on the above, it can be concluded that the origin of marketing content has a demonstrable impact on how the target group perceives and evaluates it. Based on the results, it is concluded that Generation Z respondents accept artificial intelligence suggestions better than professional suggestions and suggestions from experts. However, in the case of bedroom furniture names, expert (human) proposal performed better in emotional impact (mode 2) and originality (mode 3) than AI.

These findings are consistent with previous research (e.g., Zhang and Hur, 2025; Hanson *et al.*, 2025), which indicates the possible neutral or negative perception of AI solutions by customers, as well as poorer ratings. In line with de Cicco *et al.* (2025), who emphasize the effectiveness of hybrid human-AI content, our results confirm that the human factor and professional input remain crucial for quality and ethical

Table 1 Results

Tablica 1. Rezultati

Product name / Ime proizvoda									
Parameters studied / Proučavani parametri	Experts / Stručnjaci			Professional / Profesionalci			AI		
	Mean	Median	Mode	Mean	Median	Mode	Mean	Median	Mode
	2.68	3	3	3.53	4	4	2.33	2	1
	2.38	3	3	3.00	3	5	2.47	2	1
	2.24	3	3	3.07	3	4	3.00	3	3
	2.75	3	2	3.40	3	3	2.80	2	5
	2.33	2	2	3.00	3	3	2.20	1	1
	2.19	3	5	3.53	4	5	2.60	3	1
	2.45	2	2	3.07	3	4	3.67	3	1
	SKLIK TEXTS								
Parameters studied / Proučavani parametri	Experts / Stručnjaci			Professional / Profesionalci			AI		
	Mean	Median	Mode	Mean	Median	Mode	Mean	Median	Mode
	2.48	2	2	2.53	2	2	2.33	2	1
	1.92	2	1	2.27	2	3	1.67	1	1
	2.35	3	3	2.60	3	3	2.20	1	1
	2.57	2	2	3.00	3	3	2.47	2	1
	2.29	2	2	2.13	2	2	1.80	1	1
	2.19	3	1	2.13	2	2	3.60	4	4
	2.60	2	2	2.13	2	2	3.53	4	4

Table 1 Continued
Tablica 1. Nastavak

Visual display / Vizualni prikaz		Professional / Profesionalci				AI			
									
Attractiveness / atraktivnost		Mean	Median	Mode		Mean	Median	Mode	
Comprehensibility / razumljivost		2.00	2	3		1.53	1	1	
Originality / originalnost		2.67	3	3		1.80	1	1	
Emotional impact / emocionalni utjecaj		2.67	3	4		1.27	1	1	
Trustworthiness and credibility / pouzdanost i kredibilitet		1.87	1	1		1.80	1	1	
Memorability / pamtljivost		2.67	3	3		1.67	2	1	
Relevance to the promoted product / relevantnost za promovirani proizvod		2.27	3	3		1.67	2	1	
		1.53	1	1		1.67	2	1	
Statistical testing / Statističko testiranje									
The Wilcoxon signed-rank test / Wilcoxonov test predznačenih rangova		-2.262							
p-value / p-vrijednost		0.024							
Hypothesis testing / testiranje hipoteze		The hypothesis H_0 is rejected / Hipoteza H_0 je odbačena							
Note: Statistical significance was tested using the Wilcoxon signed-rank test ($\alpha = 0.05$). Napomena: Statistička značajnost testirana je Wilcoxonovim testom predznačenih rangova ($\alpha = 0.05$).									

oversight. Although AI can generate inspiring ideas, achieving significantly better results in the visual intelligence category (mode 1), from a textual perspective, it lacks the deeper human understanding and empathy needed for this type of industry. These results underline the importance of transparency and maintaining the human element in AI-supported communication to preserve trust and perceived authenticity (Kučinskas and Survilaitė, 2025).

As to text advertising (Slik advertising), our findings support the conclusions of Si *et al.* (2024) regarding the usefulness of AI, as AI-generated texts achieved even better results in attractiveness, comprehensibility and originality (mode 1) than experts-generated versions. This indicates that AI can outperform traditional methods in certain technical aspects, such as text structure and relevance, but not in more complex visual and emotionally motivated tasks and customer memorability (mode 4 for AI, mode 1 for experts, mode 2 for professional design). The statistically significant differences observed thus indicate that AI should be considered as a supportive tool that requires expert human supervision (Zahra, 2023; Ashkinaze *et al.*, 2024).

Both the literature and data collected indicate that while AI can contribute to innovation, human intervention is essential for ethical review and quality assurance (Ashkinaze *et al.*, 2024; Kelly *et al.*, 2023). AI cannot fully replace human intelligence (Norton, 2023), which is also reflected in our findings, where professionally created product name outperformed AI-generated visuals in aesthetic and emotional impacts. The human factor outperformed AI in Slik texts in the parameters examined – text memorability and relevance to the promoted product.

In the dynamic environment of digital marketing, companies should therefore adopt strategies to mitigate these risks and carefully consider where creativity has the greatest impact. At the same time, there is a need for new employee skills, as the nature and degree of creativity required may differ from traditional marketing approaches (Ameen *et al.*, 2022).

These findings suggest that the furniture industry should embrace digital trends to sustain growth, but with an emphasis on the balanced integration of technology and professional expertise. Innovation and adaptability to trends are key to creating value, but the professionalism of the human factor appears to be particularly important in specific tasks such as visual identity and emotional credibility. At the same time, the material dimension should not be overlooked, as wood and wood-based materials are often associated with feelings of warmth, naturalness, and comfort (e.g. Kaputa *et al.*, 2018; Jošt *et al.*, 2020; Loučanová *et al.*, 2024), which can evoke positive emotional responses

in consumers. Promoting these emotional associations through appropriate visual and communication strategies can further increase the perceived value of bedroom furniture.

A limitation of the research is that the appeal and comprehensibility of designs created using AI were evaluated by customers, which represents a subjective assessment influenced by individual preferences, as well as the composition of the research sample, which consisted of students with a marketing education. Their specific educational background may influence their perception of advertising content, which limits the generalizability of the results to the general consumer population, since this group may evaluate advertising stimuli with a different degree of criticality or knowledge. Furthermore, the study focused on only one specific bedroom furniture set, which may limit the generalizability of the results to other types of furniture or products. However, the findings create opportunities for future applications to other products and provide impetus for the wider use of artificial intelligence in furniture marketing communications. Its overly general approach to artificial intelligence is also a limitation, and for a more in-depth analysis, it would be necessary to compare human creativity with specific types of algorithms and their particular logic.

4 CONCLUSIONS

4. ZAKLJUČAK

The development of artificial intelligence (AI) brings new opportunities in the field of marketing communication, but our research focused on consumer attitudes towards AI-generated content in the furniture industry, especially in the bedroom furniture segment, which is still limited. Through an experimental comparison of the creative output of professional designers, experts -graduates, and the AI system Deeply.cz, this study provided important insights into how Generation Z perceives creativity in a simulated market environment. The results of the study focusing on specific bedroom furniture set showed statistically significant differences in the perception of marketing communication depending on whether it was created by AI or a professional. Professionally proposed product name achieved the highest ratings, particularly in terms of emotional impact and originality compared to AI. AI lagged significantly behind in terms of credibility and visual persuasiveness. The results indicate that AI-generated solutions significantly outperformed professional ones in terms of attractiveness and comprehensibility, while professional proposals achieved better results in trustworthiness and credibility (name and text proposal) compared to AI. The findings suggest that AI is a highly effective tool for generating attractive visual

contents and structured advertising texts. Nevertheless, the human factor remains indispensable for ensuring product relevance and long-term memorability of the message, which are areas where AI still faces limitations. The study highlights the need for a balanced integration of technology and professional expertise in marketing communication. The limitations of the research include the small sample size of selected students that may not represent the typical Generation Z furniture consumer and focus on a single product, which limits the generalizability of the results. These limitations define the direction of future research: in addition to simply expanding the number of products studied, it would be desirable to examine the diversity of AI models and their individual contributions to human creativity. However, the results provide ideas for further research and practical applications of AI in furniture marketing.

Acknowledgements – Zahvala

This paper was supported by the Ministry of Education, Research, Development and Youth of Slovak Republic and processed within grants VEGA 1/0513/25 and KEGA 016TU Z-4/2025.

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Comparison of Some Mechanical Performances of UV Varnish Systems Used in Furniture and Yacht Manufacturing

Usporedba mehaničkih svojstava UV lakova koji se upotrebljavaju u proizvodnji namještaja i gradnji jahti

ORIGINAL SCIENTIFIC PAPER

Izvorni znanstveni rad

Received – prispjelo: 15. 2. 2026.

Accepted – prihvaćeno: 23. 5. 2026.

UDK: 630*84; 674.07

<https://doi.org/10.5552/drind.2026.0336>

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ABSTRACT • This study comparatively evaluated the scratch and abrasion resistance of daylight UV-curable and high-energy UV-curable varnish systems applied to Scots pine (*Pinus sylvestris* L.), oriental beech (*Fagus orientalis* L.), and mahogany (*Khaya ivorensis*) wood species commonly used in furniture and yacht manufacturing. Scratch resistance was determined using a progressive loading method, while abrasion resistance was assessed based on mass loss using a Taber abrasion testing machine. The results indicated that both wood species and varnish type had statistically significant effects on scratch and abrasion resistance. High-energy UV-curable varnish systems exhibited significantly higher scratch resistance than daylight UV-curable systems across all wood species. In abrasion resistance, mahogany showed the lowest mass loss (0.11 g), indicating the highest resistance, whereas Scots pine and oriental beech exhibited higher mass loss values (0.20 g). The findings suggest that varnish type has a stronger influence on scratch resistance, whereas abrasion resistance is more closely related to wood species characteristics. Overall, high-energy UV-curable varnishes provide superior surface performance in applications requiring high durability.

KEYWORDS: daylight UV-curable varnishes; high-energy UV-cured varnishes; scratch resistance, abrasion resistance

SAŽETAK • U ovom je istraživanju provedena usporedna ocjena otpornosti na ogrebotine i habanje dvaju sustava lakova: onih koji otvrdnjavaju pod utjecajem dijela Sunčeve UV svjetlosti te onih koji otvrdnjavaju pod utjecajem visokoenergetskog UV zračenja. Sustavi lakiranja nanoseni su na uzorke borovine (*Pinus sylvestris* L.), kavkaske bukovine (*Fagus orientalis* L.) i drva mahagonija (*Khaya ivorensis*) kao drvnih vrsta koje se najčešće primjenjuju u proizvodnji namještaja i gradnji jahti. Otpornost na ogrebotine određena je metodom postupnog

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povećanja opterećenja, dok je otpornost na habanje ispitana mjerenjem gubitka mase uz pomoć Taber abraser uređaja. Rezultati su pokazali da i vrsta drva i tip laka statistički značajno utječu na otpornost na ogrebotine i na habanje. Visokoenergetski UV lakovi pokazali su znatno veću otpornost na ogrebotine od dnevnih UV lakova na svim ispitivanim vrstama drva. Pri ispitivanju otpornosti na habanje drvo mahagonija zabilježilo je najmanji gubitak mase (0,11 g), što upućuje na najveću otpornost tog drva na habanje, dok su borovina i kavkaska bukovina imale veće gubitke mase (0,20 g). Dobiveni rezultati potvrđuju da tip laka znatnije utječe na otpornost na ogrebotine, dok je otpornost na habanje više povezana sa svojstvima drva. Zaključno, visokoenergetski UV lakovi osiguravaju vrhunska površinska svojstva u primjenama koje zahtijevaju veliku trajnost i otpornost na trošenje.

KLJUČNE RIJEČI: UV lakovi koji otvrdnjavaju pod utjecajem dijela Sunčeve UV svjetlosti; UV lakovi koji otvrdnjavaju zbog djelovanja visokoenergetskog UV zračenja; otpornost na ogrebotine; otpornost na habanje

1 INTRODUCTION

1. UVOD

In mega yachts operating under open-sea conditions, cracking of varnish layers at the joints of fixed furniture and decorative wooden elements represents a frequently encountered durability problem. During navigation, vessels are exposed to dynamic loads and repetitive wave-induced shock impacts, which generate cyclic stresses on interior components. Simultaneously, wooden materials used in interior applications undergo dimensional changes due to high ambient humidity and pronounced day–night temperature fluctuations, leading to repeated swelling and shrinkage. Although the use of advanced lamination adhesives has significantly enhanced the dimensional stability of wooden substrates, the coating systems applied to these surfaces may not always exhibit sufficient elasticity to accommodate substrate movement. As a result, incompatibility between the mechanical behavior of the varnish film and the hygroscopic movement of wood can induce surface deformations and cracking over time. To mitigate this problem, laminated wood materials have increasingly been adopted in yacht interiors, a practice that continues today due to their improved dimensional stability compared to solid wood. Nevertheless, despite these advancements, coating failures such as cracking have not been entirely eliminated. Alternative materials, including carbon fiber and other advanced composites, offer superior mechanical performance and resistance to environmental stresses; however, they fail to replicate the aesthetic qualities, tactile warmth, and natural appearance of wood. In the mega-yacht market, owners and clients generally expect interiors characterized by high-quality craftsmanship and extensive use of natural wood elements, reflecting both luxury and traditional maritime design values (Tunçgenç, 2023).

Turkey holds a significant position in the world of mega yacht manufacturing. Mega yachts up to 70 meters in length are produced, particularly in shipyards located in Antalya and Istanbul. In the Antalya Free Zone in particular, numerous luxury yachts are manufactured and outfitted, benefiting from advanced ship-

yard infrastructure and creating substantial export volumes of high-end vessels. Within these facilities, daylight-curing UV varnishes are widely employed by manufacturers to protect wooden components due to their rapid curing and enhanced resistance to ultraviolet degradation, reflecting prevalent industry practices in Turkish mega yacht finishing. In mega yachts operating under open-sea conditions, one of the most critical durability issues observed in fixed interior furniture is the cracking of varnish layers at joint regions. These failures primarily result from flexural stresses induced by high wave impacts, which generate cyclic deformation at connection points of built-in furniture systems. In addition, temperature fluctuations and elevated humidity levels contribute to dimensional changes in wooden flooring materials, leading to surface deformations and coating distress. Considering these service conditions, research efforts have increasingly focused on wood species selection and varnish system performance to enhance coating durability under marine environments. Selected examples of these studies are presented below.

Altıparmak (2017) comparatively evaluated the scratch resistance of yacht, polyurethane, and epoxy varnishes applied to sapele, chestnut and limba wood. The results demonstrated that yacht varnish consistently provided the highest scratch resistance across all wood species, whereas epoxy coatings exhibited comparatively lower performance. Statistical assessment revealed that varnish type was the dominant factor affecting scratch resistance, followed by wood species. Accordingly, the use of yacht varnish was recommended for applications where enhanced scratch durability is required.

Söğütü *et al.* (2017) evaluated the abrasion and scratch resistance of polyurethane, single- and two-component water-based, and synthetic varnishes applied to sapele wood (*Entandrophragma cylindricum*) in radial and tangential sections. Varnish type significantly affected both properties, whereas cutting direction was not statistically significant. Polyurethane coating exhibited superior abrasion and scratch resistance, whereas yacht varnish performed comparatively

lower; comparative analysis indicated no significant variation between the water-based formulations.

Aykaç and Sofuoğlu (2021) examined the performance of cellulose, synthetic, polyurethane, and water-based varnishes applied to bamboo (*Bambusa*) surfaces commonly used in the furniture industry. Coating hardness, gloss, color change, and film thickness were assessed. The results showed that, except for polyurethane, all varnishes reduced surface hardness compared to the control. Gloss values increased up to three-fold, while synthetic varnish caused the greatest shift toward yellow–red tones and exhibited the highest total color change (ΔE^*); the minimum total color difference was recorded for the water-based system. The greatest film thickness was obtained with cellulose varnish, whereas the water-based coating produced the thinnest layer.

Tekin (2009) evaluated the abrasion resistance of synthetic, polyurethane, water-based, acid-catalyzed, and cellulose varnishes applied in one to three layers on several wood species. Abrasion resistance was significantly influenced by wood species, varnish system, and coating thickness. The highest performance was achieved with walnut coated with three layers of acid-catalyzed varnish, while the lowest was observed in linden with a single layer of water-based varnish. Wood species and varnish type were identified as the dominant factors, followed by layer thickness.

Numerous studies on coating performance have primarily focused on cellulosic, solvent-based, and water-based varnishes applied to different wood substrates (Ugulino *et al.* 2017; Budakçı *et al.* 2017), particularly for indoor furniture applications. In humid environments such as kitchens and bathrooms, vinyl coatings have been used; however, water-based and UV-curable systems are generally recommended due to their improved environmental and performance characteristics (Philipp, 2010). Accordingly, water-based and UV-curing technologies are widely recognized as effective and sustainable solutions for wood finishing processes (Salca, 2016; Gürleyen *et al.*, 2017).

Recent research on UV-curable coating systems has focused on varnishes cured at different wavelength ranges, with particular emphasis on optimizing resin formulations and photoinitiator chemistry. These developments aim to reduce energy consumption while improving coating flexibility and application performance. Despite their high curing efficiency, conventional high-energy UV systems require specialized equipment and substantial capital investment, limiting their adoption in small and medium-sized enterprises. In contrast, daylight-curable UV systems offer lower equipment costs and greater practical applicability for smaller-scale manufacturers. Ongoing studies continue

to promote the broader industrial implementation of UV-based coating technologies.

Göktaş *et al.* (2024) compared the effects of mechanical and ultrasonic-assisted mixing on the surface hardness and scratch resistance of varnish systems applied to Oriental beech, Scots pine, and mahogany. The highest scratch resistance values were obtained in polyester varnish mixed mechanically for 5 minutes and in acrylic varnish subjected to low-power (80 W) ultrasonic treatment. In contrast, high-power ultrasonic applications negatively affected scratch performance. Overall, ultrasonic-assisted mixing did not provide a consistent improvement over conventional mechanical mixing in terms of coating performance.

Akdemir *et al.* (2024) investigated the influence of mechanical and ultrasonic-assisted mixing of varnish components on adhesion strength, surface roughness, and gloss of polyurethane, acrylic, and polyester systems applied to mahogany, Oriental beech, and Scots pine. The findings indicated that ultrasonic mixing did not demonstrate a clear superiority over conventional mechanical stirring; however, ultrasonic treatment at 80 W for 3 minutes was suggested as a potentially favorable condition in terms of overall coating performance.

UV-curable coatings are widely applied to heat-sensitive substrates such as wooden furniture, parquet flooring, and plastic products due to their rapid curing and low thermal load (Schwalm, 2006). However, despite their extensive industrial use, the literature provides limited comprehensive studies comparing the performance characteristics of different UV-curable systems under varying application and service conditions.

When other studies on UV varnish system are examined, it is evident that scratch and abrasion performance mainly depends on coating formulation, crosslink density, and application parameters. Higher crosslink density improves surface hardness and scratch resistance, although excessive rigidity may lead to brittleness (Bertrand-Lambotte *et al.*, 2021). Coating thickness and layer number are also critical factors influencing abrasion resistance, with optimal thickness providing better performance (Papp *et al.* 2018). In addition, curing conditions and chemical structure significantly affect surface durability, while additives and multilayer systems enhance performance (Henke *et al.*, 2023; Bongiovanni *et al.*, 2002). Overall, the mechanical performance of UV varnish systems is governed by multiple interacting parameters that must be optimized for improved results.

This study compares the performance of two different UV-cured varnish systems with very short drying times and high film resistance. The main reason for preferring UV-cured varnish systems, in practice, is

that UV-cured systems represent the latest technology in wood painting technology and their use is rapidly increasing worldwide. Both high-energy UV-cured and daylight-cured UV varnishes were applied to different wood surfaces, and performance tests were conducted to determine which system provides more technical advantages in furniture and mega yachts. There is insufficient research on UV varnishes in the literature. This study will contribute to academic research and the manufacturing sector in this regard. In this respect, the study provides data that directly supports the application of UV varnish systems on the scratch and abrasion resistance of different woods.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

2.1 Wooden materials used in experiments

2.1. Drveni materijali uključeni u istraživanje

Within the scope of the study, commonly utilized wood species Scots pine (*Pinus sylvestris* L.), oriental beech (*Fagus orientalis* L.), and mahogany (*Khaya ivorensis*) were selected as the primary substrates for experimental evaluation.

2.2 Varnishes used in experiments

2.2. Lakovi upotrijebljeni u istraživanju

Two types of varnish systems were applied to the experimental samples in this research. These are acryl-



Figure 1 Samples used in experiments
Slika 1. Ispitni uzorci



ic-based varnishes cured with UV light energy at daylight wavelength and acrylic-based systems cured with high UV light energy.

2.3 Preparation of experimental samples

2.3. Priprema ispitnih uzoraka

The samples used in the scratch and abrasion tests were prepared from Scots pine (*Pinus sylvestris* L.), oriental beech (*Fagus orientalis* L.), and mahogany (*Khaya ivorensis*) wood according to TS 2470 (TS 2470 1976). The dimensions of the test samples used in the experiment are given below:

Sample dimensions for scratch tests

(100 × 100 × 5 mm)

Sample dimensions for abrasion tests

(100 × 100 × 5 mm)

Experimental specimens measuring 100 × 100 × 5 mm were initially acclimatized under standardized laboratory conditions (20 ± 2 °C and 65 ± 3 % relative humidity) and maintained until equilibrium moisture content was achieved. Then, the experimental samples were prepared by applying daylight-curing UV varnishes with a spray gun and high-power UV-curable coating systems with an automatic machine to the wood surfaces (Figure 1).

2.4 Preparation and application of varnishes

2.4. Priprema i nanošenje lakova

Daylight UV-curable varnishes consisted of varnish (100 parts), hardener (100 parts), and photoinitiator (2 parts). After mixing, the formulation was diluted with polyurethane thinner to 30 s (DIN Cup 4) and applied by spray gun.

High-energy UV-curable varnishes were single-component systems containing pre-incorporated photoinitiator. They were diluted to 12–14 s (DIN Cup 4) and applied using an automatic spray system. Images showing the application of daylight and high-energy UV-curable varnishes are given in Figure 2.

Daylight UV system application: Panels were sanded sequentially with 120-, 150-, and 180-grit abra-



Figure 2 Images of the application process of daylight UV-curable and high-energy UV-curable varnishes
Slika 2. Prikaz postupka nanošenja UV lakova

sives. A filler coat (120 g/m²) was applied, followed by 10 min flash-off and 10 min UV curing using a hand-held mercury lamp (320–400 nm). After sanding (220 grit), a second filler coat (10 g/m²) was applied and cured again. Final sanding (220–400 grit) was followed by application of a 120 g/m² topcoat and curing. Application was performed using an HVLP spray gun (0.9 mm nozzle, 3 bar). The daylight UV system used a manually operated mercury lamp system (AkzoNobel Kemipol). This system operates in the 320–400 nm range and is suitable for on-site applications and fixed furniture surfaces. Its investment cost is approximately 45 times lower than that of high-energy systems.

High-energy UV system application: Filler varnish (120 g/m²) was applied and flashed off for 10 min in a tunnel oven at 25 °C (Superfici). Curing was performed using a mercury UV lamp (120 W/cm, 400–450 mJ/cm², 320–400 nm). The process was repeated for the second filler layer. After sanding (220–400 grit), a topcoat (120 g/m²) was applied and cured under identical UV conditions. Application was carried out using a Superfici Compact automatic spray system equipped with a Kremlin pump and Airmix guns.

2.5 Scratch and abrasion tests

2.5. Ispitivanje otpornosti na ogrebotine i habanje

Scratch and abrasion tests were performed according to TS EN 15186 (2012) and TS 4755 (1986) at the AkzoNobel Kemipol R&D laboratory.

Scratch test: Scratch resistance was measured using a diamond stylus under increasing loads (0.1 N increments) (Figure 3). The scratch value was defined as the minimum load causing visible coating failure after one circular pass. Evaluations distinguished between elastic deformation and true film failure under controlled illumination.

Abrasion test: Abrasion resistance was determined using a Taber abrasion tester under 5,000 cycles with 500 g load. Mass loss was measured using a 0.0001 g precision balance. Mass loss was used as the main evaluation criterion due to differences in coating flexibility between systems. Samples were weighed before and after testing (Figure 4).

2.6 Experimental design and statistical analysis

2.6. Plan pokusa i statistička analiza

A total of 60 specimens were prepared (3 wood species × 2 varnish types × 2 tests × 5 replicates). Scratch and abrasion tests were conducted separately. A general linear model (GLM) was used to evaluate the effects of wood species, varnish type, and their interaction at a 5 % significance level. Significant differences were analyzed using the LSD test. Statistical analyses were performed using Minitab (Version 17, 2023).

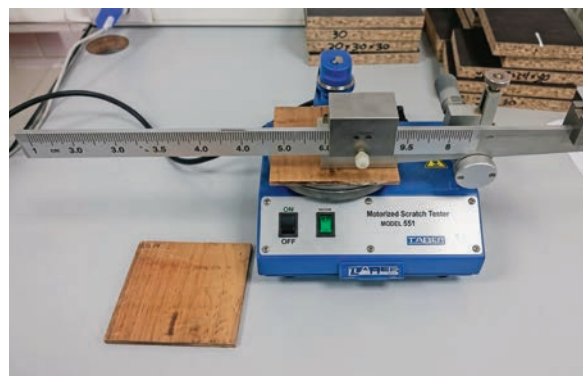


Figure 3 Erichsen Universal 413 scratch tester
Slika 3. Uređaj za ispitivanje otpornosti na ogrebotine Erichsen Universal 413



Figure 4 Taber 5135 abrasion tester
Slika 4. Uređaj za ispitivanje otpornosti na habanje Taber 5135

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

The results of scratch and abrasion resistance tests are given in Table 1.

Overall, both wood species and varnish type had a clear influence on surface performance, with significant differences observed between treatment groups.

3.1 Scratch resistance results

3.1. Rezultati mjerenja otpornosti na ogrebotine

High-energy UV-curable varnishes exhibited significantly higher scratch resistance compared to daylight UV-curable systems for all wood species. The highest scratch resistance was recorded in Scots pine treated with high-energy UV varnish (0.70 N), while the lowest values were observed in daylight-coated Scots pine and mahogany samples (0.10 N).

Among wood species, Scots pine and oriental beech showed relatively higher scratch resistance compared to mahogany when coated with high-energy UV systems. This suggests that both coating formulation and substrate structure play a combined role in determining surface hardness and resistance to mechanical

Table 1 Mean scratch and abrasion resistance ($\pm$ SD) of varnished wood specimens**Tablica 1.** Srednje vrijednosti otpornosti na ogrebotine i habanje ($\pm$ SD) lakiranih uzoraka drva

Wood species <i>Vrsta drva</i>	Varnish type / <i>Vrsta laka</i>	Scratch resistance, N <i>Otpornost na ogrebotine, N</i>	Abrasion mass loss, g <i>Gubitak mase nakon habanja, g</i>
Scots pine <i>borovina</i>	Daylight UV-curable varnish <i>dnevni UV lak</i>	0.10 $\pm$ 0.00	0.15 $\pm$ 0.04
	High-energy UV-curable varnish <i>visokoenergetski UV lak</i>	0.70 $\pm$ 0.07	0.09 $\pm$ 0.02
Oriental beech <i>kavkaska bukovina</i>	Daylight UV-curable varnish <i>dnevni UV lak</i>	0.24 $\pm$ 0.05	0.22 $\pm$ 0.04
	High-energy UV-curable varnish <i>visokoenergetski UV lak</i>	0.48 $\pm$ 0.04	0.18 $\pm$ 0.02
Mahogany <i>drvo mahagonija</i>	Daylight UV-curable varnish <i>dnevni UV lak</i>	0.10 $\pm$ 0.00	0.14 $\pm$ 0.02
	High-energy UV-curable varnish <i>visokoenergetski UV lak</i>	0.46 $\pm$ 0.04	0.09 $\pm$ 0.01

Table 2 ANOVA results for the effects of wood species and varnish type on scratch resistance**Tablica 2.** Rezultati analize varijance (ANOVA) za utjecaj vrste drva i laka na otpornost na ogrebotine

Sources of variance <i>Izvori varijance</i>	Sum of squares <i>Zbroj kvadrata</i>	Degrees of freedom <i>Stupnjevi slobode</i>	Mean squares <i>Srednji kvadrati</i>	F-Value <i>F-vrijednost</i>	Probability of error ($p < 0.05$) <i>Vjerojatnost pogreške ($p < 0,05$)</i>
Wood species / <i>vrsta drva</i>	0.07467	2	0.03733	17.23	0.000
Varnish type / <i>vrsta laka</i>	1.20000	1	1.20000	553.85	0.000
Wood species $\times$ Varnish type <i>vrsta drva $\times$ vrsta laka</i>	0.16800	2	0.08400	38.77	0.000
Error / <i>pogreška</i>	0.05200	24	0.00217	—	—
Total / <i>ukupno</i>	1.49467	29	—	—	—

Table 3 Multiple comparison results of scratch resistance values among wood species**Tablica 3.** Rezultati višestruke usporedbe vrijednosti otpornosti na ogrebotine ispitivanih vrsta drva

Wood species <i>Vrsta drva</i>	Mean, N <i>Srednja vrijednost, N</i>	Homogeneity group (HG) <i>Homogena skupina (HG)</i>
Oriental beech <i>kavkaska bukovina</i>	0.36	A
Mahogany <i>drvo mahagonija</i>	0.28	B
Scots pine <i>borovina</i>	0.40	A

damage. The results of the analysis of variance (ANOVA) regarding the effects of wood species and varnish type on scratch resistance are presented in Table 2.

According to the ANOVA results, the effects of wood species, varnish type, and the wood species $\times$ varnish type interaction on scratch resistance were evaluated. The results showed that all main factors and their interaction were statistically significant ($p < 0.05$), indicating that both individual and combined effects of wood species and varnish type significantly influenced scratch resistance. The results of the multiple comparison test for scratch resistance according to wood species are presented in Table 3.

According to the comparative analysis of scratch resistance values among wood species, the highest re-

sistance was recorded in Scots pine specimens (0.40 N), followed by Oriental beech (0.36 N), whereas the lowest value was obtained in mahogany samples (0.28 N). These findings indicate that scratch resistance is not solely governed by the coating system but is also strongly influenced by the anatomical and physical properties of the wood substrate.

The relatively higher performance observed in Scots pine and oriental beech may be attributed to their favorable fiber structure, higher density, and more effective varnish-substrate interaction. In contrast, the more porous structure and lower surface integrity of mahogany likely impaired coating uniformity, resulting in reduced scratch resistance.

These results are consistent with previous studies (Söğütü *et al.*, 2017; Tekin, 2009), which reported that scratch and abrasion resistance are closely related to wood species and density. Accordingly, the selection of an appropriate wood substrate is a critical factor in enhancing surface durability in UV-coated applications, particularly in furniture and mega-yacht manufacturing. The comparative results of scratch resistance based on varnish type are presented in Table 4.

The comparative analysis of scratch resistance among varnish types revealed that high-energy UV-curable systems exhibited the highest resistance (0.55 N), whereas daylight UV-curable coatings showed the

lowest performance (0.15 N). These findings are consistent with Söğütü *et al.* (2017), who reported that scratch resistance is strongly dependent on coating system characteristics.

The superior performance of high-energy UV-curable systems can be attributed to their higher degree of photopolymerization and increased crosslink density, resulting in the formation of a more compact three-dimensional network structure. This dense network enhances surface hardness and resistance to mechanical penetration, thereby improving scratch resistance (Schwalm, 2006; Salca, 2016).

In contrast, daylight UV-curable systems operate under lower energy activation conditions, which may limit the extent of polymer crosslinking. Consequently, a less densely crosslinked polymer network with higher segmental mobility is formed, leading to reduced surface hardness and lower resistance to scratch formation. As a result, these coatings are more susceptible to deformation under applied load. Table 5 presents the results of the multiple comparison test for scratch resistance values based on the interaction between wood species and varnish type.

According to the interaction analysis between wood species and varnish type, a pronounced combined effect of substrate and coating system on scratch resistance was observed. The highest scratch resistance

(0.70 N) was recorded in Scots pine coated with high-energy UV-curable varnish, whereas the lowest value (0.10 N) was observed in Scots pine and mahogany specimens coated with daylight UV-curable systems.

The homogeneity groupings indicated that high-energy UV-curable coatings consistently resulted in higher scratch resistance across all wood species. However, the magnitude of this improvement varied depending on the substrate, confirming a significant interaction between wood species and varnish type. In contrast, daylight UV-curable systems consistently exhibited lower performance, regardless of wood type.

These findings are consistent with Söğütü *et al.* (2017), who reported that coating type plays a critical role in determining scratch resistance. The lower performance of daylight UV-curable systems can be attributed to their lower curing energy, which limits the extent of photopolymerization and crosslinking. Consequently, a less densely crosslinked polymer network with higher chain mobility is formed, resulting in reduced surface hardness and lower resistance to mechanical scratching (Schwalm, 2006; Salca, 2016). Overall, the results suggest that both coating formulation and substrate characteristics influence scratch resistance; however, the curing mechanism and the resulting film structure appear to play a more decisive role under the conditions investigated.

Table 4 Multiple comparison results of scratch resistance values among varnish types

Tablica 4. Rezultati višestruke usporedbe vrijednosti otpornosti na ogrebotine upotrijebljenih vrsta lakova

Varnish type <i>Vrsta laka</i>	Mean, N <i>Srednja vrijednost, N</i>	Homogeneity group (HG) <i>Homogena skupina (HG)</i>
Daylight UV-curable varnish <i>dnevni UV lak</i>	0.15	B
High-energy UV-curable varnish <i>visokoenergetski UV lak</i>	0.55	A

Table 5 Interaction effects of wood species and varnish type on scratch resistance values

Tablica 5. Interakcijski utjecaji vrste drva i laka na otpornost na ogrebotine

Wood species <i>Vrsta drva</i>	Varnish type <i>Vrsta laka</i>	Mean, N <i>Srednja vrijednost, N</i>	Homogeneity group (HG) <i>Homogena skupina (HG)</i>
Oriental beech <i>kavkaska bukovina</i>	Daylight UV-curable varnish <i>dnevni UV lak</i>	0.24	C
	High-energy UV-curable varnish <i>visokoenergetski UV lak</i>	0.48	B
Mahogany <i>drvo mahagonija</i>	Daylight UV-curable varnish <i>dnevni UV lak</i>	0.10	D
	High-energy UV-curable varnish <i>visokoenergetski UV lak</i>	0.46	B
Scots pine <i>borovina</i>	Daylight UV-curable varnish <i>dnevni UV lak</i>	0.10	D
	High-energy UV-curable varnish <i>visokoenergetski UV lak</i>	0.70	A

3.2 Abrasion resistance results

3.2. Rezultati ispitivanja otpornosti na habanje

The results of the abrasion test are presented in Table 1. The test specimens were subjected to 5,000 abrasion cycles using a Taber abrasion testing machine, and abrasion performance was evaluated based on the resulting mass loss (g). The effects of wood species, varnish type, and their interaction on abrasion resistance were analyzed statistically, and the results are summarized in Table 6.

ANOVA results demonstrated the effects of wood species, varnish type, and their interaction on abrasion

Table 6 ANOVA results for abrasion resistance**Tablica 6.** Rezultati analize varijance (ANOVA) za otpornost na habanje

Sources of variance <i>Izvori varijance</i>	Sum of squares <i>Zbroj kvadrata</i>	Degrees of freedom <i>Stupnjevi slobode</i>	Mean squares <i>Srednji kvadrati</i>	F-Value <i>F-vrijednost</i>	Probability of error ($p < 0.05$) <i>Vjerojatnost pogreške ($p < 0,05$)</i>
Wood species / <i>vrsta drva</i>	0.048487	2	0.024243	27.14	0.001*
Varnish type / <i>vrsta laka</i>	0.018750	1	0.018750	20.99	0.001*
Wood species × Varnish type <i>vrsta drva × vrsta laka</i>	0.001460	2	0.000730	0.82	0.454
Error / <i>pogreška</i>	0.021440	24	0.000893	—	—
Total / <i>ukupno</i>	0.090137	29	—	—	—

* Indicates statistical significance at $p < 0.05$. / *Označava statistički značajnu razliku na razini $p < 0,05$.*

Table 7 Abrasion mass loss values according to wood species**Tablica 7.** Gubitak mase nakon habanja s obzirom na vrstu drva

Wood species <i>Vrsta drva</i>	Mean mass loss, g <i>Srednji gubitak mase, g</i>	Homogeneity group (HG) <i>Homogena skupina (HG)</i>
Oriental beech <i>kavkaska bukovina</i>	0.20	B
Mahogany	0.11	A
Mahogany <i>drvo mahagonija</i>	0.20	B

resistance. Wood species ($p < 0.001$) and varnish type ($p < 0.001$) showed statistically significant effects on abrasion resistance. In contrast, the interaction between wood species and varnish type was not statistically significant ($p = 0.454$), indicating that their combined effect did not contribute additional influence beyond their individual effects. Table 7 presents the comparative analysis of abrasion resistance values according to wood species.

The comparative analysis of abrasion resistance according to wood species showed that the lowest mass loss value (0.11 g) was recorded in mahogany samples, indicating the highest abrasion resistance among the tested wood species. In contrast, oriental beech and Scots pine exhibited higher mass loss values (0.20 g), corresponding to lower abrasion resistance. Since higher mass loss in abrasion tests indicates greater material removal and therefore lower performance, these results demonstrate that mahogany provided superior resistance to abrasive wear compared to the other wood species.

These findings suggest that abrasion performance is closely associated with the anatomical structure and surface characteristics of the wood substrate. The results are consistent with Tekin (2009), who reported significant variations in abrasion resistance depending on wood species. In denser and more homogeneous wood structures, improved coating–substrate interaction may enhance the integrity of the varnish film, thereby reducing material loss during abrasion testing. Conversely, more porous wood structures tend to ex-

Table 8 Abrasion mass loss values according to varnish type**Tablica 8.** Gubitak mase nakon habanja s obzirom na vrstu laka

Varnish type <i>Vrsta laka</i>	Mean mass loss, g <i>Srednji gubitak mase, g</i>	Homogeneity group (HG) <i>Homogena skupina (HG)</i>
Daylight UV-curable varnish <i>dnevni UV lak</i>	0.17	B
High-energy UV-curable varnish <i>visokoenergetski UV lak</i>	0.12	A

hibit weaker mechanical interlocking and reduced surface stability, which increases material removal under abrasive action. In this context, the superior abrasion resistance observed in mahogany can be attributed to its more favorable surface characteristics, which likely contributed to reduced mass loss during testing. The comparative results of abrasion resistance values according to varnish type are presented in Table 8.

The comparative analysis of abrasion resistance by varnish type revealed that the highest average mass loss (0.17 g) was obtained in daylight UV-curable varnish coatings, whereas the lowest mass loss (0.12 g) was recorded in high-energy UV-curable systems. Since higher mass loss indicates greater material removal and therefore lower abrasion resistance, these results demonstrate that high-energy UV systems exhibit superior abrasion resistance compared to daylight UV-curable coatings.

This improvement can be attributed to the denser crosslinked network formed under high-energy UV curing conditions, which enhances film integrity and reduces material loss under repetitive abrasion loads. These findings are consistent with Tekin (2009), who emphasized the decisive role of coating type in abrasion performance. In contrast, daylight UV-curable varnish systems, which form a less densely crosslinked and relatively more flexible/brittle film structure, are more susceptible to material removal under cyclic frictional stresses, resulting in lower abrasion resistance (Schwalm, 2006).

4 CONCLUSIONS

4. ZAKLJUČAK

This study comparatively evaluated the scratch and abrasion resistance of daylight UV-curable and high-energy UV-curable varnish systems applied to different wood species commonly used in furniture and yacht manufacturing. The findings demonstrated that both wood species and varnish type had significant effects on surface performance.

High-energy UV-curable varnish systems consistently exhibited higher scratch resistance compared to daylight UV-curable systems. The highest scratch resistance was obtained in Scots pine coated with high-energy UV varnish, indicating a notable interaction between curing energy and substrate characteristics.

In terms of abrasion resistance, lower mass loss values corresponded to higher resistance. Based on this criterion, mahogany exhibited the highest abrasion resistance, while Scots pine and oriental beech showed comparatively lower performance.

Overall, the results suggest that scratch resistance is more strongly influenced by varnish type, whereas abrasion resistance is more dependent on wood species. Accordingly, high-energy UV-curable systems may be preferred for applications requiring high scratch resistance, while daylight UV-curable systems may be suitable for less demanding surface performance conditions. The study provides practical guidance for the selection of wood substrates and UV-curable coating systems in furniture and megayacht manufacturing industries.

Acknowledgements – Zahvala

This paper is derived from the first author's Master of Science thesis completed at Muğla Sıtkı Koçman University, Institute of Science and Technology, Department of Wood Products Industrial Engineering (Tunçgenç, 2023). The authors gratefully acknowledge the Muğla Sıtkı Koçman University Scientific Research Projects Coordination Office (Project No: 13/177) for financial support of this research.

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In-Service Performance Assessment of a Traditional Timber House Under Real Environmental Conditions Using Ambient Vibration Measurements

Ponašanje tradicijske drvene kuće u stvarnim uvjetima eksploatacije procijenjeno mjerenjem ambijentalnih vibracija

ORIGINAL SCIENTIFIC PAPER

Izvorni znanstveni rad

Received – prispjelo: 9. 2. 2026.

Accepted – prihvaćeno: 3. 6. 2026.

UDK: 630*83

<https://doi.org/10.5552/drvind.2026.0333>

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ABSTRACT • Timber structures have gained increased attention in recent years due to sustainability-driven construction and the growing demand for reliable performance assessment of wood-based building systems under in-service conditions. Multi-storey bungalow-type timber structures require reliable performance assessment under real environmental conditions. However, such timber structures are continuously exposed to environmental actions that directly influence their stiffness-related dynamic performance. Therefore, the accurate determination of dynamic properties is essential, as these parameters serve as key indicators of the stiffness-related in-service performance and serviceability of timber structures. This study presents an in-service performance assessment of a two-storey traditional timber bungalow house and representative timber elements using a specially developed vibration measurement system, namely the Civil Engineering Vibration System (CEVS) and Civil Engineering Vibration Analysis (CEVA) software. Ambient vibration measurements were conducted under real environmental conditions and three different tension-based stiffening states (tensionless, normally tensioned, and fully tensioned). These states were defined as released, service-level, and fully tightened conditions of the tension-based stiffening elements. Experimental natural frequencies were determined as quantitative indicators of stiffness variation and mechanical performance under different tension-based stiffening levels. The identified natural frequencies ranged from 5.005 Hz to 18.066 Hz, and they consistently increased in the order of tensionless, normally tensioned, and fully tensioned states. The use of ambient vibration measurements enables a realistic evaluation of the in-service mechanical performance of the timber structure under actual environmental conditions. The results contribute to a better understanding of the in-service mechanical performance of timber structures and provide practical guidance for performance evaluation, stiffness assessment and potential strengthening decisions, and sustainable timber construction practices.

KEYWORDS: timber structures; in-service performance assessment; stiffness-related dynamic indicators; ambient vibration measurements; tension-based stiffening systems; traditional timber buildings

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SAŽETAK • Drvene su konstrukcije posljednjih godina privukle veliku pozornost zbog usmjerenosti gradnje prema održivosti te zbog sve veće potrebe za pouzdanom ocjenom stanja i ponašanja drvenih građevinskih sustava u eksploataciji. Višekatne drvene zgrade tipa bungalova zahtijevaju pouzdanu procjenu ponašanja u stvarnim okolišnim uvjetima. Međutim, takve su konstrukcije neprekidno izložene atmosferskim utjecajima koji izravno utječu na njihova dinamička svojstva povezana s krutošću. Stoga je ključno točno određivanje dinamičkih svojstava jer ti parametri služe kao glavni pokazatelji krutosti i uporabljivosti drvenih konstrukcija tijekom njihova korištenja. Ovo istraživanje pokazuje procjenu ponašanja dvokatne tradicijske drvene kuće tipa bungalova te njezinih reprezentativnih elemenata tijekom uporabe. Ispitivanje je provedeno uz pomoć posebno razvijenoga mjernog sustava odnosno računalnih programa Civil Engineering Vibration System (CEVS) i Civil Engineering Vibration Analysis (CEVA). Mjerenja ambijentalnih vibracija provedena su u stvarnim okolišnim uvjetima i pri tri različita stanja napetosti zatega: bez napetosti, pri uobičajenoj napetosti te pri potpunoj napetosti. Ta su stanja definirana kao otpušteno stanje, stanje na razini eksploatacije te potpuno pritegnuto stanje elemenata za ukrućenje. Eksperimentalno određene prirodne frekvencije poslužile su kao kvantitativni pokazatelji promjene krutosti i mehaničkog odziva pri različitim razinama napetosti zatega. Identificirane prirodne frekvencije kretale su se u rasponu od 5005 Hz do 18 066 Hz te su se dosljedno povećavale od stanja bez napetosti, preko uobičajene napetosti do potpune napetosti zatega. Mjerenje ambijentalnih vibracija omogućuje realnu procjenu mehaničkog ponašanja drvene konstrukcije tijekom eksploatacije u stvarnim okolišnim uvjetima. Rezultati pridonose boljem razumijevanju mehaničkog odziva drvenih konstrukcija tijekom njihove uporabe te daju praktične smjernice za procjenu ponašanja, ocjenu krutosti, donošenje odluka o njihovu eventualnom ojačanju, kao i za postizanje održivih praksi u gradnji drvom.

KLJUČNE RIJEČI: drvene konstrukcije; ocjena stanja u eksploataciji; dinamički pokazatelji krutosti; mjerenja ambijentalnih vibracija; sustavi ukrućenja sa zategama; tradicionalne drvene zgrade

1 INTRODUCTION

1. UVOD

Timber structures are increasingly preferred today in terms of aesthetic and environmentally friendly construction techniques. In addition, these structures have a nature compatible architecture and are suitable for sustainable construction techniques.

Wood is considered as a material of use in many buildings according to its place of use and purpose. The use of wood has been seen in most buildings due to wood availability and ease of procurement. These structures are places such as shelters, storages, wooden warehouses, places of worship. Traditional timber structures can be seen in Türkiye in Anatolia as well as in many places in the Eastern Black Sea Region. These structures were built by skilled wood craftsmen of the period, without disturbing the features of the old traditions and in line with the needs of the region, from materials and wood species suitable for the region (Karakul, 2011; Karakul, 2019; Çakiroğlu *et al.*, 2025a). The timber structures in Artvin-Şavşat can be shown as examples of traditional wooden constructions made in traditional architecture.

Multi-storey bungalow-type timber structures are increasingly used in residential and tourism-related applications. These structures are exposed to various environmental conditions and in this context, understanding the dynamic behavior of timber structures is of great importance in terms of both structural safety and comfort. Additionally, these structures may be affected by wind or natural disasters such as floods. However, experimental studies that quantify how tension-based

stiffening systems affect the in-service stiffness-related performance indicators of multi-storey timber houses under real environmental excitation remain limited. This limitation is particularly important for traditional timber houses, where connection details, interlocking members, and tension-based stiffening elements may significantly affect the measured dynamic response. Due to the anisotropic structure of wood, it is highly affected by environmental effects such as humidity and temperature, making it more important to correctly determine the dynamic characteristics of these structures. Since timber is an anisotropic material, its mechanical properties depend on grain direction, loading type, and environmental conditions such as humidity and temperature. (Rahman *et al.*, 2022).

Dynamic properties of structures are of critical importance in determining their resistance and performance against artificial or natural loads. Dynamic characteristics defined as natural frequencies, modal damping ratios and mode shapes play an active role in determining the vibration behavior of structures and obtaining these parameters correctly is necessary for ensuring structural safety. Since timber structures constructed using light and flexible materials are sensitive to environmental vibrations, the behavior of these structures can be examined in detail with experimental methods. Determining the dynamic characteristics of these structures is important for safe structural design and structural health monitoring (SHM). With SHM observations made in recent years, both short-term and long-term natural frequencies, damping ratios and mode shapes of structures can be obtained. In this context, natural fre-

quencies can be used as stiffness-related indicators because changes in boundary conditions, connection stiffness, and tension-based stiffening levels may alter the global dynamic response of the structure.

There are many studies on timber structures and wooden building models in the literature (Ross, 1994; Khoo *et al.*, 2004; Suzuki and Maeno, 2006; Løvholt *et al.*, 2011; Yamada *et al.*, 2012; Li and Xie, 2013; Conde *et al.*, 2014; Lechner *et al.*, 2014; Szafranko and Pawłowicz, 2015; Dai *et al.*, 2016; Altunisik, 2017; Kuo and Sun, 2017; Pawłowicz, 2017; Shimoi and Cuadra, 2018; Achenbach *et al.*, 2018; Toyoda *et al.*, 2019; Yu *et al.*, 2020; Landi *et al.*, 2022; Mackiewicz *et al.*, 2024). When examining timber structures, changes in material condition, connection behavior, moisture content, and boundary conditions may affect the stiffness-related dynamic response of timber structures and even alter its service life. Therefore, proper condition assessment of timber structures can be challenging due to the effects of humidity and corrosion, passage of time, the impact of strength, variable mechanical parameters of the interconnected wooden elements, and the effect of duration of load, etc. (Sørensen *et al.*, 2005; Arya *et al.*, 2010; Branco *et al.*, 2010; Kohler and Svensson, 2011; Unterwieser and Schickhofer, 2011; Lourenço *et al.*, 2013; Faggiano and Marzo, 2015; Cavalli *et al.*, 2016; Branco *et al.*, 2017; Nowogońska, 2019; Poletti *et al.*, 2019; Aydın and Aydın, 2020; Palma and Steiger, 2020; Wu *et al.*, 2020; Nocetti *et al.*, 2021). Catterou *et al.* (2024) studied the dynamics of bracing frames with bolted connections, referred to as frames. Three identical frames on a shaking table were tested, primarily using sine-swept excitation signals. Non-linear modes were identified, and the origins of these phenomena were discussed. Xue *et al.* (2025) studied the dynamic behavior of a multi-storey wooden tower structure with a high stylobate under environmental vibration, and it was stated that frequencies in these types of structures are directly related to the structure geometry. In the scope of the study, natural frequencies, damping ratios and mode shapes were verified by both numerical and experimental modeling. Tulebekova *et al.* (2025) identified the modal parameters by ambient vibration tests on 5 different multi-story timber buildings in Norway and revealed the amplitude dependence of the modes in tall buildings. This study detailed the effects of different building types and heights on the frequency response. Tulebekova *et al.* (2024) investigated the modal parameters of the selected structure and the effect of environmental conditions with long-term monitoring. Amaddeo and Dorn (2024) conducted research on a six-storey light timber framed structure in Norway, where frequency fluctuations (4-7 %) were associated with environmental factors during a four-month moni-

toring period. In a study by Reynolds *et al.* (2016), the dynamic properties of two complete multi-storey timber buildings, identical except for their structural systems, were compared through in-situ testing of the buildings. The natural frequencies, damping ratios and mode shapes of the first three vibration modes of these buildings were determined and compared with those modeled based on the properties of the core and timber walls. In Reynolds *et al.* (2014), simple prediction calculations were performed to estimate the damping in the calculation of wind-induced vibration for multi-storey timber buildings and to evaluate the stiffness of the system by resisting the lateral load.

Timber structures traditionally gave satisfactory seismic performance (Ugalde *et al.*, 2019; Cervio and Muciaccia, 2020). It was thought that their seismic performance was mostly attributed to its structural redundancy, lightweight, elastic deformation capacity, strength and stiffness, and ductility of connections (Ugalde *et al.*, 2019). However, timber structures were not immune to significant damage, especially for homes with structural design deficiencies, as seen in recent earthquakes. Many researchers studied the dynamic behavior of timber structures under seismic loads (Folz and Filiatrault, 2001; Polensek and Schimel, 1991; Filiatrault *et al.*, 2003; Filiatrault *et al.*, 2010). Ductile connections have positive effects on both response and resistance (Ceccotti *et al.*, 2013; Van de Lindt *et al.*, 2010; Tomasi *et al.*, 2015; Flatscher and Schickhofer, 2015).

In this study, the in-service dynamic performance of a two-storey traditional timber bungalow house and representative timber elements was investigated experimentally through ambient vibration measurements. The full-scale structure, located on the Artvin Çoruh University campus and inspired by traditional “Şavşat Houses”, was tested under real environmental conditions using the developed Civil Engineering Vibration System (CEVS) and Civil Engineering Vibration Analysis (CEVA) software. The main objective was to evaluate how tension-based stiffening states influence the natural frequencies and stiffness-related in-service performance of the timber structure.

Ambient vibration measurements were conducted for three different tension-based stiffening states: tensionless, normally tensioned, and fully tensioned. These states represent progressively increasing restraint provided by the tension-based stiffening elements, from released condition to service-level and fully tightened conditions. The identified natural frequencies were used as stiffness-related dynamic indicators; therefore, the study focuses on frequency-based stiffness assessment rather than direct strength evaluation. In addition to the full-scale tests, laboratory measurements on representative timber elements were per-

formed to support the interpretation of the structural-level vibration response.

Unlike many previous studies that evaluate timber structures under fixed structural or boundary conditions, this study experimentally examines the effect of adjustable tension-based stiffening states on the dynamic response of a traditional timber house. The main contributions of the study are the full-scale ambient vibration testing of traditional two-storey timber structure, the comparison of different tension-based stiffening states, the use of the developed CEVS–CEVA system for field-based vibration monitoring, and the interpretation of natural frequency changes as practical indicators of in-service stiffness variation. The findings provide useful experimental evidence for the assessment, monitoring, and potential strengthening decisions of similar traditional timber structures and will also form the basis for future studies.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

This section describes the material characteristics of the timber used in the traditional house, the main construction stages relevant to the structural system, the developed vibration measurement system, and the experimental vibration testing procedure. The methodological workflow consisted of material selection and preparation, documentation of the structural configuration, installation of the Civil Engineering Vibration System (CEVS), data acquisition using Civil Engineering Vibration Analysis (CEVA) software, ambient vibration testing of the full-scale timber house under different tension-based stiffening states, and laboratory vibration measurements on representative timber elements. The experimental data was processed to identify natural frequencies as stiffness-related dynamic indicators.

2.1 Wood material and machining preparation

2.1. Drvni materijal i mehanička obrada

It is known that the construction of Şavşat House in the countryside consists of fir, spruce, pine and chestnut trees in and around the region because they are generally more accessible and easier to obtain. In this study, Scots pine (*Pinus sylvestris* L.) compatible with the region was utilized. The Scots pine wood has a prominent annual ring boundary and yellowish white color. The wood is not shiny and is quite hard, of medium density and has a decorative appearance. When some physical properties of Scots pine wood are examined, full dry density is 0.496 g/cm³, air dry density is 0.526 g/cm³, volume-weight value is 0.426 g/cm³, radial shrinkage is 4.3 %, tangential shrinkage is 8.3 %, volume shrinkage is 12.7 %.

Some mechanical properties are compressive strength of 64 N/mm², flexural strength of 100 N/mm², elasticity modulus of 12000 N/mm², tensile strength of 104 N/mm², shear strength of 10 N/mm², brinell hardness of 40 N/mm² parallel to fibers, brinell hardness of 19 N/mm² perpendicular to fibers (As *et al.*, 2001).

CNC milling was used during the preparation of selected timber components and joint details. Since machining quality may influence the dimensional accuracy of interlocking timber members, the material preparation process was briefly considered in this study. However, CNC-related dust emission was not treated as a vibration parameter; it is mentioned only as a production-related issue associated with the selected Scots pine material.

2.2 Construction stages and structural configuration of the traditional timber house

2.2. Faze gradnje i konstrukcijski sustav tradicijske drvene kuće

The construction process of the two-storey traditional timber house is summarized with emphasis on the structural components relevant to the vibration assessment. Some images of construction stages are shown in Figure 1.

- Design and Planning: Based on research and studies conducted in the district and villages of Şavşat, the design and layout of the timber structure were generated, taking into account the location of the application area. Additionally, some unique additions were made to the structure, which was planned to resemble a traditional Şavşat House, generating a distinct design. The architectural design of the structure, the planning of the load-bearing system and the selection of materials were made at this stage. The selection of the appropriate foundation for the structure was analyzed by taking into account wind and earthquake loads.
- Foundation and Ground Preparation: A reinforced concrete foundation was poured to ensure the stability of the timber structure, and a moisture barrier was installed on top of it. Slope calculations and ground improvement works were carried out at the site.
- Load-bearing system Installation: Wooden columns and beams were joined together to form the structural frame of the structure. Steel connecting elements were used to improve connection stiffness and structural stability. Solid interlocking flooring was used between floors. The upper part between the roof and the second floor was left empty so that it would be visible, and wooden materials were used for support and decorative purposes.
- Interior Applications: Electrical and plumbing installations were completed with decorative pipes, the



Figure 1 Some images of construction stages

Slika 1. Prikaz faza gradnje

floor was laid with interlocking wood material, and the interior decoration was completed.

Before starting the construction of the traditional timber house, production and installation processes were initiated in a suitable location in the laboratory environment in accordance with the existing drawings and designs. First, wooden materials were placed using the “wood interlocking technique” starting from the foundation. As in traditional Şavşat Houses, wooden pieces were joined using a technique similar to “kurtboğaz” (wolf’s throat), with grooved joints (Figure 2). The wooden pieces joined in this way were left in this environment for a certain period of time to allow the grooves to settle. Then, a suitable site was identified, and a soil survey was conducted to verify the suitability of the foundation. High-quality first-class wooden materials were used to ensure the structural integrity of the building.

First, the ground was prepared, and the foundation was laid. Concrete foundation was frequently used. A solid foundation was important for the long life of the traditional timber house. After the foundation

was completed, the structural frame was installed. The main body of the structure was generated by mounting vertical and horizontal supports. Waterproof coatings were applied for the roof to provide protection against external factors such as rain and snow.

Non-structural architectural components, such as doors, windows, interior finishes, and decorative timber elements, were completed after the load-bearing timber frame and floor system were installed. These components were not considered as primary load-bearing elements in the vibration assessment.

In traditional Artvin Şavşat Houses, wooden pieces were joined using a technique with grooved joints and some of 3D images and tension status are shown in Figure 2.

2.3 Vibration measurement system

2.3.1 Sustav za mjerenje vibracija

Vibration tests were performed on the timber structure to identify its dynamic characteristics. To perform measurements, civil engineering vibration system (CEVS) and civil engineering vibration analysis (CEVA)



Figure 2 Some images of 3D views and grooved joints (white rectangular)

Slika 2. Prikaz 3D modela i izlijebljenih spojeva (označeno bijelim pravokutnicima)

were developed. CEVS system and CEVA software were used for data acquisition (Yanik *et al.*, 2022; Aymelek *et al.*, 2023; Yanik *et al.*, 2024; Demirtas *et al.*, 2025). The system consisted of 3-axial accelerometers, arduino, bluetooth, li-ion battery, humidity, temperature, pressure and charge modulus (Figure 3). The software included C# language in visual studio, and arduino programs in order to control the sensor system and to receive data through the sensor system. The properties and equipment of the sensors are given in Table 1.

The other part, i.e. the software part, was developed to command the sensor system. With the software developed, the objectives outlined below have been

achieved. The CEVA software was designed with the help of visual studio (Fig. 4).

The main advantage of the developed CEVS–CEVA system is its suitability for rapid in-service vibration monitoring of timber structures under field conditions. Compared with conventional laboratory-based vibration measurement systems, the proposed system is portable, low-cost, capable of wired or wireless data acquisition, and allows simultaneous recording of tri-axial acceleration and environmental parameters. The CEVA interface also enables real-time signal checking before data storage, which reduces the risk of invalid field measurements. These features make the

Table 1 Properties and equipment of sensors
Tablica 1. Svojstva i oprema mjernih senzora

Parameter / <i>Parametar</i>	CEVS
Multi-axis / <i>Višeosni</i>	Tri-axial
Accelerometer type / <i>Tip akceleratora</i>	Digital
Sensitivity / <i>Osjetljivost</i>	20-bit ADC
Range / <i>Mjerni raspon</i>	Selectable $\pm 2 \text{ g}$ / $\pm 4 \text{ g}$ / $\pm 8 \text{ g}$
Noise density / <i>Gustoća šuma</i>	$25 \mu\text{g}/\sqrt{\text{Hz}}$ for $\pm 2 \text{ g}$
Measuring sensibility / <i>Mjerna osjetljivost</i>	$3.9 \mu\text{g}/\text{LSB}$ for $\pm 2 \text{ g}$, $7.8 \mu\text{g}/\text{LSB}$ for $\pm 4 \text{ g}$, and $15.6 \mu\text{g}/\text{LSB}$ for $\pm 8 \text{ g}$
Sampling frequency / <i>Frekvencija uzorkovanja</i>	Selectable 250 Hz / 500 Hz / 1000 Hz
Content of equipment / <i>Sastav mjerne opreme</i>	Accelerometer, arduino, bluetooth, li-ion battery, humidity, temperature, pressure and charge modulus
Data transfer type / <i>Način prijena podataka</i>	Selectable Wireless or Wired
Baud rate / <i>Brzina prijena podataka</i>	115200 / 500000Baud
Protocol type / <i>Tip komunikacijskog protokola</i>	Between Accelerometer and Arduino is SPI, between Arduino and Bluetooth is UART

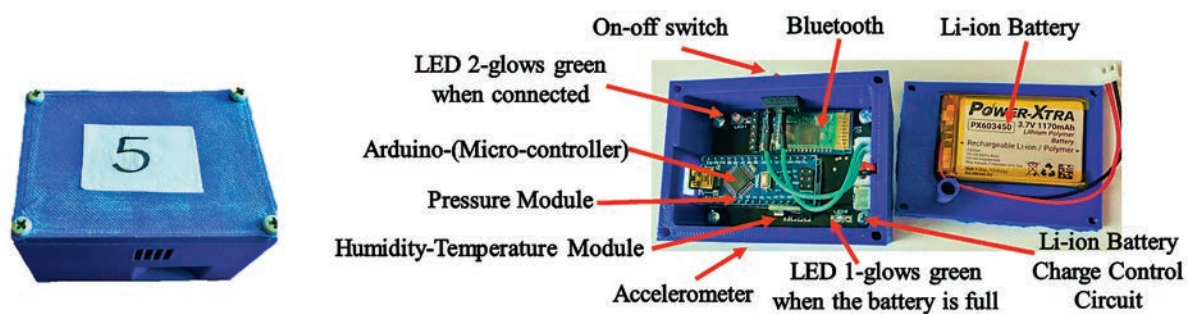


Figure 3 Placement of vibration measurement system elements (CEVS)
Slika 3. Raspored elemenata sustava za mjerenje vibracija (CEVS)

system applicable for preliminary structural health monitoring and comparative stiffness assessment of traditional timber buildings where access, cost, and installation time are important constraints.

The CEVA software was developed in C# using Visual Studio to control the sensor system and manage data acquisition. The software enables sensor connec-

tion control, selection of acceleration range, sampling frequency and measurement duration, real-time preview of signals from the *X*, *Y* and *Z* axes, channel selection, recording time monitoring, and export of measurement data in formats such as .csv and .txt. These functions allowed the recorded signals to be checked in the field before further processing.

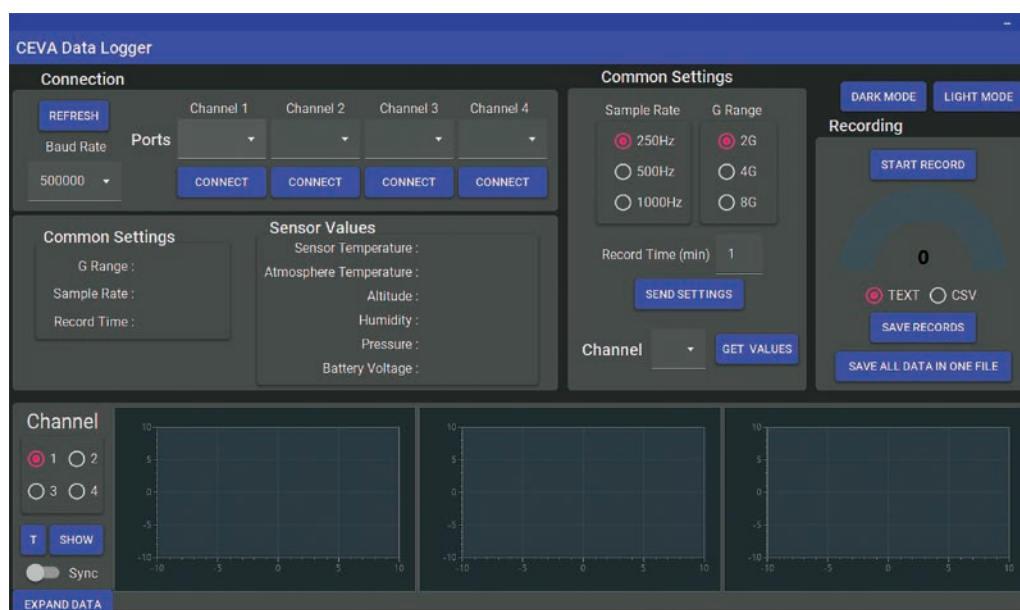


Figure 4 CEVA software interface
Slika 4. Sučelje CEVA softvera

2.4 Full-scale ambient vibration measurements on the traditional timber house

2.4. Terenska mjerenja ambijentalnih vibracija na tradicijskoj drvenoj kući

Measurement setups with different tension-based stiffening states were established for vibration measurements. Vibration measurement system and software were used in these setups. Some of the images of the sensor placement on the structure are given in Figure 5. Some of the images of the data on the CEVA taken from CEVS system are given in Figure 6.

The expression “tensionless < normally tensioned < fully tensioned” refers to the increasing level of initial pre-tension applied to the steel stiffening/tie elements of the timber house, rather than to the tensile strength of the timber material itself. In the tensionless state, the tensioning elements were released so that they did not provide effective axial restraint. The normally tensioned state corresponds to the in-service condition of the house, in which the tensioning elements were tightened to their regular service position. In the fully tensioned state, the same elements were tightened to the maximum practical level allowed by the connection details without causing visible local

damage or deformation. Therefore, the three measurement cases represent progressively increasing restraint and stiffness contribution from the tension-based stiffening system.

In the first measurement setup, 3 CEVS systems were placed in different corners on the 2nd floor. In these tests, the timber house was in the normally tensioned state. In the second measurement setup, the timber house was in the tensionless state, and in the third measurement setup, the timber house was in the fully tensioned state. In the tests, different vibration measurements were made according to the tension status of the traditional timber house.

The 3-axis (X-Y-Z) ambient vibration measurement data obtained from the traditional timber house by using the CEVS system and CEVA Data Logger software were processed in the ARTEMIS software. In the signal processing analyses, frequency and time decomposition domain methods were applied, and singular value graphs were obtained for each analysis. Some of these graphs are given in Figures 7-9 for different measurement setups, where the horizontal axis demonstrates the frequencies and the vertical axis is in decibels (dB). The maximum frequency for signal processing was rearranged as 45 Hz.



Figure 5 Sample images of vibration measurement setups (CEVS)

Slika 5. Primjeri postavljanja sustava za mjerenje vibracija (CEVS)

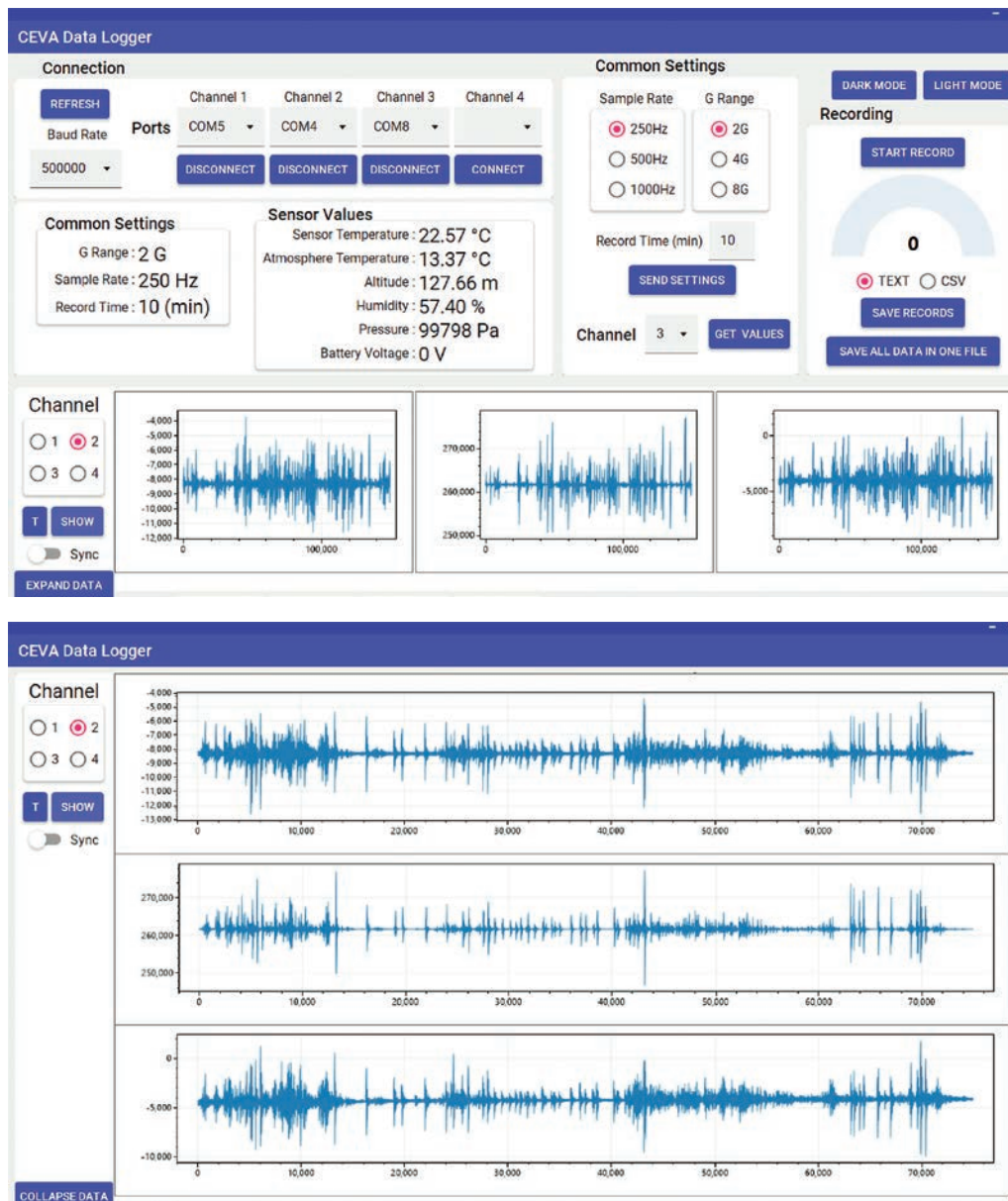


Figure 6 Sample images vibration data (CEVA)
Slika 6. Primjeri zapisa izmjerenih vibracija (CEVA)

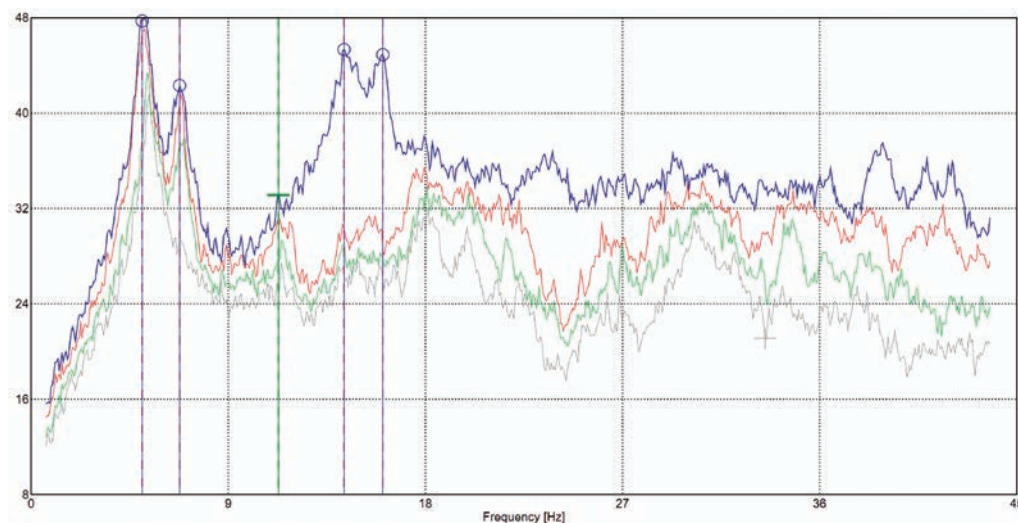


Figure 7 Singular values of spectral densities of normally tensioned state
Slika 7. Singularne vrijednosti gustoće spektra vibracija za uobičajeno napeto stanje

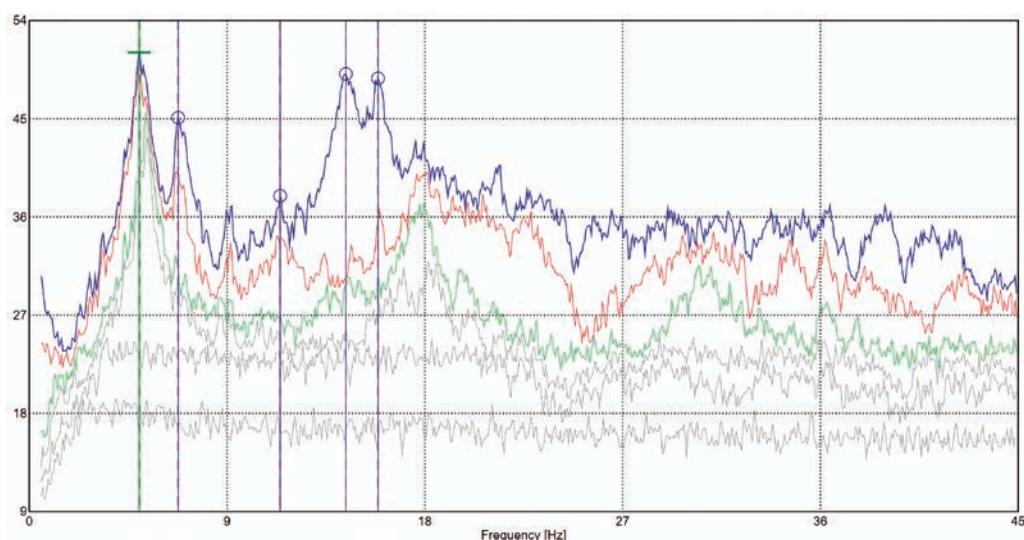


Figure 8 Singular values of spectral densities of tensionless state
Slika 8. Singularne vrijednosti gustoće spektra vibracija za otpušteno stanje

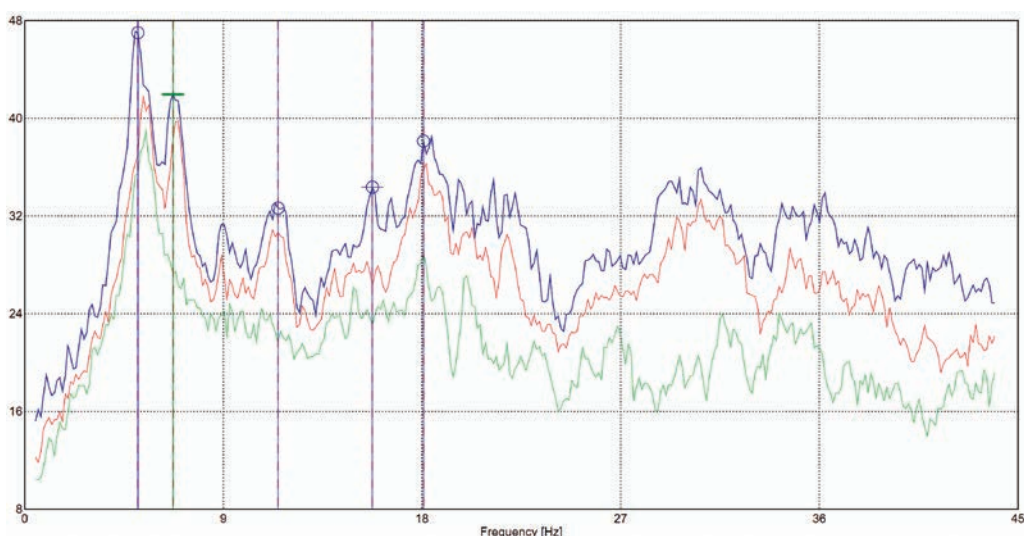


Figure 9 Singular values of spectral densities of fully tensioned state
Slika 9. Singularne vrijednosti gustoće spektra vibracija za napeto stanje

2.5 Laboratory vibration measurements on representative timber elements

2.5. Laboratorijska mjerenja vibracija na reprezentativnim drvenim elementima

Laboratory vibration measurements were performed on representative timber elements to support the interpretation of the stiffness-related dynamic response observed in the full-scale timber house. These tests were not intended to replace the full-scale measurements but to provide complementary information about the vibration characteristics of selected timber components.

Some of the materials used in the timber structure were tested in a laboratory environment. Vibration measurements were collected with the CEVS vibration measurement system on a structure consisting of wooden elements and a cantilever beam, and information about the material properties of the structure was

obtained. The measurement devices established are given in Figures 10-11.



Figure 10 Some images of cantilever vibration measurement setup

Slika 10. Primjeri postavljanja uređaja za mjerenje vibracija na konzolnim elementima



Figure 11 Sample images of individual element vibration measurement setup

Slika 11. Primjeri postavljanja uređaja za mjerenje vibracija pojedinačnih elemenata

The vibration signals received from the cantilever and individual element were manually processed using the ARTEMIS software. The resolution value was selected as 2048. In frequency selection, the enhanced frequency domain decomposition (EFDD) method was used to select the peak. In addition, some of the singular value diagrams were obtained as a result of the processing of the signals given in Figures 12-13. The analysis outputs with different visuals obtained using EFDD are shown in the graphs. The identified frequencies obtained from the laboratory measurements are reported and discussed in the Results and Discussion section.

2.6 Use of artificial intelligence-assisted tools

2.6. Primjena alata utemeljenih na umjetnoj inteligenciji

Artificial intelligence-assisted tools were used only for language editing, improving grammatical clarity, and supporting the organization of the revised manuscript. OpenAI ChatGPT (GPT-5.5 Thinking, ac-

cessed in May 2026) was used during the revision stage to assist with English language refinement and editorial restructuring in response to reviewer comments. No artificial intelligence-assisted tool was used for experimental design, data collection, signal processing, numerical analysis, generation of results, preparation of figures or tables, or interpretation of the experimental findings. All AI-assisted suggestions were critically reviewed, edited, and approved by the authors. The authors take full responsibility for the accuracy, originality, and integrity of the final manuscript.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

3.1 Full-scale ambient vibration results of the traditional timber house

3.1. Rezultati terenskih mjerenja ambijentalnih vibracija na tradicijskoj drvenoj kući

Full-scale ambient vibration measurements were conducted on the traditional timber house under three

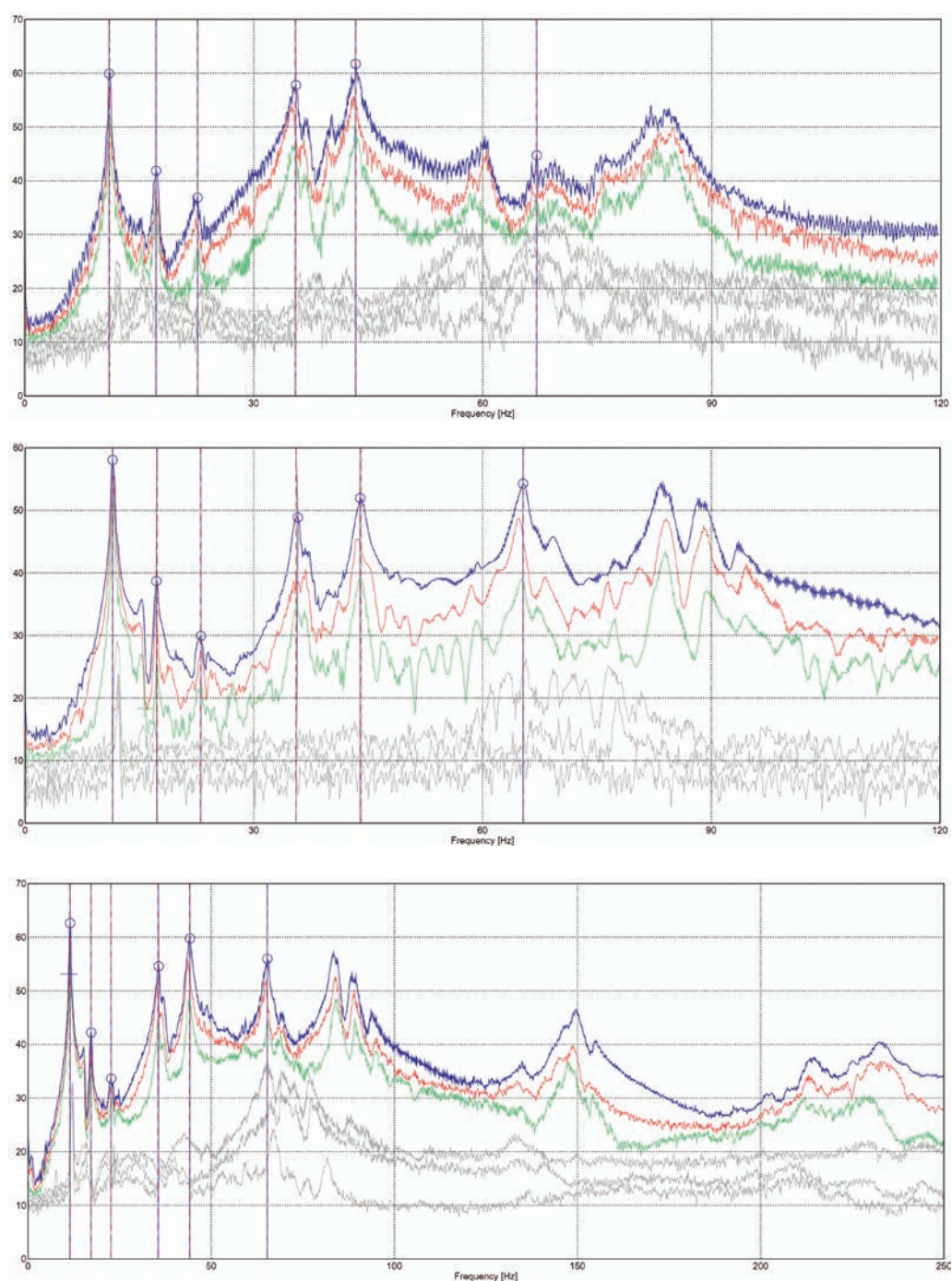


Figure 12 Some singular value graphs of cantilever beam
Slika 12. Primjeri dijagrama singularnih vrijednosti za konzolnu gredu

Table 2 Experimental natural frequencies of traditional timber house
Tablica 2. Eksperimentalne prirodne frekvencije tradicijske drvene kuće

Frequency number <i>Broj frekvencije</i>	Tensionless status, Hz <i>Opušteno stanje, Hz</i>	Normal tension status, Hz <i>Normalno napeto stanje, Hz</i>	Fully tension status, Hz <i>Potpuno napeto stanje, Hz</i>
1	5.005	5.066	5.127
2	6.775	6.897	6.958
3	11.414	11.475	11.597
4	14.494	14.832	15.747
5	15.869	16.052	18.066

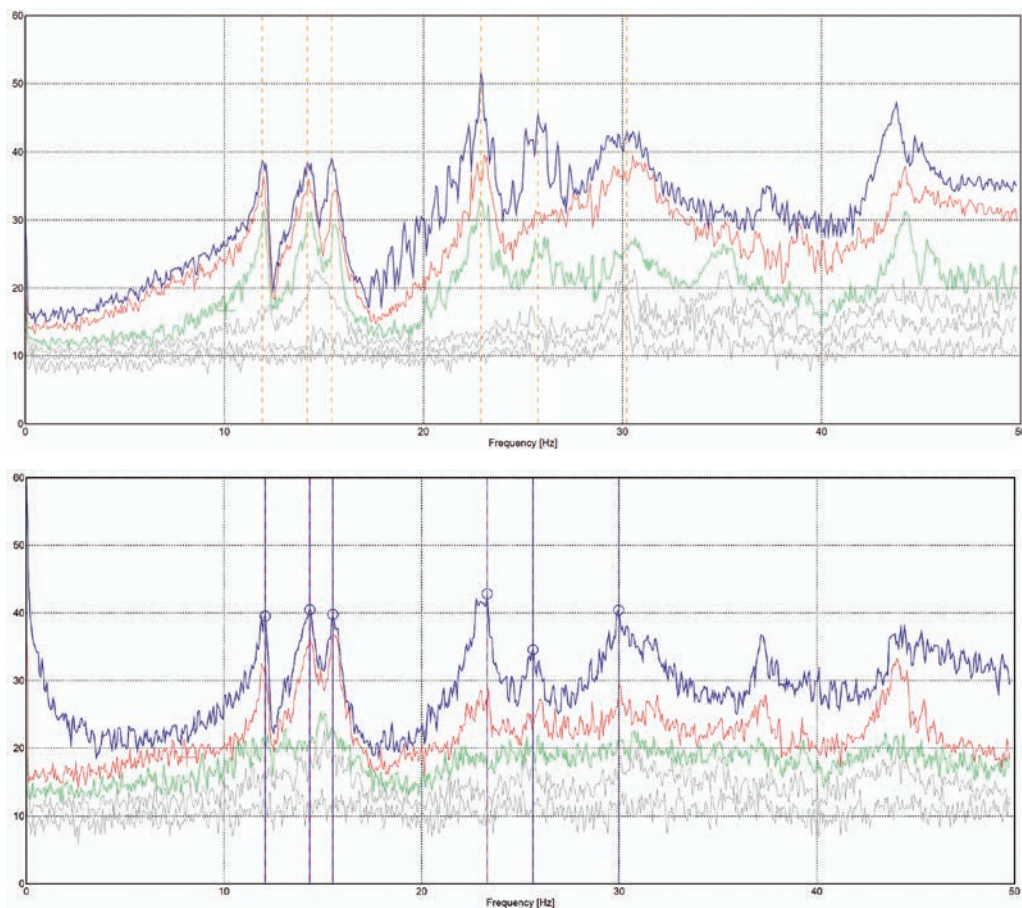


Figure 13 Some singular value graphs of individual elements
Slika 13. Primjeri dijagrama singularnih vrijednosti za pojedinačne elemente

tension-based stiffening states: tensionless, normally tensioned, and fully tensioned. The recorded three-axis acceleration data were processed using ARTeMIS software, and the experimental natural frequencies were identified from the singular value spectra. The first five natural frequencies obtained from the full-scale measurements are presented in Table 2.

Table 2 shows that the identified natural frequencies ranged between 5.005 Hz and 18.066 Hz. For all identified modes, the natural frequencies increased from the tensionless state to the normally tensioned state and then to the fully tensioned state. This trend indicates that the increase in restraint provided by the tension-based stiffening elements resulted in an increase in the effective stiffness of the traditional timber house. Since the mass of the structure was not changed during the measurements, the observed frequency increase can be interpreted as a stiffness-related dynamic response rather than a direct strength increase.

A graphical comparison of the natural frequencies obtained under different tension-based stiffening states is presented in Figure 14. The comparison clearly shows that the frequency values follow the order tensionless < normally tensioned < fully tensioned for each identified mode.

3.2 Effect of tension-based stiffening states on natural frequencies

3.2. Utjecaj stanja napetosti zatega na prirodne frekvencije

The effect of the tension-based stiffening states was more evident in the higher modes than in the lower modes. In the first mode, the natural frequency increased from 5.005 Hz in the tensionless state to 5.127 Hz in the fully tensioned state, corresponding to an increase of approximately 2.44 %. In the second and third mode, the increases were approximately 2.70% and 1.60 %, respectively. However, the fourth mode increased from 14.494 Hz to 15.747 Hz, corresponding to an increase of approximately 8.64 %, while the fifth mode increased from 15.869 Hz to 18.066 Hz, corresponding to an increase of approximately 13.84 %.

The results indicate that the tension-based stiffening system had a measurable influence on the dynamic behavior of the timber house. The relatively small changes in the first three modes suggest that the global low-frequency response was only moderately affected by the tension adjustment. In contrast, the larger increases observed in the fourth and fifth mode indicate that the stiffening contribution of the tensioning elements became more pronounced in higher-frequency

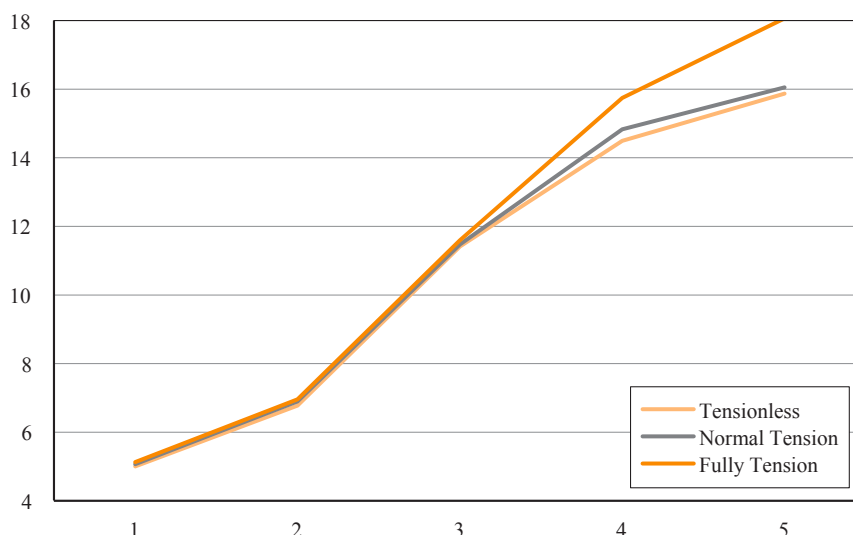


Figure 14 Natural frequencies of the traditional timber house based on tension status
Slika 14. Prirodne frekvencije tradicijske drvene kuće ovisno o stanju napetosti zatega

Table 3 Percentage increase in natural frequencies from tensionless state to fully tensioned state

Tablica 3. Postotni porast prirodnih frekvencija od otpuštenoga do potpuno pritegnutog stanja

Mode number <i>Broj načina rada</i>	Tensionless state, Hz <i>Opuštenje stanje, Hz</i>	Fully tension state, Hz <i>Potpuno napeto stanje, Hz</i>	Increase, % <i>Povećanje, %</i>
1	5.005	5.127	2.44
2	6.775	6.958	2.70
3	11.414	11.597	1.60
4	14.494	15.747	8.64
5	15.869	18.066	13.84

quency vibration modes. This behavior may be associated with the increased local and semi-global restraint provided by the tension-based stiffening elements.

These results should be interpreted as frequency-based stiffness indicators. The measurements do not directly quantify strength or load-carrying capacity. However, under comparable mass and boundary conditions, an increase in natural frequency is generally associated with an increase in effective stiffness. Therefore, the observed frequency trend supports the use of ambient vibration measurements as a practical tool for evaluating stiffness-related in-service performance changes in traditional timber structures.

3.3 Laboratory vibration results of representative timber elements

3.3. Rezultati laboratorijskih mjerenja vibracija na reprezentativnim drvenim elementima

In addition to the full-scale ambient vibration measurements, laboratory vibration measurements were performed on representative timber elements. These measurements were used to support the interpretation of the stiffness-related dynamic response observed at the structural level. The natural frequencies obtained from the cantilever element and the timber element are presented in Table 4.

Table 4 Experimental natural frequencies of the cantilever element and representative timber element

Tablica 4. Eksperimentalne prirodne frekvencije konzolnoga i reprezentativnoga drvenog elementa

Frequency Number <i>Broj frekvencije</i>	Cantilever element's experimental frequencies, Hz <i>Eksperimentalne frekvencije konzolnog elementa, Hz</i>				Wooden element's frequencies, Hz <i>Frekvencije drvenog elementa, Hz</i>	
	M1	M2	M3	M4	M1	M2
1	11.060	11.475	11.432	11.475	12.085	11.902
2	17.215	17.295	17.212	17.090	14.343	14.160
3	22.646	23.015	22.591	22.461	15.503	15.381
4	35.449	35.530	35.536	35.400	23.315	22.888
5	43.369	43.981	44.117	44.189	25.635	25.757
6	67.051	65.329	65.337	65.674	29.968	30.212

The cantilever element was tested in four different measurement sets, while the representative timber element was tested in two measurement sets. For the cantilever element, the average values of the first six natural frequencies were 11.361, 17.203, 22.678, 35.479, 43.914, and 65.848 Hz. For the representative timber element, the average values of the first six natural frequencies were 11.994, 14.252, 15.442, 23.102, 25.696, and 30.090 Hz.

The laboratory results show that the cantilever element exhibited higher frequencies in the upper modes compared with the representative timber element. This difference can be attributed to the different boundary conditions, geometry, and structural configuration of the tested elements. The laboratory measurements do not directly represent the full-scale structural response of the traditional timber house; rather, they provide complementary information on the vibration characteristics of selected timber components. Therefore, these results support the interpretation of the full-scale measurements but should not be treated as a substitute for in-service testing of the complete structure.

4. CONCLUSION

4. ZAKLJUČAK

The full-scale results demonstrate that ambient vibration measurements can be used to detect stiffness-related changes caused by different tension-based stiffening states in a traditional timber house. The consistent increase in natural frequencies from the tensionless state to the fully tensioned state indicates that the developed measurement approach is sensitive to changes in structural restraint and effective stiffness. This finding is practically important for the monitoring, assessment, and potential strengthening decisions of similar traditional timber structures.

The developed CEVS–CEVA system was also shown to be applicable for field-based vibration monitoring. Its portability, ability to record tri-axial acceleration data, and compatibility with subsequent modal identification procedures make it suitable for preliminary in-service assessment of timber structures under real environmental conditions.

However, some limitations should be noted. The tension states were defined according to the adjustment condition of the tensioning elements, and direct axial force measurement was not performed. Therefore, the results should be interpreted as a comparison of operational stiffening states rather than as a force-calibrated pre-tension analysis. In addition, the study focused primarily on natural frequencies as stiffness-related indicators. Future studies should include damping ratios, mode shapes, long-term environmental monitoring, finite element model updating, and the evaluation of

earthquake and wind effects to obtain a more comprehensive assessment of the structural performance of traditional timber houses.

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Enhancing Pyrolytic Oil Quality from Wood Biomass using Different Types of Carbonates as Catalysts

Poboljšanje kvalitete pirolitičkog ulja iz drvne biomase primjenom različitih vrsta karbonata kao katalizatora

ORIGINAL SCIENTIFIC PAPER

Izvorni znanstveni rad

Received – prispjelo: 23. 2. 2026.

Accepted – prihvaćeno: 10. 4. 2026.

UDK: 630*86

<https://doi.org/10.5552/drvind.2026.0339>

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ABSTRACT • The investigation examined woody biomass vacuum pyrolysis to understand the yield and quality of the resulting py-oil. The product characteristics and chemical composition were evaluated at varying pyrolysis temperatures and with different carbonate catalysts, including CaCO_3 , K_2CO_3 , Na_2CO_3 , MgCO_3 , and NaHCO_3 . In the absence of catalysts, the highest biomass yield was 48.58 wt.% at 500 °C. The use of carbonate catalysts has been proven to have a notable impact on py-oil yield and its elemental composition under thermal conditions. Notably, the heating value for non-catalytic py-oil was computed at 20.11 MJ/kg, with heating values of 22.49, 22.82, 23.00, 23.83, and 24.17 MJ/kg obtained upon upgrading with CaCO_3 , NaHCO_3 , MgCO_3 , Na_2CO_3 , and K_2CO_3 , respectively. Deoxygenation is the main reaction promoted by K_2CO_3 , during which the oxygen content decreased from 32.64 % to 23.30 %. In addition, the catalyst level was strongly related to the catalyst pH and the increase in py-oil heating value (HHV). GC/MS analysis demonstrated that phenolic compounds can be significantly elevated in the py-oil due to K_2CO_3 and Na_2CO_3 , indicating that this fuel is of high quality and has potential as a chemical resource. In this work, carbonate-based catalysts for the transformation of wood waste into phenolic-enriched py-oil are proposed to minimise environmental impact and possibly enhance py-oil quality in a vacuum pyrolysis process.

KEYWORDS: wood biomass; vacuum pyrolysis; carbonate catalysts; py-oil quality; phenolic enrichment

SAŽETAK • U radu je istražena vakuumska piroliza drvne biomase kako bi se utvrdili prinos i kvaliteta dobivenoga pirolitičkog ulja. Svojstva i kemijski sastav produkata procjenjivani su pri različitim temperaturama pirolize te uz primjenu različitih karbonatnih katalizatora, uključujući CaCO_3 , K_2CO_3 , Na_2CO_3 , MgCO_3 i NaHCO_3 . Bez primjene katalizatora najveći prinos tekućih produkata iz biomase iznosio je 48,58 masenog postotka pri temperaturi od 500 °C. Dokazano je da primjena karbonatnih katalizatora u zadanim termičkim uvjetima znatno utječe na prinos pirolitičkog ulja i njegov elementarni sastav. Gornja ogrjevna vrijednost pirolitičkog ulja dobivenoga nekatalitičkim postupkom iznosila je 20,11 MJ/kg, dok su vrijednosti od 22,49; 22,82; 23,00; 23,83 i 24,17 MJ/kg postignute poboljšanjem kvalitete primjenom CaCO_3 , NaHCO_3 , MgCO_3 , Na_2CO_3 i K_2CO_3 . Deoksigenacija je glavna reakcija koju potiče K_2CO_3 , pri čemu se udio kisika smanjio s 32,64 % na 23,30 %. Osim toga, aktivnost katalizatora bila je usko povezana s njegovom pH-vrijednošću i povećanjem gornje ogrjevnosti (GOV) pirolitičkog ulja. Analiza plinskom kromatografijom sa spektrometrom masa (GC/MS) pokazala je da se udio feno-

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lnih spojeva u pirolitičkom ulju može znatno povećati primjenom K_2CO_3 i Na_2CO_3 , što upućuje na visoku kvalitetu toga goriva i njegov potencijal kao kemijske sirovine. U ovome se radu za pretvorbu drvnog otpada u pirolitičko ulje obogaćeno fenolima predlaže primjena katalizatora na bazi karbonata, čime se smanjuje utjecaj na okoliš i poboljšava kvaliteta produkata u procesu vakuumske pirolize.

KLJUČNE RIJEČI: drvna biomasa; vakuumska piroliza; karbonatni katalizatori; kvaliteta pirolitičkog ulja; obogaćivanje fenolima

1 INTRODUCTION

1. UVOD

Biomass is widely acknowledged as a renewable energy source. Among the various forms of biomass, woody biomass, which includes wood chips, sawdust, shavings, and bark, is generated in millions of tons each year by the forestry sector. Approximately 25 % of the raw material output from wood processing is waste that is usually discarded or incinerated. There are four main thermochemical processes for transforming biomass into energy: combustion, pyrolysis, gasification, and liquefaction. Pyrolysis specifically refers to the thermal breakdown of biomass at temperatures between 300 °C and 700 °C in an oxygen-free environment. This method yields solid charcoal (biochar), liquid (py-oil), and gaseous products. Pyrolysis is recognised as a commercially viable technique for converting biomass (Balat and Ayar, 2005; Anderson *et al.*, 2013; Jahirul *et al.*, 2012; Bridgwater, 2012; Zhang *et al.*, 2010; Wyman, 2013; Özbay, 2015).

Py-oil is primarily a product of pyrolysis and has a high heating value (HHV), making it a suitable precursor for producing liquid fuels or other valuable compounds. It comprises a variety of organic compounds (such as phenols, aldehydes, ketones, alcohols, esters, and organic acids), giving it a diverse chemical composition. Due to their higher acidity (corrosive nature) and chemical instability during storage, these oxygenated compounds are not well-suited for commercial use. In the transport industry, it is crucial to achieve substantial improvements in py-oil quality to enable its use as a replacement for petroleum-based fuels. Hence, research efforts focus on upgrading techniques and developing suitable engine configurations, while addressing corrosion concerns and optimising combustion performance (Li and Suzuki, 2009; Oasmaa and Kuoppala, 2003; Abou *et al.*, 2021; Bridgwater, 2012; Lian *et al.*, 2017).

An increasing number of studies have been conducted to improve the quality of py-oil produced by the pyrolysis of woody biomass using various catalysts. Notably, zeolites and their derivatives (Adjaye and Bakhshi, 1995; Nokkosmäki *et al.*, 2000; Horne and Williams, 1996; Lappas *et al.*, 2002; Zhang *et al.*, 2013), dolomite (Myrén *et al.*, 2002; Charusiri and Vitidsant, 2017; Ly *et al.*, 2018), metal basic oxides

(Pütün, 2010; Yuan and Shen, 2019; Cao *et al.*, 2020), nickel-based catalysts (Ji *et al.*, 2017; Yang *et al.*, 2019; Cho *et al.*, 2020), and acidic or basic inorganic materials (Patwardhan *et al.*, 2010; Guo *et al.*, 2012; Zhao *et al.*, 2013; Zhou *et al.*, 2018; Chen *et al.*, 2020) have been studied. Additionally, various combinations of these catalysts have also been explored (Li *et al.*, 2014; Wu *et al.*, 2020; Yang *et al.*, 2020). The findings from these investigations indicate that catalyst type significantly influences both product yield and chemical composition. Thus, catalytic upgrading is recognised as one of the most effective methods for enhancing py-oil performance. To assess final product yields, both catalytic and non-catalytic pyrolysis experiments were conducted using pinewood sawdust at varying temperatures. A range of carbonate catalysts, specifically $CaCO_3$, K_2CO_3 , Na_2CO_3 , $MgCO_3$, and $NaHCO_3$, were tested for improving the quality of py oil. Subsequently, the py-oils obtained from both the non-catalytic and catalytic processes were analysed by ultimate analysis and GC/MS.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

2.1 Biomass and catalysts

2.1. Biomasa i katalizatori

Scots pine (*Pinus sylvestris* L.) is widely used in Turkey, mainly for furniture and construction, and this study used sawdust waste as a biomass feedstock. The feedstock was ground and sieved to a particle size of 0.600 – 1.000 mm, then dried at 105 °C for 12 hours to remove moisture prior to pyrolysis. Samples were subjected to proximate analysis in accordance with ASTM standards and to fixed-carbon content determination to assess variability. The chemical composition of the feedstock was examined using methods reported by Wise and Karl (1962) and Rowell *et al.* (2005), along with the relevant TAPPI recommendations (T-257, T-222, and T-204). Elemental analysis was performed with the LECO CHNS-932 elemental analyser. The findings from the fundamental characterisation of the pinewood waste are summarised in Table 1.

The commercial catalysts used in these experiments were supplied by Sigma-Aldrich and had chemical purities exceeding 99 wt.% for each. Their typical properties are summarised in Table 2.

Table 1 Proximate and ultimate analysis of Scots pine wood

Tablica 1. Tehnička i elementarna analiza borovine

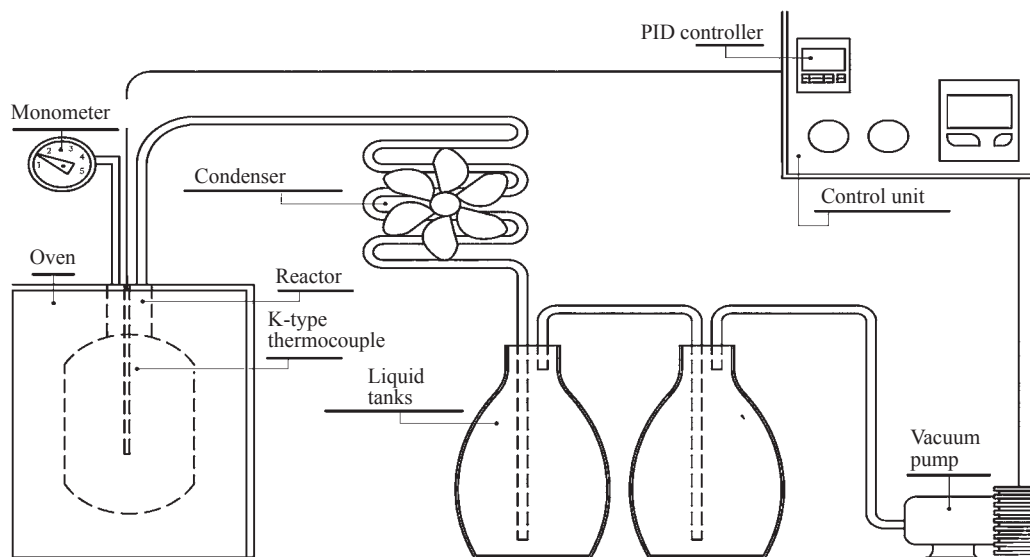
Proximate analysis (wt%, air dry) <i>Tehnička analiza (mas. %, uzorak sušen na zraku)</i>	Method <i>Metoda</i>	Value <i>Vrijednost</i>	Component analysis, % <i>Analiza komponentata, %</i>	Method <i>Metoda</i>	Value <i>Vrijednost</i>	Ultimate analysis (wt%, daf) <i>Elementarna analiza (mas. %, suha tvar bez pepela)</i>	Value <i>Vrijednost</i>
Moisture content, % <i>sadržaj vode, %</i>	(ASTM D-4442-92)	3.17	α -cellulose	(Rowell <i>et al.</i> , 2005)	48.24	Carbon <i>ugljik</i>	47.14
Volatiles <i>hlapljive tvari</i>	(ASTM E-897-88)	81.74	Holocellulose	(Wise and Karl, 1962)	78.51	Hydrogen <i>vodik</i>	5.77
Ash <i>pepeo</i>	(ASTM D-1102-84)	0.39	Lignin	(TAPPI T 222 om-02)	28.17	Nitrogen <i>dušik</i>	0.01
Fixed carbon <i>vezani ugljik</i>	calculated from the difference	14.70	Extractive	(TAPPI T 204 cm-97)	5.26	Oxygen <i>kisik</i>	47.08
						HHV ^a (MJ/kg)	12.90

^a HHV of pine sawdust was calculated according to the Dulong-Berthelot Correlation (Channiwala and Parikh, 2002). / ^aHHV piljevine od borovine izračunan je prema Dulong-Berthelotovoj korelaciji (Channiwala i Parikh, 2002.).

Table 2 Some typical properties of the catalysts

Tablica 2. Tipična svojstva katalizatora

Properties / <i>Svojstvo</i>	CaCO ₃	K ₂ CO ₃	Na ₂ CO ₃	MgCO ₃	NaHCO ₃
Solubility in water, g/L / <i>topljivost u vodi, g/L</i>	0.017	138	220	0.0139	9.4
Melting point, °C / <i>talište, °C</i>	825	891	851	990	3000
Molecular mass, g/mol / <i>molekulska masa, g/mol</i>	100.09	138.205	106	84.31	84.01
Density, g/cm ³ / <i>gustoća, g/cm³</i>	2.93	2.43	2.54	2.96	2.2
pH value / <i>pH-vrijednost</i>	8	11-13	11	9.3	8.4


Figure 1 Experimental scheme of the vacuum pyrolysis apparatus

Slika 1. Shematski prikaz eksperimentalne aparature za vakuumsku pirolizu

2.2 Pyrolysis experiments

2.2. Provođenje pirolize

Pyrolysis was conducted under vacuum in a fixed-bed reactor. An outline of the experiment is shown in Figure 1. The reactor is a stainless-steel cylinder with an internal diameter of 24 cm and a height of 36 cm. A 200 g sample was added to the reactor for non-catalytic tests. In the catalytic experiments, the biomass was mixed with selected catalysts at a 5 wt – %

loading and introduced into the reactor. Heating was applied using an electric furnace with target temperatures of 450, 500, and 550 °C, and the temperature was closely controlled by a PID (Proportional-Integral-Derivative) controller. The temperature within the internal bed was recorded using a K-type thermocouple at one-minute intervals. The temperature was maintained at the prescribed level for 30 minutes during the isothermal stage in each experiment. The pyrolysis products

consisted of three main components: bio-oil (py-oil), biochar, and non-condensable gas. Condensable products were collected by a condenser attached to the reactor outlet. The solid biochar yield was determined from the gravimetric mass of the remaining reactor residue at each test iteration, while the gas yield was predicted using mass-balance calculations.

2.3 Characterisation of py-oil

2.3. Karakterizacija pirolitičkog ulja

The liquid product extraction was carried out using an equal volume of diethyl ether. Extraction of ether extracts for gas chromatography-mass spectrometry (GC/MS) and elemental analysis were carried out. Elemental analysis (LECO CHNS-932 analyser) was performed to quantify the carbon (C), hydrogen (H), nitrogen (N) and sulphur (S) content in the pyrolysis oil; the oxygen (O) content was determined by difference. The higher heating value (HHV) was estimated using the Dulong–Berthelot correlation reported by Channiwala and Parikh (2002). In contrast, pyrolysis oil was quantified using an Agilent 6890 GC coupled to an Agilent 5973 mass spectrometer to determine its chemical composition. Separation was performed on an HP-5 capillary column (30 m × 0.25 mm i.d., film thickness: 0.25 µm) with helium as the gas carrier (at a flow rate of 1.2 mL/min). The temperature program was as follows: hold at 40 °C for 10 minutes, ramp up at 2 °C/min to 170 °C, and hold for 5 minutes. This was followed by a repeated ramp-up to 250 °C (8 °C/min, held for 15 minutes), before a final ramp-up to 300 °C (10 minutes). The injector was run in split mode at 250 °C with a split ratio of 1:10. Mass spectrometer conditions were set to electron impact (EI) ionisation mode, and compound identification was performed by comparison with the NIST mass spectral library using G1035A software.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

3.1 Yields of pyrolysis products

3.1.1. Prinosi produkata pirolize

Figure 2 depicts the percentages of products produced by pyrolysis at different temperatures, in non-catalytic and carbonate-catalysed processes. For non-catalytic pyrolysis, the maximum py-oil yield was around 48.58 wt.% at 500 °C, then decreased at 550 °C; however, the biochar yield decreased consistently from 39.28 wt.% at 450 °C to 36.71 wt.% at 550 °C, and the gas yield increased at high temperature. This is consistent with the literature, which shows a temperature effect on product distribution. The best py-oil yield from woody biomass, as shown in Figure 2, occurs at 500 – 550 °C, with a significant effect of the carbonate catalyst on gas, liquid, and char yields between 450 – 550 °C. The optimal yield was approximately 47 wt.% at 500 °C with CaCO₃ as the catalyst. Notably, it was determined that at these temperatures, lower py-oil yields were obtained than in non-catalytic pyrolysis when K₂CO₃ and Na₂CO₃ were used as catalysts. The marginal decline in py-oil yield with K₂CO₃ (from 48.58 wt.% to 43.3 – 45.0 wt.%) is part of an inherent technical trade-off for catalytic pyrolysis. As alkaline catalysts promote gas and char formation in chemistry, the liquid yield is lower, but the deoxygenation process improves the quality of the py-oil. As Mahasweta (2025) has stated, the reduced liquid yield can be technically and economically acceptable, as the improved stability and energy density of the upgraded py-oil will be more economical. In the current study, a further ~20 % increase in HHV (to 24.17 MJ/kg) and a significant decrease in oxygen content (from 32.64 % to 23.30 %) result in a much stronger fuel. These results are reflected in similar studies that demonstrate signifi-

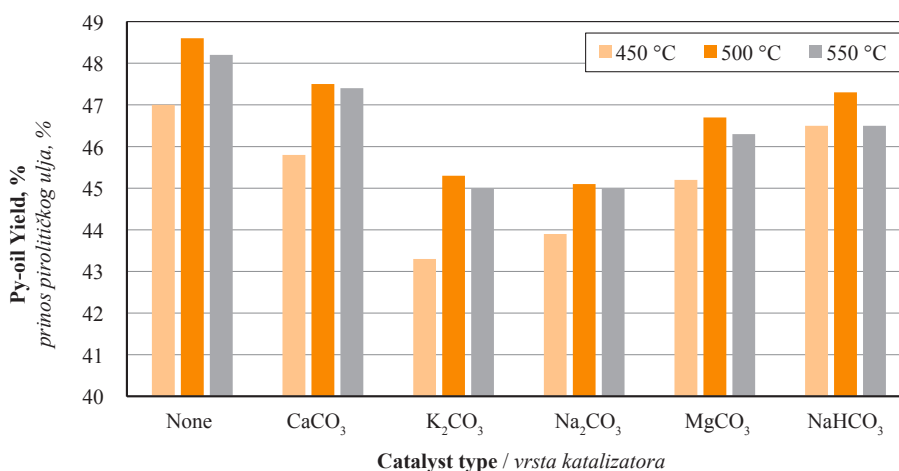


Figure 2 Comparison of product yields and py-oil production using carbonate catalysts at different temperatures
Slika 2. Usporedba prinosa produkata pirolize i proizvodnje pirolitičkog ulja u ovisnosti o temperaturi i vrsti karbonatnog katalizatora

cant differences in the distribution of lignocellulosic biomass-derived pyrolysis products among catalysts (Tirapanampai *et al.*, 2019; Fan *et al.*, 2020; Bagi and Baseri, 2021).

3.2 Py-oil characterisation

3.2. Karakterizacija pirolitičkog ulja

The elemental compositions of the produced py-oils are summarised in Table 3. It was observed that the presence of carbonate catalysts significantly modified the elemental distribution of the liquids. Among the tested catalysts, K_2CO_3 was identified as the most effective, reducing the oxygen content from 32.64 % (non-catalytic) to 23.30 % while increasing the carbon content to 68.74 %. The superior deoxygenation performance of alkali carbonates (K_2CO_3 and Na_2CO_3) compared to alkaline earth carbonates ($CaCO_3$ and $MgCO_3$) was attributed to their higher alkalinity and solubility, as reported in Table 2. The catalytic performance in this study was further compared with modern catalytic systems, such as zeolites (e.g., ZSM-5), which were frequently cited in recent literature (Mahasweta, 2025; Fan *et al.*, 2020). While acidic zeolites are highly effective in aromatics production through severe deoxygenation, they often promote extensive dehydration, leading to significant carbon loss as coke and a

substantial decrease in liquid yield. This resulted in a maximum liquid yield (~45 wt.%) and a significantly improved HHV of 24.17 MJ/kg. Specifically, the HHVs for py-oils generated with $CaCO_3$, $NaHCO_3$, $MgCO_3$, Na_2CO_3 , and K_2CO_3 were 22.49, 22.82, 23.00, 23.83, and 24.17 MJ/kg, respectively. These findings demonstrate a strong correlation between the catalyst alkalinity (pH) and the energy density of the resulting py-oil. This suggests that carbonate-based vacuum pyrolysis offers a more balanced and viable route for producing stable, oxygen-reduced py-oils with lower operational and hydrogen-conversion costs than high-surface-area synthetic zeolites.

The abundance of oxygen-containing functional groups was assessed by GC/MS analysis. The py-oil from non-catalytic pyrolysis shown in Table 4 primarily consists of oxygenated compounds such as aldehydes, ketones, phenols, organic acids, benzenes, and alcohols. Phenolic compounds were identified as the most prevalent. The identified phenolic compounds were phenol, 2-methylphenol, 4-methylphenol, 2-methoxyphenol (guaiacol), 2-methoxy-4-methylphenol, and 4-ethyl-2-methoxyphenol. The identified compounds also corresponded to the previously reported chemical characterisation of pyro-oil obtained from biomass pyrolysis (Kanauija *et al.*, 2013; Özbay, 2015; Nhuchhen *et al.*,

Table 3 Elemental composition and HHV of py-oils^a

Tablica 3. Elementarni sastav i gornja ogrjevna vrijednost pirolitičkih ulja^a

	C	H	N	O ^b	HHV (MJ/kg)
None	61.16	7.18	0.02	32.64	20.11
$CaCO_3$	65.17	7.85	0.05	26.93	22.49
K_2CO_3	68.74	7.88	0.08	23.30	24.17
Na_2CO_3	68.26	7.67	0.08	23.99	23.83
$MgCO_3$	66.72	7.46	0.06	25.76	23.00
$NaHCO_3$	66.45	7.37	0.05	26.13	22.82

^a Dry basis, ^bCalculation from difference / ^aSuha tvar; ^bizračunano iz razlike

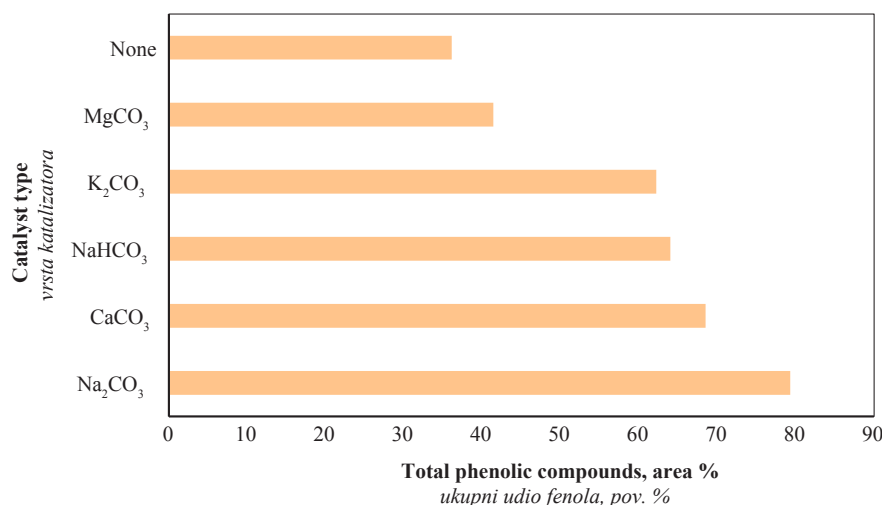


Figure 3 Comparative analysis of total phenolic compound concentrations (area %) in py-oils obtained from non-catalytic and carbonate-catalysed vacuum pyrolysis

Slika 3. Usporedba koncentracije ukupnih fenolnih spojeva (pov. %) u pirolitičkim uljima iz nekatalitičke i katalitičke vakuumske pirolize s karbonatima

Table 4 Main organic components of py-oils with GC-MS analysis**Tablica 4.** Glavne organske komponente pirolitičkih ulja dobivene GC-MS analizom

RT, min	Name of compounds <i>Ime spoja</i>	Area / Površina, %						Category
		None	CaCO ₃	K ₂ CO ₃	Na ₂ CO ₃	MgCO ₃	NaHCO ₃	
5.58	Propanoic acid	0.21	3.69	–	–	0.12	–	Acid
7.28	Cyclopentanone	–	1.42				1.88	Ketone
7.76	Butanoic acid	0.14	2.54					Acid
8.67	Furancarboxaldehyde	0.45	2.44	0.11		0.16		Aldehyde
9.68	1,3-Dimethyl-benzene	–	1.67			0.11		Benzene
9.69	Furanmethanol		–		0.72		2.04	Alcohol
10.57	1,3-Dimethyl-benzene	–	1.20				9.49	Benzene
11.46	2-Methyl-2-cyclopenten-1-one	0.32	1.17	0.14	1.53	0.11	2.16	Ketone
12.69	1,3-Dimethyl-1-one-cyclopentene	–	2.07		1.16		0.72	Ketone
13.40	1-Ethyl-2methyl-benzene					0.05	0.88	Benzene
14.00	5-Methyl-2-furancarboxaldehyde	0.31	4.52	0.97		0.05		Aldehyde
14.70	Phenol	5.36	13.54	8.02	8.93	7.54	8.92	Phenol
15.11	Benzofuran	0.11	0.55	1.16		1.45		Furan
15.50	2,3-Dimethyl-1-one-cyclopentene		0.47	0.20	1.38		1.22	Ketone
16.19	2-Ethyl-3,4-dimethyl-benzene			0.14		0.17	3.41	Benzene
16.36	Limonene						0.84	Benzene
17.24	Indene	–	0.79	0.06	0.84	0.21	0.80	Benzene
17.25	1-Ethyl-3methyl-benzene	0.18	1.72	1.24	0.73	1.18		Benzene
17.60	1,3-Dimethyl-1-one-cyclopentene			0.22	1.48			Ketone
18.00	2-Methyl-phenol	4.79	8.29	4.22	6.94	4.43	5.86	Phenol
18.44	Ethenone			0.11	2.03			Ketone
18.58	Acetophenone	–	1.08					Ketone
19.06	4-Methyl-phenol	9.52	14.56	14.68	15.95	9.86	11.55	Phenol
19.51	2-Methoxy-phenol	7.62	11.97	11.40	12.10	8.24	11.69	Phenol
20.01	2-Methyl-benzofuran	0.08	–			0.07		Furan
20.30	2,6-Dimethyl-phenol	0.20	1.72	1.06		0.12	1.35	Phenol
22.35	2,4-Dimethyl-phenol	0.61	5.37		0.92		7.22	Phenol
22.10	1-Methyl-1H-indene				0.89	0.08	1.40	Benzene
23.35	3-Ethyl-phenol	0.27	1.75	0.12	0.58	0.13	3.46	Phenol
23.74	2,3-Dimethyl-phenol			2.18	1.94	0.39	1.42	Phenol
23.75	Benzoic acid	–	4.14					Acid
23.76	Naphthalene	0.67	0.69			0.10		Benzene
24.87	2-Methoxy-4-methyl-phenol	4.80	7.54	6.65	9.82	5.30	5.73	Phenol
24.78	3,4-Dimethyl-phenol	0.09		4.20	4.38		1.21	Phenol
26.41	4-Ethyl-3-methyl-phenol	0.11	0.51	6.32	7.93			Phenol
26.42	3-(1-Methyl)-Phenol			2.44	1.29			Phenol
28.13	4-Ethyl-2-methoxy-phenol	2.49	3.24		6.13	5.23	4.73	Phenol
28.69	2-Methyl-naphthalene	0.28		0.06	0.75	0.09	0.87	Benzene
29.43	1-Methyl-naphthalene	0.16	1.09		0.72	0.06	0.61	Benzene
31.53	2-Methoxy-4-(2-propenyl)-phenol	0.24		0.88	2.30	0.14	0.84	Phenol

2018; Khuenkao and Tippayawong, 2020; Li *et al.*, 2025). When carbonate catalysts were used for wood pyrolysis (K₂CO₃ and Na₂CO₃), the composition of the pyro-oil changed substantially with an increase in phenolic content. This trend was also observed with other carbonates (Figure 3).

The fact that phenolic compounds are remarkably enriched indicates that alkali carbonates are useful for the selective cleavage of lignin in this molecule. Li *et al.* (2015) and Tang *et al.* (2025) have reported that the transformation of lignin into aromatic compounds is caused by the depolymerisation of its polymer structure, in which β-O-4 ether linkages are the most abun-

dant and most vulnerable targets for catalytic treatment. In this work, CO₃²⁻ ions were also used as the base catalyst. The alkaline environment facilitates the deprotonation of the phenolic hydroxyls in lignin, thereby enabling reactions with quinone methide molecules. At the same time, the intermediates accelerate the fragmentation of the β-ether bonds. In the process, the macromolecule is decomposed into one of its monomeric components, such as guaiacols or methylphenols. In addition, the alkali carbonates Na₂CO₃ and K₂CO₃ scavenge acidic intermediates, and they cannot be repolymerised in subsequent reactions. Thus, high pH levels of catalysts preserve the main breakdown

products in the py-oil, yielding high-value volatile phenols. This catalytic enhancement is crucial, given that abundant phenolics indicate a strong potential for alternative fuel production. These findings are consistent with the literature on the chemical composition of py-oil from the alkaline-catalysed pyrolysis of woody biomass (Rutkowski, 2011; Bu *et al.*, 2012; Kabir and Hameed, 2017; Rangel *et al.*, 2023; Zhang *et al.*, 2024).

The practical and industrial value of carbonate-based catalysts is enhanced by their potential for recovery and reuse from solid residue. Alkali carbonates such as Na_2CO_3 and K_2CO_3 are highly soluble in water and can be readily recovered from biochar via a simple aqueous leaching process. Wang *et al.* (2021) reported that using K_2CO_3 in biochar and pyrolysis promotes easy recovery in water through improved porosity and environmentally friendly processing methods, and that a solution of purified water can remove the carbonate salts. Although a small percentage of catalyst can be incorporated into the ash matrix, previous research indicates that recovered carbonates are very catalytic. This process reduces overall operational costs and aligns with the principles of green chemistry by avoiding chemical waste in biomass-to-fuel conversion.

4 CONCLUSIONS

4. ZAKLJUČAK

In this study, the vacuum pyrolysis of Scots pine (*Pinus sylvestris* L.) sawdust was investigated, and the subsequent improvement of the py-oil using various carbonate catalysts was also examined. The study resulted in the following main analytical findings:

It shows that the value of the liquid products generated was strongly temperature dependent in non-catalytic vacuum pyrolysis, with the highest value of 48.58 wt.% at 500 °C, and the value at 500 °C was noted; more than 500 °C results in decreased py-oil yield as a consequence of secondary cracking reaction, which promoted gas production.

The influence of various carbonate catalysts on product distribution was found to be very strong. So, a py-oil yield of 47 wt.% was sustained by calcium carbonate (CaCO_3); gasification and char formation were favoured by alkaline carbonate catalysts (potassium carbonate (K_2CO_3) and sodium carbonate (Na_2CO_3), and a decrease in liquid yield was observed, despite an appreciable improvement in quality.

The elemental compositions of py-oil were positively modified in all tested carbonate catalysts. K_2CO_3 was found to be the most efficient catalyst for deoxygenation, where the oxygen content decreased from 32.64 % (in non-catalytic pyrolysis) to 23.30 %. Therefore, there is a significant increase in carbon content and stability in the produced py-oil.

There was a significant positive correlation between the pH values of the carbonate catalysts and the higher heating value (HHV) of the py-oil formed. The py-oil with the highest HHV (24.17 MJ/kg) was formulated from K_2CO_3 , which has higher alkalinity and is more favourable than the non-catalytic oil (20.11 MJ/kg). A gas chromatography-mass spectrometry (GC/MS) analysis showed that the concentration of phenolic compounds increases when Na_2CO_3 and CaCO_3 are used for catalytic pyrolysis. This indicates that these catalysts enhance the breakdown of complex lignin structures into simpler aromatic compounds, yielding simpler yet more significant structures.

It was concluded that combining vacuum pyrolysis with carbonate-based catalysts is a practical way of producing high-quality py-oil with low oxygen content and high energy density. The new research suggested that inexpensive carbonates can also serve as green catalysts in a biomass-to-fuel conversion system. Also, the high enrichment of phenolic compounds suggests that this py-oil could serve as a sustainable precursor for wood adhesives, resins, and preservatives in the wood-processing and furniture industries.

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Physical Properties of Three Commercial Hardwoods in Indonesia

Fizička svojstva triju komercijalnih vrsta drva listača u Indoneziji

ORIGINAL SCIENTIFIC PAPER

Izvorni znanstveni rad

Received – prispjelo: 8. 3. 2026.

Accepted – prihvaćeno: 8. 6. 2026.

UDK: 630*81; 674.038

<https://doi.org/10.5552/drvind.2026.0341>

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ABSTRACT • Indonesia has abundant biodiversity and valuable timber species are used as essential raw materials in various industries. The objective of this study was to provide physical properties and dimensional stability information of three kinds of wood species that are categorized as fast-growing wood, namely *Gmelina* (*Gmelina arborea* Roxb.), *Nyatoh* (*Palaquium* spp.), and *Waru* (*Hibiscus tiliaceus*), which can support the appropriate and sustainable use of these woods. *Gmelina* exhibited the lowest tangential-to-radial shrinkage ratio (T/R) (1.01), indicating better dimensional stability compared to *Nyatoh* and *Waru*. *Nyatoh* exhibited intermediate physical properties with a T/R ratio of 1.83. *Waru* exhibited the lowest dimensional stability with a T/R ratio of 2.13. Overall, the results of this study highlight the differences in physical properties and dimensional stability among the three wood species under identical testing conditions and provide reference data to support material selection and further research on these commercially important tropical woods.

KEYWORDS: commercial wood; *gmelina*; *nyatoh*; *waru*; wood physical properties

SAŽETAK • Indonezija obiluje bioraznolikošću, a njezine vrijedne drvene vrste služe kao ključne sirovine u različitim industrijama. Cilj ovoga istraživanja bio je utvrditi fizička svojstva i dimenzijsku stabilnost triju brzorastućih vrsta drva: *gmelina* (*Gmelina arborea* Roxb.), *nyatoha* (*Palaquium* spp.) i *warua* (*Hibiscus tiliaceus*), kako bi se pridonijelo njihovoj pravilnoj i održivoj primjeni. Za drvo *gmelina* zabilježen je najmanji omjer tangencnog i radijalnog utezanja (T/R), koji je iznosio 1,01, što upućuje na bolju dimenzijsku stabilnost u usporedbi s drvom *nyatoha* i *warua*. Drvo *nyatoha* pokazalo je prosječna fizička svojstva s T/R omjerom od 1,83. Najmanja dimenzijska stabilnost izmjerena je za drvo *warua*, s T/R omjerom od 2,13. Zaključno, rezultati ovoga istraživanja istaknuli su razlike u fizičkim svojstvima i dimenzijskoj stabilnosti triju ispitivanih vrsta drva u jednakim uvjetima ispitivanja te su dali referentne podatke kao podlogu za odabir materijala i daljnja istraživanja tih komercijalno važnih tropskih vrsta drva.

KLJUČNE RIJEČI: komercijalne vrste drva; *gmelina*; *nyatoh*; *waru*; fizička svojstva drva

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1 INTRODUCTION

1. UVOD

Indonesia is known as one of the countries with abundant forest resources, including a high diversity of economically valuable timber species (Djafar *et al.*, 2023). Wood is an essential raw material in various industries such as construction, furniture, and handicrafts (Barbu and Tudor, 2022). Among the different types of traded wood, gmelina wood (*Gmelina arborea* Roxb.), nyatoh wood (*Palaquium spp.*), and waru wood (*Hibiscus tiliaceus*) are three well-known and widely used species in the local timber industry (Basri *et al.*, 2019; Yunianti, *et al.*, 2019; Meiganati *et al.*, 2023). These three types of wood are interesting for further study. In addition to being fast-growing and adaptable to tropical environments, especially in Southeast Asia, they are also widely available in local markets and are widely used in community-based industries such as furniture, handicrafts, and light construction (Husna *et al.*, 2021; Phang *et al.*, 2023; Kabir *et al.*, 2025). Although their use has become widespread, these types of wood are still classified as lesser-known species in the global timber market. In practice, their use is based more on experience than on scientific foundations, particularly regarding their physical properties, especially in small and medium-scale timber industries. This situation creates a mismatch between material performance and end-use requirements, which has the potential to lead to inefficient processing, reduced product durability, and limited value-added utilization.

Gmelina is a fast-growing wood that is often cultivated in agroforestry and community forests (Suri *et al.*, 2021). It is widely used in the light furniture, particle boards, and handicraft industries (Setiadi, 2018; Vallesteros, 2020). Nyatoh, which belongs to several species in the Sapotaceae family, has a smooth texture and attractive color, making it widely used for construction and interior materials (Muchtar *et al.*, 2024; Putra *et al.*, 2024). Waru, although classified as lightweight wood, is frequently utilized for panels, packaging boxes, lightweight construction, boats, and lightweight structural components in coastal areas because of its ability to grow in coastal environments (Irwan and Aras, 2023).

Although physical property datasets exist for many tropical wood species, most studies have focused only on well-established commercial species, while comparative and standardized data for widely used community-level wood species, such as gmelina, nyatoh, and waru, remain fragmented, inconsistent, or derived from varying test conditions. This lack of comparable data hinders direct evaluation of their relative performance and limits broader industry acceptance and global recognition of these wood species. Further-

more, previous studies generally report physical and mechanical properties individually for a particular species, with limited efforts to provide side-by-side comparisons under uniform sampling, preparation, and testing procedures. Such comparative analyses are important because differences in site conditions, sampling methods, and testing procedures can significantly affect the measured physical properties, leading to uncertainty when the data is used for material selection or industrial processing (Cai *et al.*, 2019). Therefore, there is a clear research gap regarding the provision of comparative and standardized evaluations of the physical properties and dimensional stability of these three Indonesian wood species, which have high commercial value but have not been extensively studied.

This has led to the limited and less innovative utilization of these woods, considering that recent investigations on wood modification have been of interest to many researchers worldwide (Zelinka *et al.*, 2022). Physical properties, such as moisture content, density, and specific gravity, are important indicators for determining wood strength, durability, and suitability for specific uses (Shukla, 2025). For instance, higher density is often associated with greater mechanical strength, while high moisture content reduces dimensional stability and weakens bonding performance in wood processing. Dimensional stability, which is the ability of wood to maintain its shape and size in response to changes in environmental humidity, is a critical factor for ensuring the longevity and quality of the final product (Sargent, 2022). Based on these considerations, this study proposes the hypothesis that gmelina, nyatoh, and waru exhibit significantly different physical properties and dimensional stability when evaluated under the same test conditions, and that these differences can be used to identify their suitability for specific industrial applications. Accordingly, the objective of this study is not only to report physical properties but also to provide a standardized comparative dataset and identify the relative performance of these three species as a scientific basis for material selection, value-added processing, and sustainable utilization.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

2.1 Materials

2.1. Materijali

The materials used in this study were Gmelina (*Gmelina arborea* Roxb.), Nyatoh (*Palaquium spp.*), and Waru (*Hibiscus tiliaceus*). These woods were harvested from a community forest in Bogor, West Java. A total of three mature and healthy trees were sampled for each species ($n=3$ trees per species). Trees were selected to represent similar age class (≈ 6 years), diam-

eter class (31-37 cm), and site conditions to reduce environmental variability. Logs were taken from the bottom section of the stem (0-2 m height) to ensure comparable wood maturity among trees.

2.2 Sample preparation

2.2. Priprema uzoraka

Test samples were prepared according to British Standard BS 373:1957. From each tree, boards were obtained from the radial direction and carefully separated into sapwood and heartwood zones based on color and anatomical appearance. Samples were taken from middle radial position (between pith and bark) to minimize radial variability. Only clear wood specimens free from knots, checks, and reaction wood were selected.

Test samples measuring 2 cm × 2 cm × 2 cm were prepared to measure moisture content, density, and specific gravity. Meanwhile, test samples were made into 5 cm × 5 cm × 1 cm pieces to measure the dimensional stability. For each species, a total of 9 specimens were tested for each property (3 trees × 3 specimens per tree), and each measurement was conducted in triplicate.

2.3 Physical properties test

2.3. Ispitivanje fizičkih svojstava

Moisture content, density, and specific gravity were evaluated according to BS-373:1957. The selection of BS 373:1957 was justified because this standard is still widely used in tropical wood research, enabling direct comparison with existing datasets and previous studies on Indonesian wood species. The initial volume and weight of the test sample were measured, then dried at 103 ± 2 °C using an oven (Memmert UN55, Germany) until the weight was constant, and finally, the volume and weight were measured. Moisture content, density, and specific gravity were calculated as follows (Nugroho *et al.*, 2024; Savero *et al.*, 2020):

$$MC_g (\%) = \frac{W_g - W_{od}}{W_{od}} \cdot 100 \quad (1)$$

$$MC_{ad} (\%) = \frac{W_{ad} - W_{od}}{W_{od}} \cdot 100 \quad (2)$$

$$D (\text{g/cm}^3) = \frac{W_g}{V_g} \quad (3)$$

$$SG = \frac{\frac{W_{od}}{V_g}}{\rho_{\text{water}}} \quad (4)$$

Where MC_g is the green moisture content (%), W_g is green weight (g), W_{od} is oven dried weight (g), MC_{ad} is air-dried moisture content (%), W_{ad} is air-dried weight (g), D is density (g/cm³), V_g is green volume (cm³), SG is specific gravity, and ρ_{water} is water density at 4 °C (g/cm³).

2.4 Dimensional stability measurement

2.4. Mjerenje dimenzijske stabilnosti

Dimensional stability was evaluated by measuring the volume of the longitudinal, tangential, and radial sections of the wood sample after oven-drying at 103 ± 2 °C until it reached a constant weight. Subsequently, the volume was measured again in a similar plane. Dimensions were measured before and after drying to determine the dimensional changes in each anatomical direction. The dimensions of each specimen (in the longitudinal, tangential, and radial directions) were measured using a digital caliper with an accuracy of ± 0.01 mm. The mass of the samples was measured using an analytical balance with a precision of ± 0.001 g. The ratio of tangential shrinkage to radial shrinkage (T/R ratio) was used as an indicator of the dimensional stability. The dimensional stability of wood can be indicated by a T/R ratio close to one (Savero *et al.*, 2020). All measurements were taken three times, and the average values were used for further analysis.

2.5 Statistical analysis

2.5. Statistička analiza

All data were analyzed using statistical methods to evaluate variability and differences among species. For each property, results are presented as mean ± standard deviation (SD). Data normality was evaluated using the Shapiro–Wilk test, and homogeneity of variance was checked using Levene's test. Differences among wood species were analyzed using one-way analysis of variance (ANOVA) at a 95 % confidence level ($\alpha = 0.05$). All statistical analyses were performed using statistical software.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

3.1 Moisture content

3.1. Sadržaj vode

The green moisture contents of *G. arborea*, *Palaquium spp.*, and *H. tiliaceus* were 176.41 ± 13.84 %, 103.45 ± 0.84 %, and 82.49 ± 2.53 %, respectively (Figure 1). The ANOVA results indicate that wood species have a highly significant effect on fresh moisture content ($F = 131.14$; $p < 0.001$). The mean values show that Gmelina has the highest fresh moisture content, followed by Nyatoh and Waru. This highly significant difference indicates that water-holding capacity in the fresh state is strongly influenced by the characteristics of the wood species. Green moisture content is a critical factor affecting the suitability and performance of wood during mechanical processing operations (Seta *et al.*, 2023). This is because wood with a high level of green moisture content tends to be more prone to cracking, surface checking, and dimensional instability during cutting and drying, whereas lower levels may

reduce workability but improve drying efficiency (Mezui *et al.*, 2022; Elustondo *et al.*, 2022). The results of the green moisture content study on all types of wood are aligned with those reported by Shmulsky and Jones (2011), which range from 33 – 249 %. A green moisture content value greater than 100 % indicates that wood contains a significant amount of water in living trees (Bergman, 2021). The difference in the moisture content of wood under green conditions is influenced by the trees age and growing location, and changes according to the temperature and humidity of the surrounding air (Bowyer *et al.*, 2007; Uslinawaty *et al.*, 2024). For example, younger trees generally contain higher amounts of water due to the dominance of juvenile wood, while older trees tend to show lower values as mature wood develops (Alfikri *et al.*, 2020). In this study, *G. arborea* showed the highest green moisture content, reflecting its fast-growing nature and higher proportion of juvenile tissues. *Palaquium spp.* exhibited intermediate values, consistent with its denser structure and slower growth rate, whereas *H. tiliaceus* had the lowest green moisture content, making it relatively more dimensionally stable compared to the other two species. These differences highlight the importance of considering both species characteristics and growth conditions when evaluating wood utilization.

The green moisture content of *G. arborea* wood was slightly higher than that reported by Yau *et al.* (2024), who reported that the green moisture content of *G. arborea* wood ranged from 121.6 – 171.82 %, which increased from the apical to the middle section of the wood and began to decrease at the base. This was caused by the presence of juvenile wood in the middle section of the wood, which formed a thinner cell wall

with larger lumens and cavities that accommodate larger amounts of moisture. Moya and Fo (2008) also stated that the lumen diameter and cell wall thickness of *G. arborea* wood were 12.25 – 35.53 μm and 2.37 – 6.01 μm . Augustina *et al.* (2020a) found that the lumen diameter and cell wall thickness of *Palaquium spp.* were 25.01 μm and 3.61 μm . On the other hand, *H. tiliaceus* has a lumen diameter of 19.96 μm and cell wall thickness of 4.09 μm , according to Andianto *et al.* (2024). This is in accordance with the assumption that wood with a smaller lumen diameter and thicker cell walls has a remarkable effect on the lower moisture content of wood (Klement *et al.*, 2020). In terms of wood processing, a higher moisture content can facilitate wood cutting. However, it can also increase the susceptibility of the cutting tool to corrosion, thereby increasing maintenance costs (Bendikiene and Keturakis 2017). A higher moisture content also accelerates wood decay by fungi and termites, leading to a loss of wood performance, especially in its mechanical properties (Marais *et al.*, 2020; Kherais, *et al.*, 2024). In addition, this parameter also plays an important role in wood bonding with adhesives, as a higher water quantity reduces the adhesion strength (Favis *et al.*, 2024). As green wood dries, most of the water evaporates and the wood tends to reach equilibrium with the relative humidity of the surrounding air (Bergman 2021). Under these conditions, the air-dried moisture content of wood can facilitate wood processing by reducing the tendency for dimensional changes and the risk of wood defects (Coto 2005).

The air-dried moisture content of *G. arborea*, *Palaquium spp.*, and *H. tiliaceus* was 16.34 ± 3.30 %, 17.65 ± 0.76 %, and 12.18 ± 0.49 %, respectively (Figure 1). The type of wood also had a significant effect on

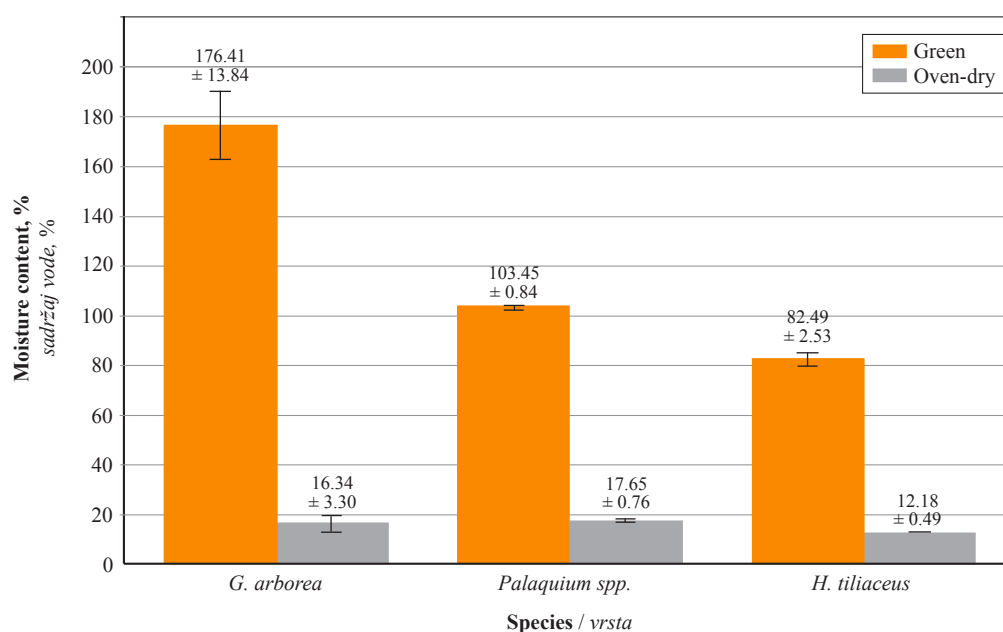


Figure 1 The average moisture content in green and air-dried conditions

Slika 1. Prosječni sadržaj vode u sirovome i prosušenom drvu

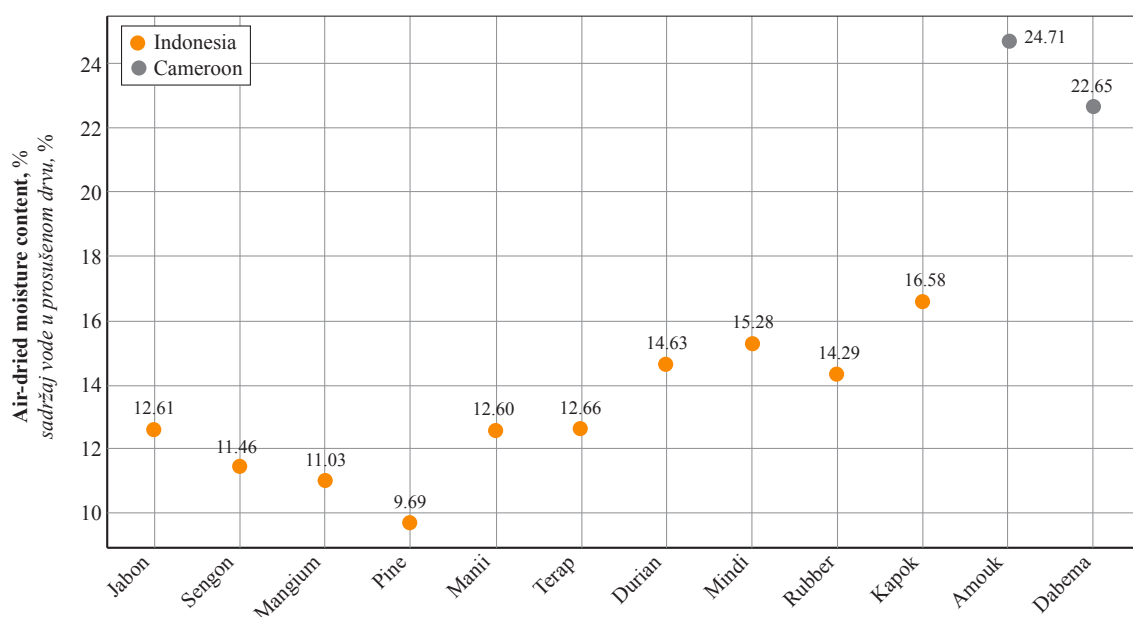


Figure 2 Comparison of air-dried moisture content in tropical wood species from Indonesia and other countries (Hadi *et al.*, 2022; Komariah *et al.*, 2015; Herawati *et al.*, 2021; Nawawi *et al.*, 2023; Kana *et al.*, 2024)

Slika 2. Usporedba sadržaja vode u prosušenom drvu tropskih vrsta iz Indonezije i drugih zemalja (Hadi *et al.*, 2022.; Komariah *et al.*, 2015.; Herawati *et al.*, 2021.; Nawawi *et al.*, 2023.; Kana *et al.*, 2024.)

the dry air moisture content ($F = 9.70$; $p = 0.013$). The mean values indicate that Nyatoh and Gmelina have relatively higher equilibrium moisture contents than Waru. This suggests that the hygroscopic properties of wood vary among species. After reaching the air-dried moisture content, the wood no longer underwent significant water absorption or release into the air. The air-dried moisture content results for all types of wood were directly proportional to those reported by Rahmayanti *et al.* (2016), who stated that the moisture content in Indonesia's climate ranges between 12 – 20 %. The results of this study showed that the air-dried moisture content of *G. arborea*, *Palaquium spp.*, and *H. tiliaceus* falls within the range comparable to most tropical wood species listed in Figure 2. For instance, the air-dried moisture content of Jabon, Sengon, Mangium, Manii, and Terap are comparable to that observed in *H. tiliaceus*. Meanwhile, Kapok and Mindi exhibit values that are relatively comparable to *G. arborea* and *Palaquium spp.*

On the other hand, several tropical wood species from outside Indonesia, such as Amouk and Dabema from Cameroon, show much higher values than the average of tropical wood species in Indonesia. These differences highlight that both species characteristics and growing conditions significantly influence the physical properties of wood, particularly air-dried moisture content. Air dried moisture content above 20 % is more susceptible to attacks by wood-destroying organisms, such as fungi (Simangunsong, 2016). This condition

indicates that Indonesia tropical wood species tend to be more stable under air-dried conditions and fall within a safe range for drying processes as well as industrial applications.

The moisture content under air-dry conditions obtained in this study falls within the range commonly reported for tropical hardwoods. However, direct comparisons with previous studies should be interpreted with caution because moisture content is strongly influenced by environmental conditions, sample conditioning protocols, and the location where the trees grew. Some previous reports on Gmelina, Nyatoh, and Waru were conducted under different climatic conditions or equilibrium moisture contents, which may explain the variations between studies (Marini *et al.*, 2021; You *et al.*, 2021). This study reduces such variability by conditioning all samples under identical laboratory conditions, thereby producing a more reliable set of comparative data among the three species.

3.2 Density

3.2. Gustoća drva

Wood density is the ratio of wood mass to volume under the same conditions (Wulandari *et al.*, 2024). The density values of *G. arborea*, *Palaquium spp.*, and *H. tiliaceus* wood are 0.9 ± 0.04 g/cm³, 0.76 ± 0.02 g/cm³, and 0.67 ± 0.03 g/cm³, respectively (Figure 3). The ANOVA results showed a significant difference in density among the wood species ($F = 11.26$; $p = 0.009$). Gmelina had the highest density, followed by Nyatoh and Waru. These differences confirm that spe-

cies variation has a strong influence on the physical structure of wood. The results of this study are much larger than those of previous studies (Iwuoha *et al.*, 2021; Arifudin and Wahyudi, 2020; Reyes *et al.*, 1992), which reported *G. arborea* densities of 0.69, 0.55, and 0.57 g/cm³. These results are known to be higher compared to short and long rotation teak wood (0.66 and 0.47 g/cm³, respectively), as the most well-known commercial wood in Indonesia (Rizanti *et al.*, 2018). In addition to wood type, wood density is influenced by its location on the tree, growing conditions, and tree age (Miranda *et al.*, 2011; Savero *et al.*, 2020; Wulandari and Amin, 2023). Furthermore, wood density is also an important parameter in determining wood quality (Li *et al.*, 2024). Deepa and Shukla (2024) found a strong correlation between wood density and chemical extractives with wood durability and mechanical properties, especially wood hardness (Damayanti *et al.*, 2020). Thus, the relatively high density indicates potential mechanical strength, although mechanical testing was not conducted in this study (Cabral *et al.*, 2022), and therefore structural suitability should be interpreted with caution.

The density of *G. arborea* is relatively high compared to most tropical woods found in Indonesia and other countries (Figure 4). This value is comparable to imported woods such as Bilinga (0.73 – 0.89 g/cm³) and Tali (0.8 – 1.05) from Brazil, indicating the potential of *G. arborea* as a wood with good structural quality. This is in line with several studies reporting that *G. arborea* can be used for furniture and construction (Iwuoha *et al.*, 2021; Olaniran *et al.*, 2024).

In *Palaquium spp.*, the density value is in the moderate range, higher than most tropical woods found in Indonesia such as Jabon, Sengon, Mangium, Teak, Manii, Terap, Durian, Mindi, Rubber, Kapok, Cundlenut, and Samama, but still lower than *G. arborea* and hardwoods from Brazil such as Iroko, Bilinga, and Tali. Meanwhile, Pine is Indonesian tropical wood comparable to the density of *Palaquium spp.*, as well as Dabema from Cameroon (Figure 4). This places *Palaquium spp.* as a wood with moderate to heavy density with quite a potential for light construction applications. This is in line with Arifudin and Wahyudi (2020), who reported that this wood can be used for light construction, furniture, and flooring. In addition, Meiganati (2023) added that *Palaquium spp.* can be used as raw material for pencil sticks and veneer.

Meanwhile, *H. tiliaceus* has the lowest density among the three species studied. This value is still higher than that of Jabon, Sengon, Manii, Terap, Durian, Mindi, Rubber, Kapok, Cundelnut, and Samama, but lower than that of Pine from Indonesia as well as Bilinga and Tali from Brazil. However, its density is comparable to Teak from Indonesia, as well as several types of tropical wood from other countries such as Iroko, Amouk, and Dabema (Figure 4). Thus, *H. tiliaceus* has the potential to be used for non-structural or industrial purposes. This is in line with several studies indicating that *H. tiliaceus* is widely used for making bags, ropes, and woven products (Purnowidodo *et al.*, 2020; Wirawan *et al.*, 2023). The density values obtained are generally consistent with the wide range of densities reported for these species in the previous lit-

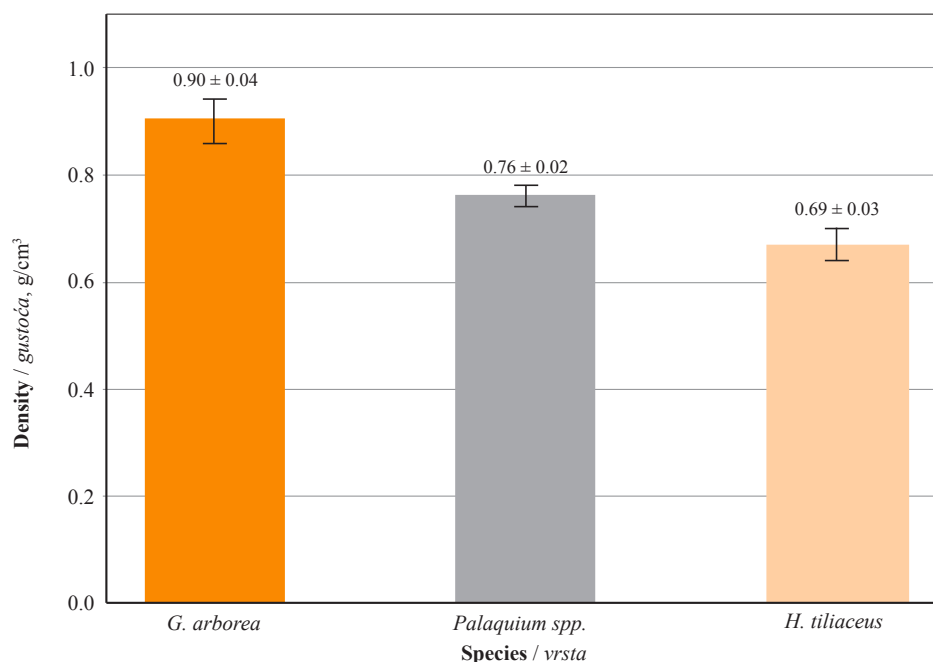


Figure 3 Density
Slika 3. Gustoća drva

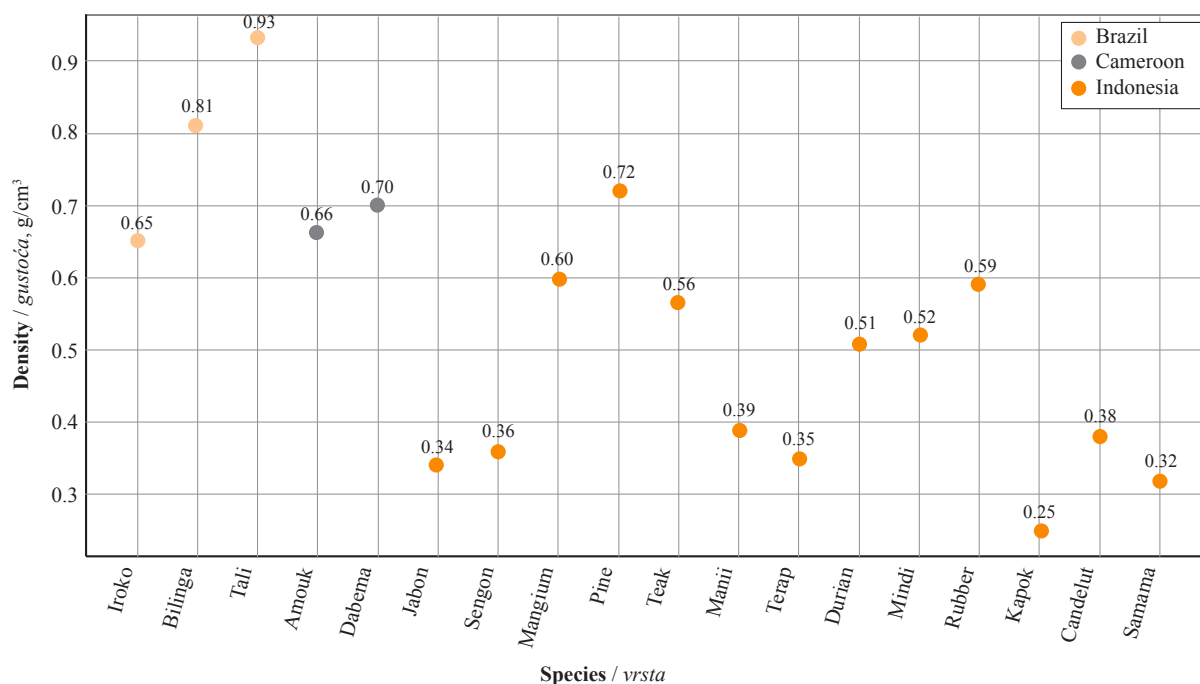


Figure 4 Comparison of density in tropical wood species from Indonesia and other countries (Hadi *et al.*, 2022; Rizanti *et al.*, 2018; Komariah *et al.*, 2015; Herawati *et al.*, 2021; Nawawi *et al.*, 2023; Azis *et al.*, 2020; Augustina *et al.*, 2023; Myondo *et al.*, 2017; Kana *et al.*, 2024)

Slika 4. Usporedba gustoće tropskih vrsta drva iz Indonezije i drugih zemalja (Hadi *et al.*, 2022.; Rizanti *et al.*, 2018.; Komariah *et al.*, 2015.; Herawati *et al.*, 2021.; Nawawi *et al.*, 2023.; Azis *et al.*, 2020.; Augustina *et al.*, 2023.; Myondo *et al.*, 2017.; Kana *et al.*, 2024.)

erature. However, previous studies have often shown wide variations due to differences in tree age, site quality, and sampling location within the trunk. In contrast, this study minimized these sources of variation through standardized sampling and testing procedures. This highlights the importance of standardized comparative measurements, as the density differences observed in this study are more likely to reflect the inherent characteristics of the species rather than methodological differences.

3.3 Specific gravity

3.3. Specifična gustoća drva

The specific gravities of three different commercial wood species were successfully evaluated in this study. Shmulsky and Jones (2011) stated that the specific gravity of wood is the ratio of the oven-dried weight to the volume of wood under green conditions. The specific gravities of *G. arborea*, *Palaquium spp.*, and *H. tiliaceus* wood are 0.33 ± 0.01 , 0.37 ± 0.01 , and 0.39 ± 0.01 , respectively (Figure 5). The type of wood has a highly significant effect on specific gravity ($F = 61.80$; $p < 0.001$). Waru and Nyatoh exhibited higher specific gravity values than *Gmelina*. The very large F -value indicates that the variation among species is the dominant factor influencing wood specific gravity. At first glance, the density and specific gravity values appear inconsistent, particularly for *G. arborea*, which

shows high density but relatively low specific gravity. This discrepancy is due to the different reference conditions used in the calculations. In this study, density was calculated based on air-dry volume, while specific gravity was calculated using oven-dry mass divided by green volume, in accordance with BS 373:1957. As wood undergoes volumetric shrinkage during drying, the air-dry volume is smaller than the green volume, resulting in a higher density value compared to specific gravity. Therefore, these results are methodologically consistent and not contradictory.

Based on the specific gravity values obtained, all wood types were classified as having relatively low specific gravity values. According to the PKKI 1961 classification, the three types of wood were included in strength class IV. Based on PKKI classification, the three species fall into strength class IV. This classification suggests potential suitability for light and non-structural applications, although mechanical testing is required for confirmation (Somadona *et al.*, 2020). Interestingly, Yau *et al.* (2024) reported that the specific gravity of *Gmelina arborea* from Nigeria reached 0.51, which is higher than the value obtained in the present study. This discrepancy may be attributed to several factors, including differences in site conditions, growth rates, and age of the sampled trees, as well as variations in sample preparation and measurement methods (Listyanto *et al.*, 2020).

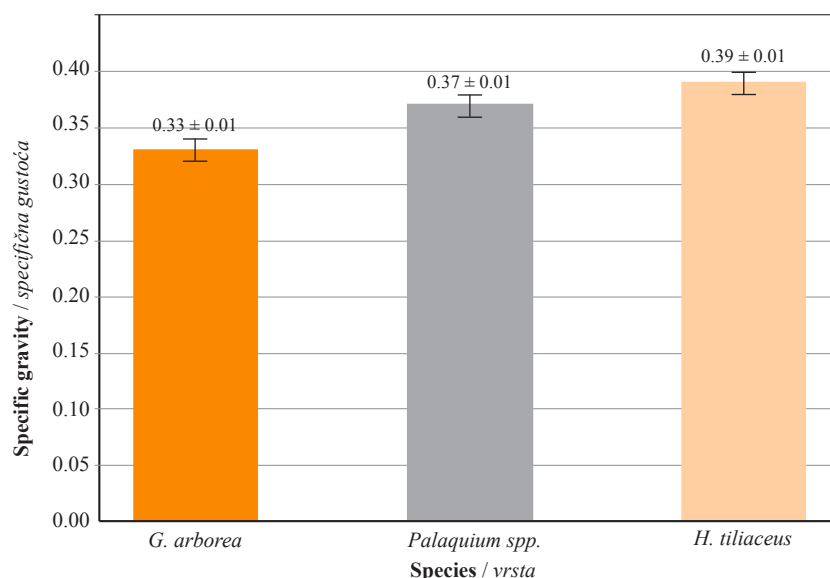


Figure 5 Specific gravity

Slika 5. Specifična gustoća drva

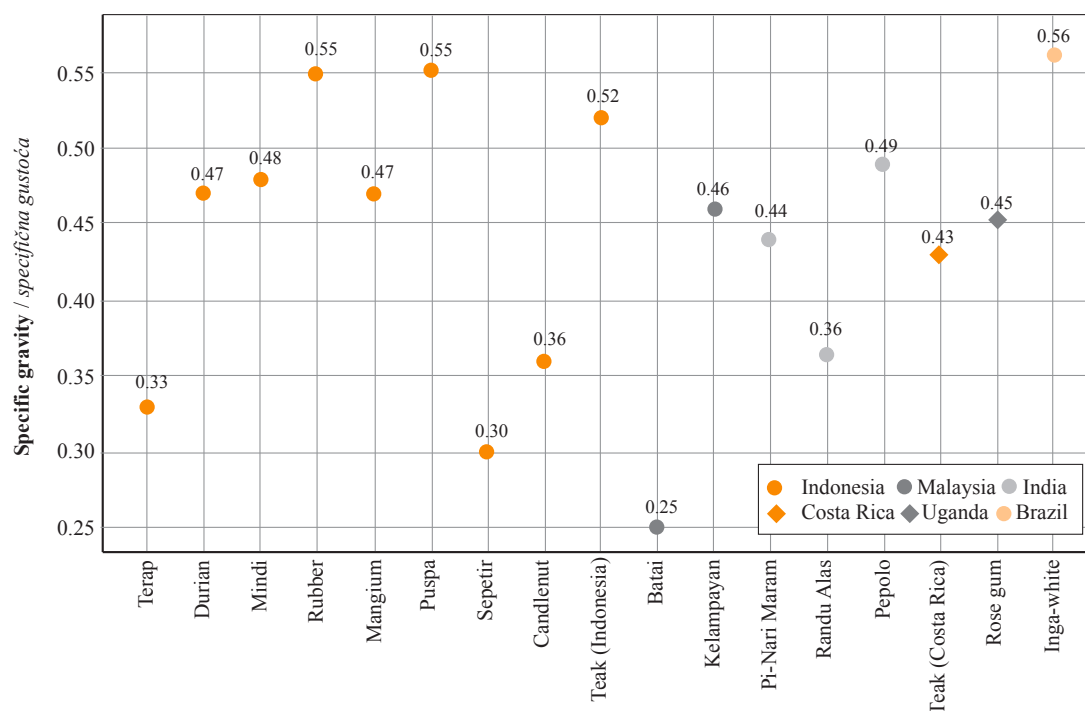


Figure 6 Comparison of specific gravity in tropical wood species from Indonesia and other countries (Herawati *et al.*, 2021; Hariz *et al.*, 2023; Augustina *et al.*, 2020b; Azis *et al.*, 2020; Savero *et al.*, 2020; Rahman *et al.*, 2020; Meghwal *et al.*, 2020; Pati *et al.*, 2025; Berrocal *et al.*, 2018; Sseremba *et al.*, 2020; Nascimento *et al.*, 2023)

Slika 6. Usporedba specifične gustoće tropskih vrsta drva iz Indonezije i drugih zemalja (Herawati *et al.*, 2021.; Hariz *et al.*, 2023.; Augustina *et al.*, 2020b; Azis *et al.*, 2020.; Savero *et al.*, 2020.; Rahman *et al.*, 2020.; Meghwal *et al.*, 2020.; Pati *et al.*, 2025.; Berrocal *et al.*, 2018.; Sseremba *et al.*, 2020.; Nascimento *et al.*, 2023.)

The results of this study are not linear with the wood density obtained in this study, which differs from the results of Damayanti *et al.* (2020), who stated that there was a positive correlation between density, specific gravity, and wood hardness. However, the relationship between density and specific gravity cannot be directly explained by anatomical characteristics in this study, because microscopic measurements were not performed (Borrega *et al.*, 2015). Unfortunately, this parameter was

not tested in the present study. Several previous studies by Moya and Fo (2008), Augustina *et al.* (2020a), and Andianto *et al.* (2024) mentioned that the cell wall thicknesses of *G. arborea*, *Palaquium spp.*, and *H. tiliaceus* woods are 2.37 – 6.01, 3.61, and 4.09 μm , respectively. Agustina *et al.* (2020) stated that variations in specific gravity values in several wood species are correlated with their microscopic structure and cell wall composition. In addition to influencing the mechanical character-

istics and utilization of wood, specific gravity is also closely related to its biological resistance and interaction with wood-degrading organisms (Kutana *et al.*, 2025). Thus, understanding the specific gravity of wood can provide an important basis for determining the application and utilization of each type of wood.

When compared to the data in Figure 6, the three types of wood tested show a relatively lower specific gravity than other tropical woods found in Indonesia, such as Durian, Mindi, Rubber, Mangium, Puspa, and Teak, which are in the moderate category (strength class III). However, their values are still comparable to Terap, Sepetir, and Candlenut. This condition indicates that the wood species studied have light characteristics with low specific gravity, making them more suitable for use in products with low structural loads (Yau *et al.*, 2025). As stated by Herawati *et al.* (2021), wood species with a low strength class (IV) are suitable for light construction. However, when compared to species from abroad, it can be seen that the specific gravity value of Inga-white found in Brazil is much higher, namely 0.56, thus falling into the category of wood with better strength (Nascimento *et al.*, 2023). On the other hand, Kelampayan, Pi-Nari Maram, Pepolo, and Teak wood found in several other countries also have a higher specific gravity range than species tested in this study. These differences further emphasize the influence of species and growing environment on the variation in the physical properties of wood (Nagar *et al.*, 2021). The specific gravity values reported in previous studies vary widely across regions and experimental conditions. This variability makes it difficult for practitioners to rely on values cited in literature when making industrial decisions. The results of this study present a controlled

comparison under identical testing conditions, which strengthens the reliability of cross-species comparisons and provides a more practical reference for wood processing and product design. However, direct comparisons with previous studies should be interpreted with caution, as differences in tree age, site conditions, sampling methods, moisture conditions, and testing procedures between studies may affect the reported values. Therefore, the comparisons presented in this study are intended for general reference only, while the interpretation of comparative performance remains limited.

3.4 Dimensional stability

3.4. Dimenzijska stabilnost drva

Changes in wood dimensions owing to increased moisture content are the primary factors affecting dimensional stability and wood quality, particularly in structural applications and material engineering. Wood exhibits anisotropic properties, meaning that shrinkage does not occur uniformly in all three directions of wood fiber orientation. Figure 7 shows the shrinkage values with significant variations in the longitudinal, radial, and tangential directions. The longitudinal shrinkage values ranged from 0.48 ± 0.02 % to 0.74 ± 0.01 %, with *H. tiliaceus* having the lowest value and *G. arborea* having the highest. Radial and tangential shrinkage values are important indicators for determining the degree of anisotropy and dimensional deformation tendency of wood. *G. arborea* exhibited similar radial and tangential shrinkages of 4.95 ± 0.02 % and 4.98 ± 0.03 %, respectively, indicating good wood shrinkage. According to Owoyemi *et al.* (2015), Gmelina shrinkage ranged from 8.65 % to 9.30 %, based on the position of the cut within the log. Addi-

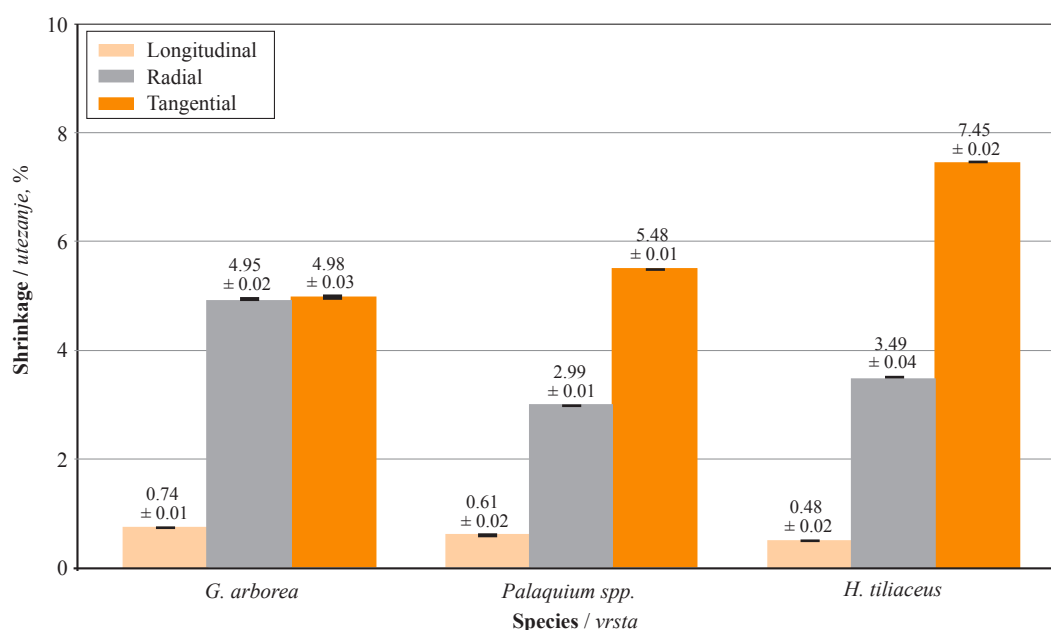


Figure 7 Shrinkage
Slika 7. Utezanje drva

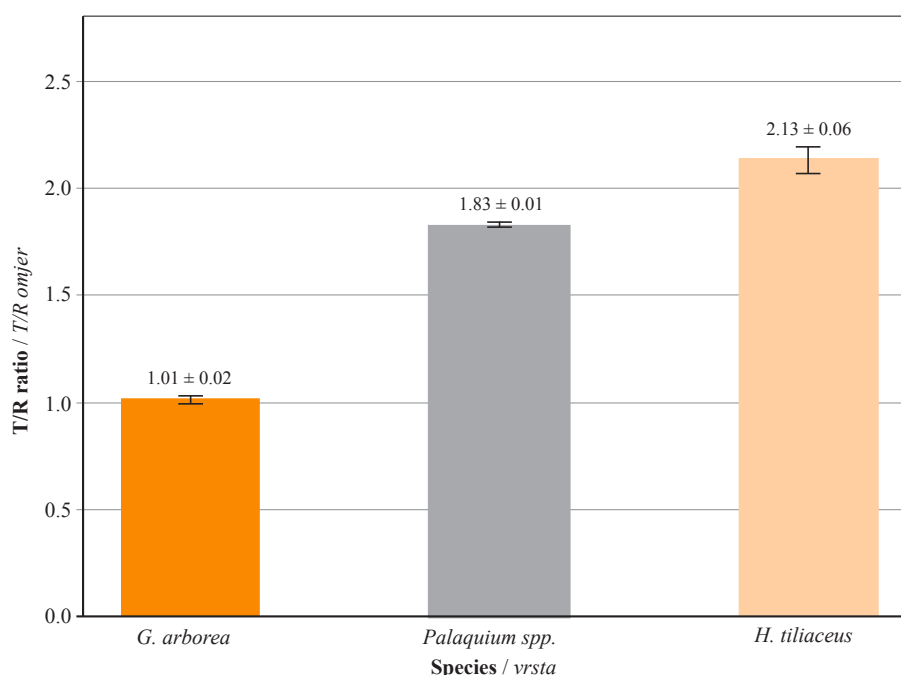


Figure 8 T/R ratio

Slika 8. Omjer tangენტnoga i radijalnog utezanja

tionally, Olaniran and Miltz (2024) stated that Gmelina subjected to thermal treatment exhibited a tangential-to-radial shrinkage ratio (T/R ratio) of 1.4 and experienced approximately 9.36 % shrinkage, indicating low volume changes in the wood. As shown in Figure 8, the T/R ratio of gmelina is 1.01 ± 0.02 , indicating excellent dimensional stability. The T/R ratio is an important parameter for wood dimensional stability, suggesting that the best use of wood in terms of drying quality leads to dimensional stability (Christoforo *et al.*, 2016; Seta *et al.*, 2023).

Unlike nyatoh, although it has a lower longitudinal shrinkage (0.61 ± 0.02 %), its tangential shrinkage is quite high (5.48 ± 0.01 %) and radial shrinkage (2.99 ± 0.01 %) (Figure 7). These values resulted in a T/R ratio of 1.83 ± 0.01 , indicating a higher risk of deformation compared to that of *G. arborea* (Figure 8). This ratio suggests that changes in moisture content can cause significant changes in shape, particularly in wood products, such as boards or veneers. *H. tiliaceus* had the lowest longitudinal shrinkage but produced the highest tangential shrinkage value of 7.45 ± 0.02 %, with a radial shrinkage of 3.49 ± 0.04 % (Figure 7). This results in a T/R ratio of 2.13 ± 0.06 , which significantly exceeds the ideal stability threshold and indicates high potential for shape changes and cracking during drying (Figure 8).

The results indicate that gmelina is the most dimensionally stable wood among the wood samples, as evidenced by a T/R ratio close to 1 and a minimal difference between radial and tangential shrinkage. The results for *Palaquium spp.* showed moderate deforma-

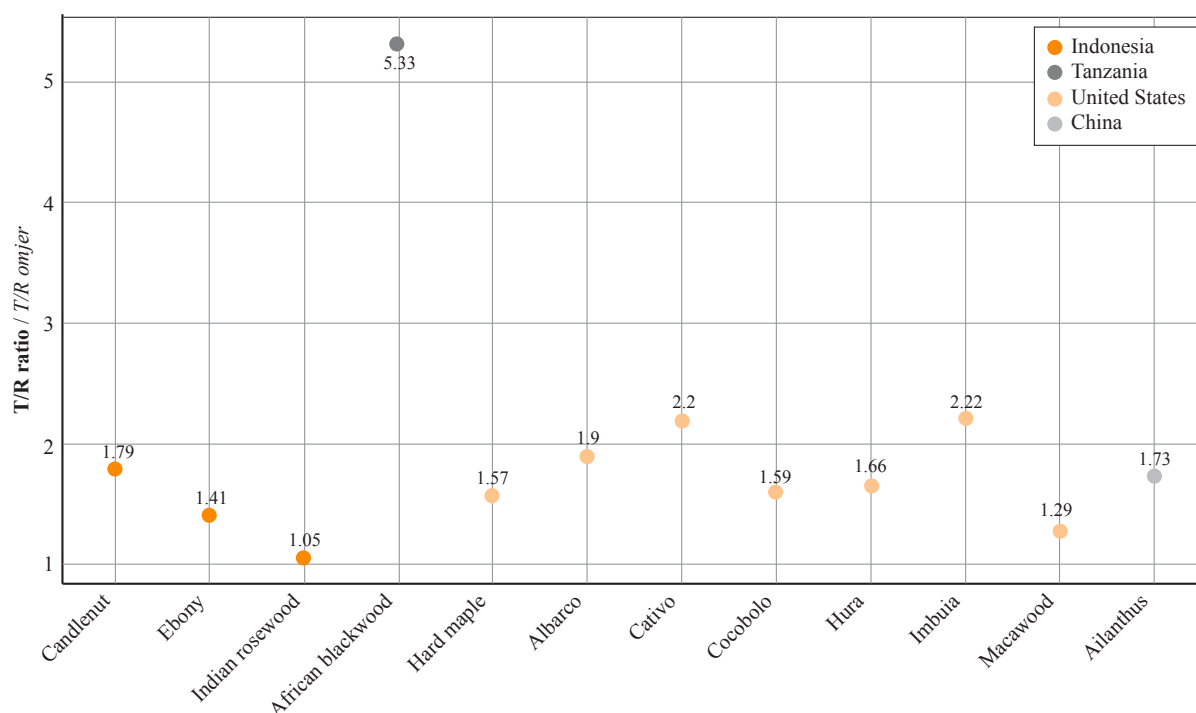
tion tendencies, particularly with respect to cupping. In contrast, *H. tiliaceus* exhibited the lowest stability. Therefore, its use should be limited to non-structural applications or decorative products that do not require high dimensional stability. Variations in the shrinkage ratio between the tangential and radial directions significantly influence the development of internal stresses during the wood drying process. This anisotropic behavior, particularly the T/R ratio, is a critical factor to consider in industrial applications, as it directly affects the dimensional stability and potential deformation of wood products over time (Fu *et al.*, 2016).

The results show that the three species of wood tested exhibit varying shrinkage behavior in all three directions, particularly radial and tangential. Compared to the data in Table 1 and Figure 9, the shrinkage value of *G. arborea* is within a range comparable to that of Indian Rosewood, an Indonesian tropical wood, which has a T/R ratio close to 1 (Liu *et al.*, 2020). This indicates fairly good dimensional stability. Meanwhile, *Palaquium spp.* and *H. tiliaceus* have shrinkage and T/R ratio values comparable to several Indonesian tropical woods such as Candlenut and Ebony. In addition, the two woods studied also have T/R ratios comparable to several tropical woods from other countries, such as Hard Maple, Albarco, Catiyo, Cocobolo, Hura, Imbuia, and Macawood from the United States, as well as Ailanthus from China. In fact, African Blackwood tropical wood from Tanzania has a T/R ratio that is very far from the indicator of wood dimensional stability.

The differences in shrinkage values and dimensional stability between tropical wood from Indonesia

Table 1 Comparison of shrinkage in tropical wood species from Indonesia and other countries**Tablica 1.** Usporedba utezanja tropskih vrsta drva iz Indonezije i drugih zemalja

Species / Vrsta	Tangential <i>Tangentno utezanje</i>	Radial <i>Radijalno utezanje</i>	Country <i>Zemlja</i>	Reference / Referenca
Candlenut (<i>Aleurites moluccanus</i> (L.) Willd.)	2.37	1.32	Indonesia	Azis <i>et al.</i> (2020)
Ebony (<i>Diospyros crassiflora</i> J. Kenig ex Retz.)	2.56	1.81	Indonesia	Liu <i>et al.</i> (2020)
Indian rosewood (<i>Dalbergia latifolia</i> Roxb.)	1.97	1.88	Indonesia	Liu <i>et al.</i> (2020)
African blackwood (<i>Dalbergia melanoxylon</i> Guill. & Perr.)	0.16	0.03	Tanzania	Liu <i>et al.</i> (2020)
Hard maple (<i>Acer saccharum</i>)	2.74	1.74	United States	Liu <i>et al.</i> (2020)
Albarco (<i>Cariniana spp.</i>)	5.4	2.8	United States	Glass and Zelinka (2021)
Cativo (<i>Prioria copaiifera</i>)	5.3	2.4	United States	Glass and Zelinka (2021)
Cocobolo (<i>Dalbergia retusa</i>)	4.3	2.7	United States	Glass and Zelinka (2021)
Hura (<i>Hura crepitans</i>)	4.5	2.7	United States	Glass and Zelinka (2021)
Imbuia (<i>Phoebe porosa</i>)	6	2.7	United States	Glass and Zelinka (2021)
Macawood (<i>Platymiscium spp.</i>)	3.5	2.7	United States	Glass and Zelinka (2021)
Ailanthus (<i>Ailanthus desf.</i>)	3.08	1.78	China	Liu <i>et al.</i> (2021)

**Figure 9** Comparison of T/R ratio in tropical wood species from Indonesia and other countries (Azis *et al.*, 2020; Liu *et al.*, 2020; Glass and Zelinka, 2021; Liu *et al.*, 2021)**Slika 9.** Usporedba T/R omjera tropskih vrsta drva iz Indonezije i drugih zemalja (Azis *et al.*, 2020.; Liu *et al.*, 2020.; Glass i Zelinka, 2021.; Liu *et al.*, 2021.)

and species from other countries are not only influenced by anatomical factors, cell wall proportions, and variations in chemical composition, but also by ecological conditions and growing environments (Fejfer *et al.*, 2020; Zhao and Yang, 2025). The humid climate with high rainfall and relatively constant temperatures in Indonesia causes tropical wood to grow faster, resulting in low to medium specific gravity. However, this study shows that Indonesian tropical wood, par-

ticularly Gmelina and Indian Rosewood, actually exhibits better dimensional stability than some species from other countries. This can be attributed to the relatively homogeneous anatomical structure of the wood, balanced cell wall proportions, and more even pore distribution, which reduces the level of shrinkage anisotropy (Fredriksson *et al.*, 2023). On the other hand, wood from regions with long dry seasons, such as Africa or Latin America, often grows more slowly and

has a high specific gravity. This growth does produce denser fibers, but it also increases the risk of differences in shrinkage between the radial and tangential directions, resulting in lower dimensional stability (Qian *et al.*, 2022; Nascimento *et al.*, 2023). Thus, understanding the shrinkage value and T/R ratio can be used as a basis for determining the suitability of wood applications, both for structural and non-structural needs, especially for products that require high dimensional stability.

Overall, a comparison with previous studies indicates that the variability reported in the literature is influenced not only by species characteristics but also by methodological differences across studies. Therefore, the main contribution of this study is not merely to generate additional data, but to provide a statistically supported and methodologically consistent comparison among three commercially important yet underrepresented tropical timber species. This standardized dataset helps bridge the gap between fragmented literature and practical industry needs.

4 CONCLUSIONS

4. ZAKLJUČAK

The green moisture content was highest in *G. arborea* (176.41 %), followed by *Palaquium spp.* (103.45 %) and *H. tiliaceus* (82.49 %). At the air-dried condition, the moisture content decreased to 16.34 %, 17.65 %, and 12.18 % for *G. arborea*, *Palaquium spp.*, and *H. tiliaceus*, respectively. The density values were 0.90 g/cm³ for *G. arborea*, 0.76 g/cm³ for *Palaquium spp.*, and 0.67 g/cm³ for *H. tiliaceus*. In contrast, the specific gravity values were 0.33 for *G. arborea*, 0.37 for *Palaquium spp.*, and 0.39 for *H. tiliaceus*. *G. arborea* showed the lowest T/R ratio (1.01), indicating better dimensional stability compared to *Palaquium spp.* (1.83) and *H. tiliaceus* (2.13). These results indicate differences in physical properties and dimensional stability among the three species under identical testing conditions. *G. arborea* demonstrated comparatively higher dimensional stability, while *H. tiliaceus* showed greater tangential shrinkage and higher T/R ratio. *Palaquium spp.* exhibited intermediate characteristics. The findings of this study are limited to physical properties and dimensional stability; therefore, further research including mechanical and durability testing is necessary before determining suitability for specific structural or engineering applications.

Acknowledgements – Zahvala

This research was supported by IPB University, Bogor, Indonesia, and the Integrated Laboratory of Wood Quality Improvement Technology, IPB University, Bogor, Indonesia.

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Borax and Calcite Modified Water-Based Acrylic Varnish: A Comprehensive Characterization Study

Vodeni akrilni lak modificiran boraksom i kalcitom: sveobuhvatna karakterizacija

ORIGINAL SCIENTIFIC PAPER

Izvorni znanstveni rad

Received – prispjelo: 12. 3. 2026.

Accepted – prihvaćeno: 5. 5. 2026.

UDK: 630*84; 674.07

<https://doi.org/10.5552/drind.2026.0342>

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ABSTRACT • Wood surfaces should be coated in order to protect wooden materials from adverse environmental conditions. In this study, calcite (CaCO_3) and borax ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$) were added to the varnish to increase the protection effectiveness of the water-based acrylic varnish used for protection on fir tree (*Abies alba* L.) timber. The varnish mixture was applied on the samples with a brush. Rapid aging was applied to the samples with the QUV accelerated weathering tester to determine the surface durability of the samples. After rapid aging, color analysis and Taber abrasion test were performed on the sample surfaces for surface characterization. Then, the test results were compared with the pre-aging test results. The results were statistically analyzed. The results showed that the addition of filler did not significantly affect color stability after UV exposure ($p > 0.05$). Abrasion resistance was affected by both the type of filler and the UV treatment. 4 % calcite provided the highest resistance before aging. High filler content reduced UV resistance in some cases. Overall, lower filler ratios (≤ 2 %) resulted in a more balanced performance.

KEYWORDS: acrylic varnish; calcite; borax; UV aging; abrasion resistance; PCA

SAŽETAK • Drvene je površine potrebno zaštititi premazom kako okolišni uvjeti ne bi nepovoljno utjecali na njih. U ovom su istraživanju radi povećanja učinkovitosti zaštite vodenom akrilnom laku, koji se upotrebljavao za zaštitu je-lovine (*Abies alba* L.), dodani kalcit (CaCO_3) i boraks ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$). Lak je na uzorke nanosen kistom. Za određivanje trajnosti površine uzoraka provedeno je ubrzano starenje u QUV uređaju za ubrzano izlaganje vremenskim utjecajima. Nakon ubrzanog starenja na površinama uzoraka provedene su analiza boje i otpornosti na habanje radi karakterizacije površine. Potom su rezultati ispitivanja uspoređeni s rezultatima izmjerenim prije starenja. Rezultati su statistički obrađeni i prikazani u radu. Oni su pokazali da dodatak punila nije značajno utjecao na stabilnost boje nakon izlaganja UV zračenju ($p > 0,05$). No, na otpornost na habanje utjecali su i vrsta punila i izlaganje UV zračenju. Najveću otpornost prije starenja osigurao je dodatak 4 % kalcita. Visok udio punila u pojedinim je slučajevima smanjio otpornost na UV zračenje. Općenito, niži udjeli punila (≤ 2 %) rezultirali su uravnoteženijim svojstvima.

KLJUČNE RIJEČI: akrilni lak; kalcit; boraks; UV starenje; otpornost na habanje; PCA

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1 INTRODUCTION

1. UVOD

Wood is one of the oldest materials in human history. Wood productivity has also increased with human history (Mezentsev and Gavrikov, 2015) and today, there are over 5 thousand wooden products (Aboulnaga and Elsharkawy, 2022). It has an indispensable place in human life (Al-Kubaisy, 2022). It is an organic product, obtained from forest resources and has an important role in terms of ecology (Said, 2018). For this reason, wood must be protected carefully against adverse biotic and abiotic factors.

In the first centuries, simple protective methods were used such as burning the outer surface and applying pitch or tar (Žigon and Pavlič, 2023). These techniques aimed to protect wood from mechanical and chemical harm, is a common goal of protective coatings (Alam *et al.*, 2023). Nowadays, many techniques have been developed for the protection of wood surfaces that involve the protection of wood by forming a film on the surface. This technique emerged with the advancement of polymer chemistry about 150 years ago (Prieto and Kiene, 2018).

In addition to the protective function of surface coating materials used to protect wood materials, their aesthetic appearance is also important. For this reason, paints and varnishes are often preferred in the protection of wood surfaces (Feist and Abdullahi, 2016). Coatings such as varnishes and paints not only provide protection against environmental factors like UV radiation and moisture but also enhance the visual appeal of the wood (Teacă and Bodîrlău, 2016). For instance, varnishes can improve the surface durability and resistance to weathering, while also highlighting the natural beauty of the wood (Pánek *et al.*, 2017). Thus, the use of aesthetic coatings is integral to both preserving and enhancing wood materials (Jirouš-Rajković and Miklečić, 2021).

The paint and varnish sector is very dynamic. The formulation in their compositions is constantly renewed, and efforts are made to improve their superior features. For this reason, a wide variety of fillers are added to paints and varnishes. The added fillers reach up to 50 %. This amount is higher in water-based paints and varnishes. Some of the fillers used are titanium dioxide (rutile and anatase), calcite, mica, clay minerals (thickeners), quartz, feldspar, barite and color pigments (McGonigle and Ciullo, 1996).

Calcite (CaCO_3) in paint recipes is cheaper than many fillers. The production process of calcite is also simple. Therefore, the use of calcite in paint recipes provides not only financial but also environmental advantages. Calcite reduces paint and varnish cost and changes some physical properties. It is not as good as some fillers such as titanium dioxide (TiO_2) in terms of refractive index and particle size, but calcite improves

this filler distribution in the matrix through interaction with TiO_2 particles (Karakaş and Çelik, 2012).

In fact, neither the particle size nor the refractive index of calcite samples are at the desired level to obtain good opacity. Calcite is positively charged in the paint environment (Barhoum *et al.*, 2014). Some fillers can be negatively charged. Due to this feature, calcite helps negatively charged fillers to create a homogeneous distribution in the matrix (Machida *et al.*, 2023). Thus, it helps paints and varnishes to be opaquer (Altiner *et al.*, 2021).

Borax has several properties that make it suitable for paints, including high dispersion ability, optimum corrosion inhibition effect, and the ability to increase the density of paint films (Jianfeng *et al.*, 2012).

Borax's high affinity for electronegative atoms such as oxygen and its ability to form strong covalent bonds have made it suitable for use in impregnating, painting and varnish industries (Wu, 1955; Bhat *et al.*, 2005; Baysal, 2008; Atar *et al.*, 2009; Wei *et al.*, 2016).

Borax minerals have natural antiseptic properties and prevent microbial growth. Borax-added varnishes protect wooden surfaces against fungi, mold and bacteria. Thus, the life of varnishes is extended, especially on wooden surfaces used in humid and outdoor areas (Borges *et al.*, 2018; Estevez-Fregoso *et al.*, 2021).

In the presented study, borax and calcite were added to water-based acrylic varnish in certain proportions to improve its mechanical and physical properties. Prepared varnish mixtures were painted on the fir wood and their characterization was performed. The results were compared with neat waterborne acrylic varnish.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

The experiments conducted in this study encompassed all steps from material selection and varnish preparation to coating application to samples, conditioning, accelerated UV aging, and subsequent color change (ΔE^*) and abrasion resistance measurements. A summary of the entire experimental flow is presented in Figure 1 (Workflow).

2.1 Materials

2.1. Materijali

In the study, water-based acrylic varnish, which is harmless to the environment and human health, was preferred and calcite and borax (Tincal) were used as filler particles in the varnish.

Calcite was obtained from the "Somgroup Company" of Türkiye. Some technical properties of calcite are given in Table 1.

Tincal ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$) was purchased from online market. Its other commercial name is borax. In fact, borax is a boron mineral, which is a natural com-

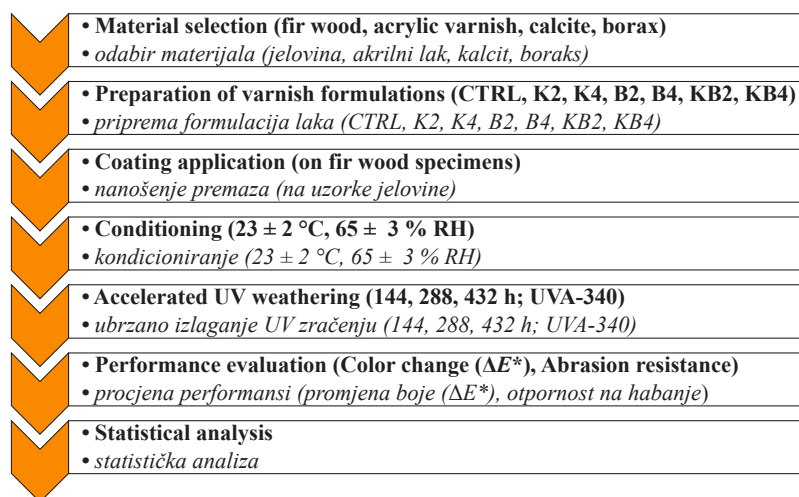


Figure 1 Schematic representation of the experimental workflow of the study. The varnish formulation codes (CTRL, K2, K4, B2, B4, KB2, KB4) are detailed in Table 2.

Slika 1. Shematski prikaz eksperimentalnog tijeka istraživanja. Oznake formulacija laka detaljno su objašnjene u tablici 2.

pound containing varying amounts of boron oxide in its structure. There are more than 230 different boron minerals in nature. The most important boron minerals in commercial terms are Tincal, Colemanite, Kernite, Ulexite, Pandermite, Boracite, Szaybelite and Hydroboracite. We preferred Tincal borax in this study due to its prevalent usage. Some technical properties are given in Table 1.

2.2 Preparation of samples

2.2. Priprema uzoraka

In this study, three different varnish groups (borax, calcite, and borax/calcite-supplemented varnishes) were prepared based on a conventional method reported in the literature (Azani and Hassanpour, 2024; Goktas *et al.*, 2024a; Goktaş *et al.*, 2024b), with minor modifications introduced to improve particle (borax and calcite) dispersion. First, 10 % aqueous solutions of borax, calcite and mixtures of these two materials were mixed with a mechanical mixer for 5 minutes, followed by ultrasonic mixing for 10 minutes to achieve homogeneous distribution. These solutions were then added to the water-based acrylic varnish, en-

suring the solid content ratio of 2 % and 4 %. The varnish and particle mixtures were initially mixed in a mechanical mixer at 1500 rpm and for 10 minutes (Aksu *et al.*, 2022). To ensure homogeneous distribution, the mixtures were further processed in a water bath containing ethylene glycol using a high-speed ultrasonic mixer for 20 minutes (Vardanyan *et al.*, 2014). The cooling provided by the water bath during mixing was intended to prevent the degradation of the polymeric structure, which could result from the increase in solution temperature due to molecular agitation caused by ultrasonic mixing (Azani and Hassanpour, 2024). Before application, the prepared particle-added varnish was mixed with a mechanical mixer at 2000 rpm for 5 minutes to ensure it was ready for use (Aksu *et al.*, 2022).

All varnish mixtures belonging to the three groups are given in Table 2. Wood sample surfaces were initially sanded with 180 grid sandpaper. Varnishes were applied with a brush (180 gr/m²) on 100 mm × 100 mm × 8 mm samples. The samples were kept at 23 ± 2 °C for 3 days to ensure that the varnish solidified on the surface.

Table 1 Typical properties of calcite (Karakaş and Çelik, 2012) and borax

Tablica 1. Tipična svojstva kalcita (Karakaş i Çelik, 2012.) i boraksa

Property / Svojstvo	Calcite/ Kalcit	Borax / Boraks
Chemical formula / kemijska formula	CaCO ₃	Na ₂ B ₄ O ₇ ·10H ₂ O
Density, g/cm ³ / gustoća, g/cm ³	2.7	1.73
Crystal system / kristalni sustav	Trigonal (3 2/m)	—
Refractive index / indeks loma	n _e = 1.486, n _o = 1.658	—
Hardness, Mohs / tvrdoća, prema Mohsu	3	—
Oil absorption, mL/100 g / upojnost ulja, mL/100 g	17	—
Appearance / izgled	—	White granules
Purity, % / čistoća, %	—	99.9
B ₂ O ₃ content, % / udio B ₂ O ₃ , %	—	36 – 38
Na ₂ O content, % / udio Na ₂ O, %	—	17

Table 2 Prepared varnish samples
Tablica 2. Pripremljeni uzorci laka

Sample code <i>Oznaka uzorka</i>	Samples / <i>Uzorci</i>	Varnish, g <i>Lak, g</i>	Calcite, g <i>Kalcit, g</i>	Borax, g <i>Boraks, g</i>
CTRL	Neat acrylic varnish / <i>čisti akrilni lak</i>	100	—	—
K2	2 % calcite supplemented / <i>dodatak 2 % kalcita</i>	98	2	—
K4	4 % calcite supplemented / <i>dodatak 4 % kalcita</i>	96	4	—
B2	2 % borax supplemented / <i>dodatak 2 % boraksa</i>	98	—	2
B4	4 % borax supplemented / <i>dodatak 4 % boraksa</i>	96	—	4
KB2	2 % calcite/borax supplemented / <i>dodatak 2 % kalcita/boraksa</i>	98	1	1
KB4	4 % calcite/borax supplemented / <i>dodatak 4 % kalcita/boraksa</i>	96	2	2

2.3 Methods

2.3. Metode

2.3.1 Color analysis

2.3.1. Analiza boje

Samples colors were analyzed before and after the UV treatment with CS-10 colorimeter (CHN Spec, China). Measurement conditions were CIE 10° standard observer; CIE D65 light source, illumination system: 8/d (8°/diffused illumination). To minimize the effect of surface heterogeneity, color measurements were performed at predefined and marked points on each sample. Furthermore, multiple measurements were taken and averaged to ensure repeatability. Therefore, the observed differences between measurements taken before and after UV irradiation were primarily attributed to UV-induced color changes. After color measurement, color differences (ΔE^*) were evaluated according to DIN 5033 (2017) (Table 3), and ΔE^* was calculated according to equations below. The percentage of reflection of light is expressed in the CIELAB color system, which is the visible light spectrum at a wavelength of 10 nm. L^* represents the darkness value, a^* and b^* represent the axes from green to red and from blue to yellow, respectively.

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad (1)$$

$$\Delta a^* = (a^* \text{ before UV} - a^* \text{ after UV}) \quad (2)$$

$$\Delta L^* = (L^* \text{ before UV} - L^* \text{ after UV}) \quad (3)$$

$$\Delta b^* = (b^* \text{ before UV} - b^* \text{ after UV}) \quad (4)$$

Table 3 Comparison criteria for ΔE^* evaluation (DIN 5033, 2017)**Tablica 3.** Kriteriji usporedbe za procjenu ΔE^* (DIN 5033, 2017.)

Total color difference (ΔE^*) <i>Ukupna promjena boje (ΔE^*)</i>	Visual color score difference <i>Vizualna razlika u ocjeni boje</i>
< 0.2	Imperceptible / <i>neprimjetna</i>
0.2 – 0.5	Very weak / <i>vrlo slaba</i>
0.5 – 1.5	Weak / <i>slaba</i>
1.5 – 3.0	Noticeable / <i>primjetna</i>
3.0 – 6.0	Very noticeable / <i>vrlo primjetna</i>
6.0 – 12.0	Strong / <i>izražena</i>
> 12.0	Very strong / <i>vrlo izražena</i>

2.3.2 Abrasion analysis

2.3.2. Analiza otpornosti na habanje

The test was carried out in accordance with the German Industrial Standard, European Norm (DIN EN) 13329 (also DIN 53799) (2021) using the Taber Abrasive. The test specimen was first divided into four marked quadrants and then fixed to the measuring device. Calibrated sandpaper was attached to two abrasive wheels with a defined weight (5.4 ± 0.2 N each). The wheels were placed on the test specimen. After pressing the start button, the sample holder rotated at a constant speed. The sandpaper was renewed after 200 revolutions (or earlier if necessary). The first wear point (IP) was determined when visible wear spots of at least 0.60 mm^2 each were present in two quadrants and a spot of equal size in a third quadrant. Abrasion resistances were evaluated according to the average abrasion point of the initial abrasion point (IP) and the final abrasion point (FP) and results were compared statistically ($P < 0.05$).

2.3.3 UV weathering

2.3.3. Ubrzano izlaganje UV zračenju

After the varnish mixtures prepared were applied to the fir samples ($100 \text{ mm} \times 100 \text{ mm} \times 8 \text{ mm}$), they were left to dry for three weeks in the climate laboratory at 20 ± 2 °C temperature and 65 ± 3 % relative humidity, corresponding to an equilibrium moisture content (EMC) of approximately 12 %. Then, the varnished materials were prepared by modifying the aging environment conditions of the ASTM G 154-06 (2006) standard (15 minutes water spray, 8 hours UV) (0.67 light intensity, 18 minutes water spray, 2 hours UV and 50 °C ambient temperature). The samples were exposed to UV aging effects for 144, 288 and 432 hours in the QUV accelerated weathering tester with UV-A 340 fluorescent lamps (Q-Lab, 2026).

2.3.4 Statistical analysis

2.3.4. Statistička analiza

For the evaluation of the analysis data, one-way analysis of variance (ANOVA) and Duncan's multiple range test were used. One-way ANOVA was applied to

determine whether there were statistically significant differences among the group means. In cases where significant differences were detected, Duncan's multiple range test was performed to identify which groups differed from each other. The significance level was set at $P < 0.05$.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

3.1 Optical properties

3.1. Optička svojstva

Color changes in varnished samples after UV irradiation are presented in Table 4. The ΔE^* values of the samples ranged from 28.8 to 32.5. Significant color changes occurred in all varnish formulations after UV aging. Among the samples, formulation B2 showed the highest color change ($\Delta E^* = 32.5$), while formulation KB4 showed the lowest value ($\Delta E^* = 28.8$). The control sample showed a ΔE^* value of 30.4, which is within the observed range for modified varnish systems.

Although small differences were observed between the varnish mixtures, the one-way ANOVA test showed that the differences in total color change (ΔE^*) were not statistically significant ($F(6,35) = 1.149$, $p = 0.355$). This indicates that the addition of calcite, borax or a combination thereof does not significantly affect the color stability of acrylic varnish under UV exposure. A graphical representation of the total color difference (ΔE^*) values is presented in Figure 2.

The direction of color change in the $CIEL^*a^*b^*$ color space is shown in Figure 3. The trajectories generally show a shift towards positive a^* and b^* coordinates. This confirms that the coatings tend to develop reddish and yellowish tones after exposure to UV light.

Principal Component Analysis (PCA) was performed using the $CIEL^*a^*b^*$ color coordinate changes (ΔL^* , Δa^* , and Δb^*) in order to evaluate the multivariate behavior of the varnish formulations after UV exposure. The PCA score plot based on the first two principal components is presented in Figure 4.

The first principal component (PC1) explained the majority of the variance in the dataset, while the second principal component (PC2) accounted for a smaller proportion of the remaining variability. Together, the first two components explained a substantial portion of the total variance, indicating that the PCA model effectively represented the main variation patterns in the color change data.

Examination of PCA score distributions revealed that sample groups largely clustered in a similar region of the multivariate space. This overlap meant that the addition of calcite, borax, or their co-addition to the acrylic varnish system did not lead to a clearly separated multivariate color response under the conditions studied.

Loading vectors showed that the overall variation in the dataset was primarily related to the contributions of CIELAB color coordinates. Positive contributions of Δa^* and Δb^* indicate that the dominant color shift

Table 4 Color difference of samples

Tablica 4. Promjena boje uzoraka

Samples	K2	K4	B2	B4	KB2	KB4	Control
ΔE^* (Mean $\pm$ SD) (Sig. 0.355*)	30.7 ($\pm 2.29^{***}$) AB**	31.44 (± 3.55) AB	32.5 (± 1.73) B	29.8 (± 2.74) AB	30.2 (± 2.53) AB	28.8 (± 2.86) A	30.4 (± 2.73) AB

*Significance ($P < 0.05$), **Duncan groups groups, ***Standard deviation / *Značajnost ($P < 0,05$), **Duncanove skupine, ***standardna devijacija

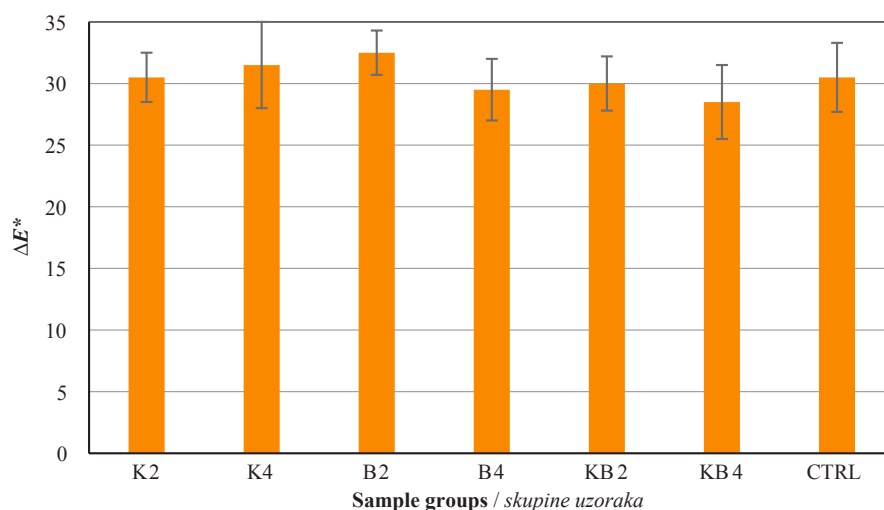


Figure 2 Total color difference (ΔE^*) after UV aging

Slika 2. Ukupna promjena boje (ΔE^*) nakon UV starenja

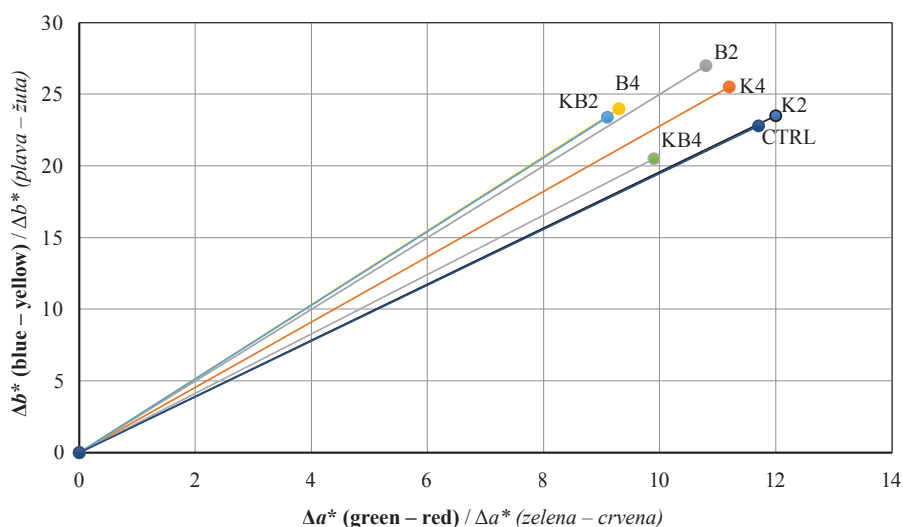


Figure 3 *CIEL*a*b** color shift vector diagram (mean Δa^* and mean Δb^*) of varnish formulations after UV exposure

Slika 3. Vektorski dijagram promjene boje u *CIEL*a*b** sustavu (srednja vrijednost Δa^* i srednja vrijednost Δb^*) formulacija laka nakon izlaganja UV zračenju

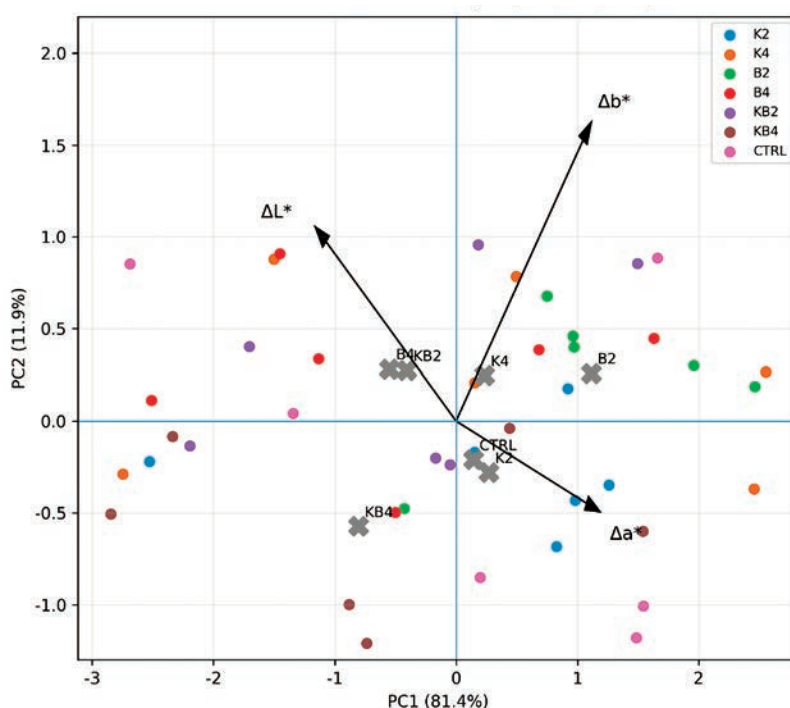


Figure 4 PCA score plot (PC1 – PC2) based on CIELAB color changes (ΔL^* , Δa^* , Δb^*) after UV exposure

Slika 4. Grafički prikaz rezultata PCA analize (PC1 – PC2) na temelju promjena CIELAB koordinata boje (ΔL^* , Δa^* , Δb^*) nakon izlaganja UV zračenju

after UV exposure occurs towards the red and yellow regions. This trend is consistent with the typical photo-degradation behavior of polymeric coating systems where UV radiation causes chromophore formation and yellowing in the polymer matrix.

The principal component analysis (PCA) graph obtained with 95 % confidence interval ellipses and PCA score ellipses is presented in Figure 5.

In this graph, CIELAB color coordinate changes (ΔL^* , Δa^* , and Δb^*) were used to examine the multi-

variate relationships between varnish formulations after exposure to UV light.

The varnish formulations showed a significant overlap in the PCA score graph with 95 % confidence interval ellipses (Figure 5), as well as in the PCA score graph based on CIELAB color changes (ΔL^* , Δa^* , Δb^*) after exposure to UV light (PC1–PC2) (Figure 4), revealing a similar multivariate color change response after UV exposure. This visual pattern is consistent with the one-way ANOVA result for ΔE , which showed

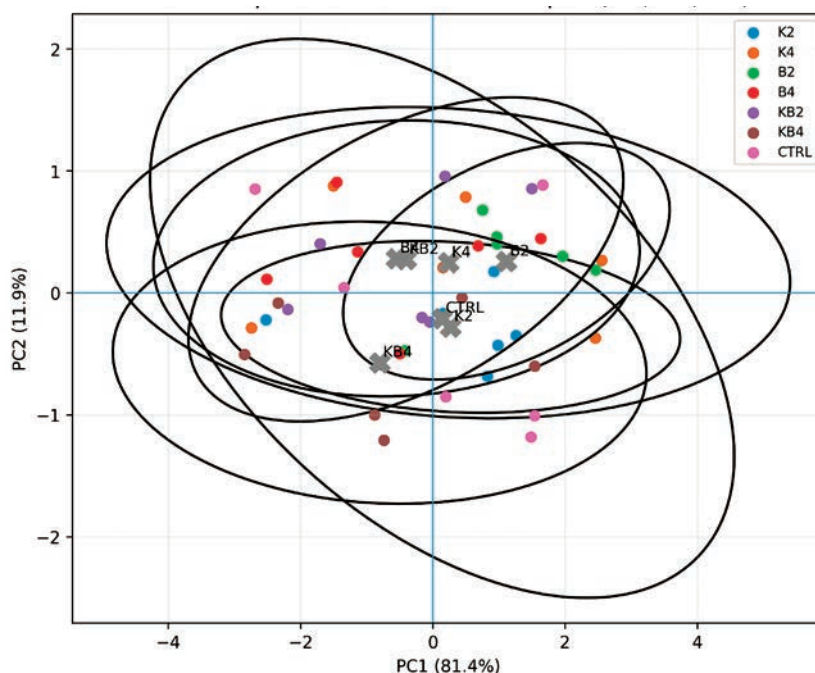


Figure 5 PCA score plot with 95 % confidence ellipses based on *CIEL***a***b** color-coordinate changes (ΔL^* , Δa^* , Δb^*) after UV exposure

Slika 5. Grafički prikaz rezultata PCA analize s 95-postotnim elipsama pouzdanosti na temelju promjena *CIEL***a***b** koordinata boje (ΔL^* , Δa^* , Δb^*) nakon izlaganja UV zračenju

no significant differences between groups ($F(6,35) = 1.149$, $p = 0.355$).

3.2 Abrasion properties

3.2. Svojstva otpornosti na habanje

The abrasion resistance and weight loss values of the varnish formulations before and after UV exposure are presented in Table 5, while the interaction between varnish formulation and UV exposure is illustrated in Figure 6.

The percentage change values represent the relative difference in abrasion resistance after UV expo-

sure compared to before UV exposure and were calculated using the following equation:

$$\text{Change (\%)} = \frac{[(\text{after UV} - \text{before UV}) / \text{before UV}] \times 100}{(5)}$$

Before exposure to UV weathering, K4 was the sample with the highest abrasion resistance. After UV treatment, this value decreased by 52.4 %. In contrast, the KB4 group, which had the lowest resistance at 41.67 cycles, showed a 116.0 % increase in abrasion resistance after exposure to UV weathering (reached 90.00 cycles). This may have been caused by UV rays creating cross-links in the varnish mixture. The forma-

Table 5 Abrasion resistance and weight loss values of varnish formulations after abrasion testing

Tablica 5. Otpornost na habanje i gubitak mase formulacija laka nakon ispitivanja

Samples Uzorci	Abrasion resistance before UV (Mean $\pm$ SD) Otpornost na habanje prije UV zračenja (srednja vrijednost $\pm$ standardna devijacija)	Duncan group Duncanove skupine	Abrasion resistance after UV (Mean $\pm$ SD) Otpornost na habanje nakon UV zračenja (srednja vrijednost $\pm$ standardna devijacija)	Duncan group Duncanove skupine	Weight loss before UV, g Gubitak mase prije UV zračenja, g	Weight loss after UV, g Gubitak mase nakon UV zračenja, g	Change in abrasion resistance, % Promjena otpornosti na habanje, %	p-value (UV effect) p-vrijednost (utjecaj UV zračenja)
Control	76.67 $\pm$ 15.06	BC	115.00 $\pm$ 8.37	a	0.0350	0.0617	+50.0	0.005
K2	71.67 $\pm$ 7.53	BC	96.67 $\pm$ 8.16	a	0.0567	0.0483	+34.9	0.002
K4	136.67 $\pm$ 66.23	A	65.00 $\pm$ 12.25	b	0.0467	0.0583	-52.4	0.041
B2	68.33 $\pm$ 4.08	BC	111.67 $\pm$ 25.63	a	0.0750	0.0717	+63.4	0.012
B4	76.67 $\pm$ 5.16	BC	90.00 $\pm$ 8.94	ab	0.0567	0.0300	+17.4	0.043
KB2	103.33 $\pm$ 21.60	AB	65.00 $\pm$ 15.17	b	0.0550	0.0733	-37.1	0.001
KB4	41.67 $\pm$ 4.08	C	90.00 $\pm$ 15.49	ab	0.0517	0.0567	+116.0	0.001

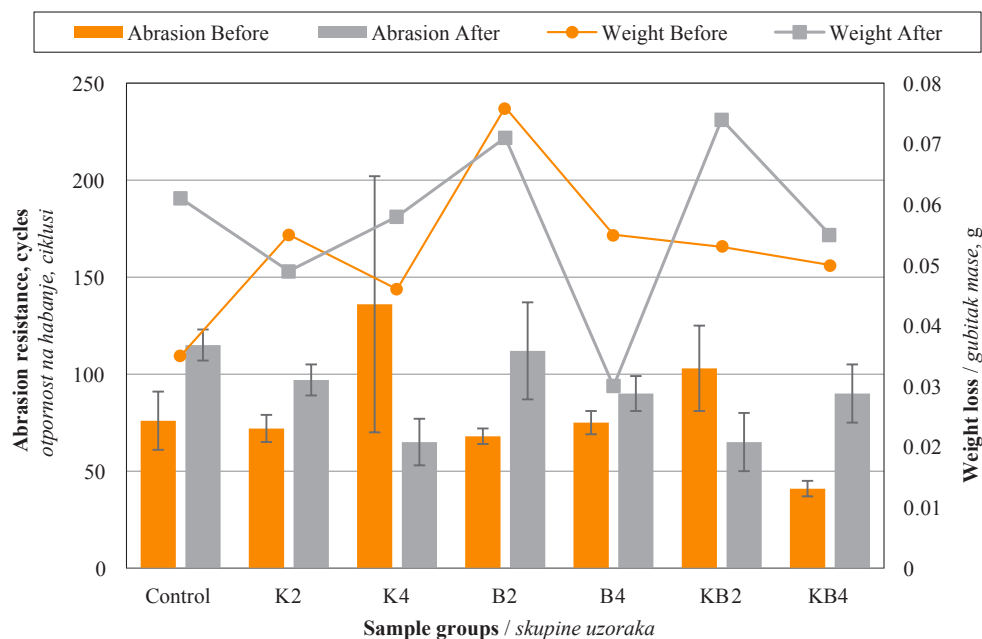


Figure 6 Interaction plot showing the effect of varnish formulation and UV exposure on abrasion resistance
Slika 6. Grafikon interakcije koji prikazuje utjecaj formulacije laka i izlaganja UV zračenju na otpornost na habanje

tion of a tighter bond structure in the matrix has increased abrasion resistance. Calcite is a material that is also used as a filling material in epoxy resins (Chindaprasirt *et al.*, 2023). The matrix is known to improve durability. In this study, the addition of 4 % calcite/borax improved the abrasion resistance of the sample.

A clear inverse relationship between abrasion resistance and weight loss was observed in K4 and KB2 samples. The decrease in abrasion resistance was at the same rate as the increase in mass loss. The addition of 4 % calcite (K4) initially provided high resistance. However, after UV weathering, the abrasion resistance decreased by approximately 60 %. In this case, it can be concluded that the filling rate reduces UV resistance by more than 2 %. In contrast, balanced hybrid fillers (KB4) can improve wear resistance under environmental stress better than other samples.

4 CONCLUSIONS

4. ZAKLJUČAK

In this study, the effects of calcite and borax filler on the optical stability and wear resistance of water-based acrylic varnish were investigated. The samples were weathered (by UV radiation) and their surface characterization was investigated.

The addition of calcite and borax did not cause significant change in the total color difference (ΔE^*) after the weathering process. In all specimens, color shift towards reddish and yellowish tones occurred. It was determined that the sample with the highest abrasion resistance before UV treatment was the varnish sample (K4) with the addition of 4 % calcite. After UV

treatment, a significant difference occurred in the abrasion resistance of the samples. Abrasion resistance increased after UV treatment in B2 and control samples to which borax was added. However, weathering results and outdoor weathering results may differ. As a result of rapid aging, the acrylic particles may have physically moved closer together. This may have caused the UV treatment to make the varnish film layer more resistant to wear.

As a result, the addition of 4 % calcite demonstrated the highest resistance to abrasion prior to UV treatment. After UV treatment, the control sample showed the highest abrasion resistance. The varnish sample with 2 % borax added showed the closest abrasion resistance to the control sample. As the filling rate increased, UV durability decreased. It can be said that it is not appropriate to use a filling rate above 2 % in acrylic varnishes. UV treatment has unexpectedly changed the abrasion resistance of the specimens. For example, K4 and KB2 samples had the highest abrasion value before UV, but their abrasion resistance decreased after UV irradiation. On the contrary, samples that had low abrasion resistance before UV (K2, B2, B4, KB4, CTRL) showed increased abrasion resistance after UV treatment. In order to confirm the results obtained, it is necessary to perform an aging test in real conditions.

Acknowledgements – Zahvala

We would like to thank Gazi University, Faculty of Technology and Mudurnu Süreyya Astarıcı Vocational School for providing us with laboratory facilities. Artificial intelligence (AI) based tools were used in this study to improve language editing and visual

quality by preparing figures. All outputs were checked by the authors. The authors are solely responsible for the content of this article.

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Integration of Engineered Wood Products Knowledge in Architectural Education: Evidence from North Macedonia

Integracija znanja o kompozitnom drvu u arhitektonsko obrazovanje: primjeri iz Sjeverne Makedonije

ORIGINAL SCIENTIFIC PAPER

Izvorni znanstveni rad

Received – prispjelo: 31. 3. 2026.

Accepted – prihvaćeno: 18. 6. 2026.

UDK: 630*83; 674.038; 674.8

<https://doi.org/10.5552/drind.2026.0346>

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ABSTRACT • Engineered wood products (EWPs) are wood-based materials created by engineering and combining wood elements into high-performance products with improved structural, functional, aesthetic, and environmental characteristics. They have become a very important segment in sustainable construction in recent years, which highlights the need for their integration into architectural education. Unfortunately, in many developing countries, including North Macedonia, their presence in architectural curricula, and in the design practice, remains limited and insufficiently explored. The aim of this study was to explore the knowledge, perception, and application of EWPs among architecture students, with a focus on the relationship between the theoretical insights and practical application. The research was based on a case study conducted at the Department of Architecture, Faculty of Engineering, at the International Balkan University in Skopje, North Macedonia. The methodology in this study comprises three steps to enable more holistic analyses. First, a survey questionnaire was distributed among architecture students at different levels of study to assess their familiarity with wood and EWPs, and their experience with their practical application throughout their studies. Second, analyses of the curriculum were conducted to evaluate the presence of wood-based topics in the courses of the study programme. Lastly, the study was further supported by research on the students' projects to detect the level of application of wood and wood-based materials. The results indicate that students have relatively high theoretical knowledge of wood and EWPs. However, their experience remains limited, with a tendency towards non-structural use and less frequent implementation of these structural materials. Although there has been a gradual increase in the consideration of timber-based solutions in recent years, further research is required. In addition, there is a lack of dedicated courses that specifically focus on timber construction, which is the reason for limited practical and technical knowledge related to their application. This study reveals that practice-oriented approaches, including project-based learning and exposure to contemporary timber construction, are crucial in architectural education for strengthening the integration of wood-based materials. Finally, the find-

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ings of this study can contribute to a better understanding of the role of education in promoting sustainable material choices and provide guidelines for future curriculum development.

KEYWORDS: timber; student projects; construction

SAŽETAK • Kompozitno je drvo materijal na bazi drva nastao inženjerskim oblikovanjem i spajanjem drvnih elemenata u proizvode visokih performansi i poboljšanih konstrukcijskih, funkcionalnih, estetskih i ekoloških svojstava. Posljednjih godina ti su proizvodi postali iznimno važan segment održive gradnje, što naglašava potrebu integracije znanja o njima u arhitektonsko obrazovanje. Nažalost, u mnogim zemljama u razvoju, uključujući Sjevernu Makedoniju, njihova je zastupljenost u arhitektonskim kurikulumima i projektantskoj nastavi i dalje ograničena te nedovoljno istražena. Cilj ovog istraživanja bio je ispitati znanje, percepciju i primjenu kompozitnog drva među studentima arhitekture, s naglaskom na odnos između teorijskih spoznaja i praktične primjene. Istraživanje se temelji na studiji slučaja provedenoj na Odsjeku za arhitekturu Fakulteta inženjerstva Međunarodnog sveučilišta Balkan u Skoplju, Sjeverna Makedonija. Metodologija rada obuhvatila je tri koraka kako bi se omogućila holistička analiza. Prvo, među studentima arhitekture na različitim razinama studija provedeno je anketno istraživanje radi procjene njihova znanja o drvu i kompozitnom drvu te njihovih iskustava s praktičnom primjenom tih materijala tijekom studija. Drugo, provedena je analiza kurikuluma kako bi se utvrdila zastupljenost tema vezanih za materijale na bazi drva u kolegijima studijskog programa. Na kraju, istraživanje je dodatno potkrijepljeno analizom studentskih projekata radi utvrđivanja stupnja primjene drva i drvnih materijala. Rezultati pokazuju da su studenti u relativno visokoj mjeri teorijski upoznati s drvom i kompozitnim drvom. Međutim, primjena tih materijala je ograničena, uz snažnu tendenciju prema nekonstrukcijskoj uporabi i rjeđoj implementaciji u svojstvu konstrukcijskih materijala. Iako je posljednjih godina primijećen postupni porast konstrukcijskih rješenja na bazi drva, to još uvijek nije dovoljno. Osim toga, uočava se nedostatak namjenskih kolegija koji su specifično usmjereni na drvene konstrukcije, što je uzrok ograničenoga praktičnog i tehničkog znanja o njihovoj primjeni. Ovo istraživanje pokazuje da su za snažniju integraciju materijala na bazi drva u arhitektonsko obrazovanje ključni pristupi usmjereni na praksu, uključujući učenje utemeljeno na projektima i izloženosti suvremenoj drvenoj gradnji. Zaključno, spoznaje iz ovog istraživanja mogu pridonijeti boljem razumijevanju uloge obrazovanja u promicanju odabira održivih materijala te ponuditi smjernice za budući razvoj kurikuluma.

KLJUČNE RIJEČI: drvo; studentski projekti; graditeljstvo

1 INTRODUCTION

1. UVOD

The construction sector is lately oriented towards sustainable and environmentally friendly materials. Engineered wood products (EWPs) have gained significant attention in contemporary architectural design due to their advantages and overcoming the disadvantages of the primary processed wood such as sawn timber, veneer and different types of by-products from these main-product processes. EWPs have very good structural performance, offer design flexibility and reduce the negative environmental impact compared to the many non-biobased construction materials, such as traditional concrete and steel. Moreover, EWPs enable the development of efficient structural systems, functionality and better aesthetic qualities (Janakieska *et al.* 2024; Sandberg *et al.*, 2023).

Despite these advantages and the global growth of timber construction, the application of timber-based structural systems remains relatively limited in many regions, including North Macedonia, where reinforced concrete and steel continue to dominate in the construction practices (Janakieska *et al.*, 2021). There are numerous reasons for this, but some of the most important are market conditions and industry tradition.

Moreover, the architectural education is crucial for shaping the students' understanding of the structural systems, materials, their properties and their potential application in the projects. A comprehensive architectural education requires integrating design thinking with material and technological knowledge, allowing students to make informed decisions in the design process (Tzonis, 2014).

General wood material and wood-based products are often introduced as part of broader courses on structural systems and building materials within the architectural curricula. Therefore, their treatment is usually solely theoretical, with limited opportunities for practical application or detailed technical understanding. Without dedicated courses that focus specifically on timber as a construction material and its application in the structural systems and non-structural elements, students could feel more confident in using other materials, such as concrete and steel for which there are dedicated courses. Students often think that they are more familiar with concrete and steel, especially in primary load-bearing systems, since these materials are more included in the curricula.

In this context, it is highly important for architecture students to understand the perception of EWPs and the level of their application into their projects during

the studies. Some previous studies highlight the importance of materials knowledge and hands-on experience in architectural education, emphasizing the need to connect theory with practice (Fahmy, 2025; Fernández, 2023; Kalamkar and Sinhal, 2023). However, there is limited research addressing this topic in the local context of North Macedonia.

Therefore, the aim of this study was to analyse theoretical knowledge and practical application of EWPs among architecture students at the Department of Architecture, Faculty of Engineering at the International Balkan University in Skopje. Although the study is based on a specific institutional context, it addresses a broader challenge in architectural education, such as the limited integration of EWPs and sustainable construction practices in the curricula, particularly in institutions where timber construction is not a primary educational focus. The combined approach in methodology allows identification of existing gaps in the education and recommendations for improving the integration of EWPs in architectural curricula, with protentional applicability beyond the local context and relevance for institutions facing similar challenges in design education.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

The study uses a case study approach at International Balkan University in Skopje. A combination of quantitative and qualitative data is used. The methodology is divided into three different parts: (1) a survey conducted among architectural students from different levels of study, (2) analyses of the architectural curriculum through official documentation, and (3) evaluation of student design projects developed within a master-level course. This combined approach allows for a comprehensive understanding of the implementation of EWPs in the architectural education.

The collected data were analysed using descriptive statistical methods. The survey results were analysed using percentage distributions to identify trends in familiarity and the application of EWPs. These results were also compared with findings from the curriculum analysis and students' projects evaluation to identify consistencies and discrepancies between theoretical knowledge and practical application.

This comparative approach enabled a more comprehensive interpretation of the role of architectural education in shaping students' understanding and use of wood-based materials.

2.1 Survey methodology

2.1. Metodologija anketnog istraživanja

The participants in the survey included students at different levels of study, including bachelor's, mas-

ter's, and doctoral programmes. First-year students were not included, as their curriculum does not yet cover specialised courses related to building materials and structural systems.

Data were collected using an online questionnaire distributed via the SurveyPlanet platform (<https://surveyplanet.com/>). The questionnaire consisted of both closed-ended and open-ended questions, allowing for the collection of quantitative and qualitative data. The questions were structured into several sections, including general information about the respondents, familiarity with EWPs, their application in design projects, and students' perceptions of the sufficiency of knowledge gained during their studies.

The survey was conducted from 1st of October until 31st of December 2025 and was distributed among the students via email and quick response (QR) codes during student classes. The survey was distributed among 103 architecture students, and a total of 71 valid responses were collected. The respondents included students from different levels of study: 21 responses were obtained from second-year students, 13 from third-year students, 16 from fourth-year students, 19 from master's students, and 2 from doctoral students. 34 % of the respondents were male and 66 % were female. Participation was voluntary and anonymous, ensuring unbiased responses. The collected data were exported and used for further analysis.

2.2 Curriculum analysis

2.2. Analiza kurikuluma

To evaluate the educational context, an analysis of the architectural curriculum was conducted based on the official study programme documentation. The analysis focused on courses related to structural systems, building materials, and construction technologies offered during bachelor's and master's studies. The analysis of the architectural curriculum was based on a comparison of the accreditation documents from 2013, 2019, and 2025 (International Balkan University, 2013; International Balkan University, 2019; International Balkan University, 2025).

The reviewed courses included:

- Architectural Structures I–IV,
- Statics,
- Strength of Materials,
- Theory of Structures,
- Reinforced Concrete,
- Steel Structures,
- Building Materials, and
- Building Physics.

The course objectives and content were analysed to identify the presence and extent of topics related to wood and EWPs.

2.3 Analysis of student projects

2.3. Analiza studentskih projekata

Another method was used to understand the practical application of wood and EWPs in the student projects. Projects developed within the Architectural Structures course at the master's level were examined. As part of the exercises for this course, students are assigned to design a semester project – design of a building in which they select the structural system and the materials for both structural and non-structural elements based on their research, knowledge, and design approach. This course was particularly chosen for analyses, as it reflects students' final level of competence after completing a series of courses related to structures, materials, and construction during their bachelor studies.

Projects from 2020-2025 were examined in detail to identify trends in material selection among students. This examination included analyses of the materials used for the structural systems in the projects – concrete, steel, timber-based or other, and the application of wood or wood-based products on the building's façade. Moreover, selected student projects with EWPs in the structural systems were analysed in greater detail to illustrate specific design approaches and the practical application of timber-based systems.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

3.1 Survey results: knowledge and perceptions of EWPs

3.1. Rezultati anketnog istraživanja: znanje i percepcija o kompozitnom drvu

Based on the survey results, familiarity with EWPs among architecture students at International Balkan University is high (72 % of students reported familiarity). A total of 89 % of the students reported learning about timber and EWPs during their architectural studies within the Department of Architecture, indicating a high level of theoretical knowledge.

In addition, students were asked to select the EWPs they were familiar with from a list that included photos. The results are given in Table 1. The cells with a percentage greater than 50 are marked in orange. The most familiar wood-based product for students is glued laminated timber (GLT or glulam), followed by cross-laminated timber (CLT). This can be seen as positive since both GLT and CLT are structural materials and are implemented as structural elements in building construction. Being familiar with these products is a good step towards implementing them in the projects. Students were less familiar with the following wood-based products: veneered particle board (VP), particle board (PB), laminated strand lumber (LSL), oriented

strand board (OSB) and parallel strand lumber (PSL), marked in grey.

Although, the results show high theoretical exposure during the studies, 31 % of students reported that they had not applied these materials in their design projects, suggesting a gap between knowledge and practical implementation. Among those who used EWPs, the majority used them as interior elements (51 %) and as part of the façade design (49 %). The implementation of EWPs in the structural systems was significantly lower (39 %), as shown in Figure 1. This suggests that students perceive the timber primarily as a non-structural material, where aesthetic and design aspects are more dominant. This can be explained by limited technical confidence in timber as a structural material and hesitation regarding its structural and load-bearing properties. In addition, reinforced concrete and steel are dominant in local construction practice, which further influences students' choices, as these materials are well known and widely used in the region (Janakieska and Kitek Kuzman, 2025). Similar findings have been reported in previous studies, in which architects demonstrate a positive perception of wood but limited knowledge of its structural application (Kitek Kuzman *et al.*, 2018), and where its use remains constrained by technical concerns and established industry practices (Ilgin and Karjalainen 2021).

Students were also asked whether the knowledge gained during their studies was sufficient for the practical application of EWPs. A total of 45 % of students considered their knowledge sufficient, 38 % partially sufficient, and 17 % insufficient. In addition, 56 % of the participants expressed a desire to gain more knowledge about different EWPs during their studies.

Students were also asked to identify the gaps they perceived in the curriculum, and their answers indicate several recurring themes. The biggest concerns were the lack of practical and hands-on training. Workshops,

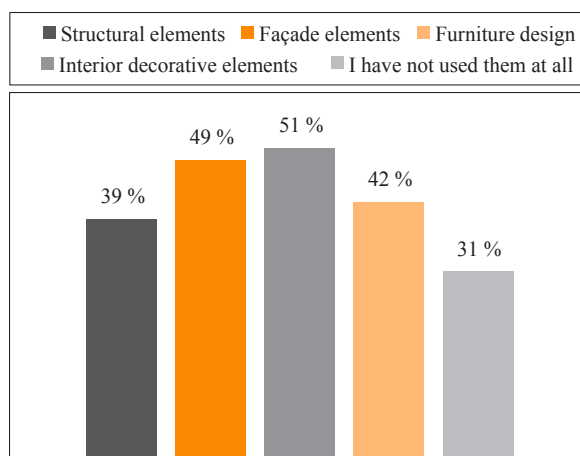


Figure 1 Application of EWPs in students' design projects
Slika 1. Primjena kompozitnog drva u studentskim projektima

Table 1 Students' familiarity with different EWPs**Tablica 1.** Upoznatost studenata s različitim kompozitnim drvom

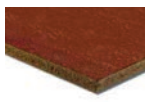
EWPs <i>Kompozitno drvo</i>	Number of students that are familiar <i>Broj upoznatih studenata</i>	Percentage of students that are familiar <i>Postotak upoznatih studenata</i>
GLT Glued-laminated timber (glulam) <i>lijepljeno lamelirano drvo</i> 	45	63 %
CLT Cross-laminated timber / <i>križno lamelirano drvo</i> 	44	62 %
PSL Parallel strand lumber / <i>drvo od paralelno orijentiranih dugih vlaknaca dobivenih od furnira</i> 	15	21 %
LSL Laminated strand lumber <i>drvo od slojevito lijepljenih vlaknaca</i> 	12	17 %
SWP Solid wood panel / <i>ploča od masivnog drva</i> 	40	56 %
LVL Laminated veneer lumber / <i>lamelirano furnirsko uslojeno drvo</i> 	16	23 %
PW Plywood / <i>furnirsko uslojeno drvo</i> 	43	61 %
LDF/MDF/HDF Low/ medium/ high-density fibreboard <i>ploča vlaknatica niske/srednje/visoke gustoće</i> 	37	52 %
VP Veneered particle board / <i>furnirana ploča iverica</i> 	8	11 %

Table 1 Continued
Tablica 1. Nastavak

EWP <i>Kompozitno drvo</i>	Number of students that are familiar <i>Broj upoznatih studenata</i>	Percentage of students that are familiar <i>Postotak upoznatih studenata</i>
PB Particle board / <i>ploča iverica</i> 	9	13 %
OSB Oriented strand board / <i>ploča s orijentiranim iverjem</i> 	13	18 %
LS Light sandwich panel / <i>lagana sendvič-ploča</i> 	23	32 %

model-making, visits to production facilities and construction sites were emphasised as essential components of the learning process. Besides the theoretical knowledge, that is generally provided, direct engagement with timber construction is also needed. Unfortunately, this is limited by the relatively low number of timber production facilities and construction sites where timber is implemented in North Macedonia (Petrovski *et al.*, 2019). However, the lack of timber construction sites could be compensated through analysis and presentation of contemporary international case studies or organised visits in the neighbouring countries where such examples can be observed.

Another frequently mentioned issue was the lack of technical knowledge, particularly in areas such as structural analysis, detailing, fire performance, moisture resistance, and durability, which greatly affects students' confidence in the application of EWPs, particularly as a structural material. Several respondents suggested that EWPs should be addressed with the same level of depth as reinforced concrete and steel within the curriculum.

Furthermore, some students pointed out the need for a deeper understanding of the sustainability aspects of wood-based materials. While this topic is introduced in existing courses such as *Sustainable Architecture* and *Energy Efficiency in Buildings*, respondents expressed interest in more comprehensive coverage.

A smaller number of respondents pointed out institutional and regional factors, specifically the limited use of timber in local construction practices in our country. Some of the students feel that learning about timber is unnecessary, given its limited practical application in North Macedonia and the fact that they will

not need it in the future when they start working as architects.

Finally, a minority of respondents answered that their current knowledge is sufficient and that there is no need for deeper information on the topic.

3.2 Curriculum analysis: integration of wood and EWPs in architectural education

3.2. Analiza kurikuluma: integracija drva i kompozitnog drva u arhitektonsko obrazovanje

The examination shows that the study programme includes several courses related to structural systems, construction technologies, and building materials throughout the first and second cycles of studies at the Department of Architecture. In the most recent curriculum (2025), an additional course, *Architectural Structures IV*, has been introduced, further expanding the coverage of contemporary structural systems, advanced non-structural elements and materials.

As shown in Table 2, the curriculum provides a comprehensive foundation in structural engineering principles through courses such as *Statics*, *Strength of Materials*, *Theory of Structures*, *Reinforced Concrete*, and *Steel Structures*. Moreover, the series of courses *Architectural Structures I – IV* progressively develops the students' knowledge of structural systems, structural elements, materials, and construction technologies. These courses are specifically designed to be adapted for architectural students. The syllabi for *Architectural Structures III* and *Architectural Structures IV* cover more advanced structural systems and innovative materials, including wood and EWPs. In addition, in these courses, the application of EWPs is ana-

Table 2 Curriculum analyses (International Balkan University, 2024)**Tablica 2.** Analiza kurikuluma (International Balkan University, 2024.)

Course <i>Kolegij</i>	Level of study <i>Razina studija</i>	Course objective (A brief description) <i>Cilj kolegija (kratki opis)</i>
Statics	2 nd year	Learning fundamental principles of forces, moments, and equilibrium in structures. Development of analytical skills for reaction, internal forces, and stability of the structural system in 2D and 3D.
Architectural structures I	2 nd year	Provides foundational knowledge of construction materials and basic structural systems. Focuses on understanding load-bearing elements, such as columns, beams, foundations, and slabs, and their role in forming simple architectural structures.
Strength of materials	2 nd year	Explores how materials behave under different loads, including stress, strain, and deformation. Equips students to evaluate material performance and structural safety.
Architectural structures II	2 nd year	Increases the knowledge of structural systems through detailed study of structural elements such as floors, roofs, and stairs. Emphasises integration of materials and construction methods into architectural design.
Architectural structures III	3 rd year	Develops advanced understanding of modern structural systems and materials, including steel, timber, and prefabrication. Introduces façade systems, fire protection, and seismic design principles.
Reinforced concrete	4 th year	Focuses on the behaviour and design of reinforced concrete elements and systems. Teaches basic analytical and design principles for structural applications.
Theory of structures 1	3 rd year	Introduces structural analysis concepts, including stability, determinacy, and influence lines. Develops analytical skills to understand complex structural behaviour.
Steel structures	4 th year	Provides knowledge of design principles and dimensioning of steel structural elements and connections. Enhances the ability to apply structural design methods in practice.
Building physics	3 rd year	Introduces principles of thermal performance, insulation, and energy efficiency in buildings. Focus on the application of materials for environmental control and sustainable design.
Building materials	3 rd year	Develops understanding of physical and mechanical properties of construction materials. Enables informed selection and application of materials in structural and architectural contexts.
Architectural structures IV	Master's studies	Advances knowledge of contemporary structural systems and materials in line with modern standards. Introduces Eurocodes and their application in structural design practice.

lysed not only from a structural point of view but also as a non-structural element in the façade or the interior design. These courses cover a wide range of materials and systems, including conventional and contemporary solutions, as well as aspects of façade design, fire protection, and seismic performance.

Despite this broad coverage in the general courses, the analysis shows that wood and EWPs are not addressed as a distinct subject within the curriculum. There are dedicated courses for reinforced concrete and steel, but unfortunately, none for timber. A positive thing is that they are at least introduced as part of broader courses, particularly in Architectural Structures II, III, and IV; unfortunately, in these courses, the focus cannot be solely on timber structures. Thus, their treatment remains relatively limited and generalised, without a specific focus on their characteristics, structural behaviour, detailing, or technical performance.

This absence affects the depth of students' knowledge and also their confidence in applying these materials in the design projects. The curriculum places greater emphasis on reinforced concrete and steel across course content, technical depth, and practical application. Consequently, wood and EWPs may be perceived as secondary or supplementary materials rather than primary structural solutions.

Overall, the curriculum provides a solid theoretical foundation in structural systems and materials, but the integration of wood-based materials remains limited.

3.3 Analysis of student projects: application of EWPs in design

3.3. Analiza studentskih projekata: primjena kompozitnog drva u projektiranju

Students' projects from the period 2020 – 2025 were analysed and the results show clear trends in the selection of the materials, as shown in Table 3. The cells that have a percentage higher than 50 are marked with yellow, while the cells that have a percentage less than 30 are marked with grey in the table. In the earlier period (2020 – 2021), timber-based structural systems were not applied at all in the designs. The building projects from that period feature structural system made of reinforced concrete and steel. From 2022 onwards, the timber and EWPs application has emerged, reaching 43 % in 2022, followed by fluctuating but consistent application in subsequent years. This is an indicator of growing awareness and willingness among students to explore alternative structural materials.

Despite this increase, the traditional materials remain dominant. Reinforced concrete and steel continue to be widely used, particularly steel in recent years (56

Table 3 Share of materials used by students in the structural system and in façades. Results from the Architectural Structures project course at the master's level between 2020 and 2025**Tablica 3.** Udio materijalâ koje su studenti primijenili u nosivoj konstrukciji i oblikovanju pročelja. Rezultati izbornog/obveznog kolegija Arhitektonske konstrukcije na diplomskom studiju u razdoblju 2020. – 2025.

Year Godina	Material used for the structural system <i>Materijal upotrijebljen za nosivu konstrukciju</i>				Material used for façade <i>Materijal upotrijebljen za pročelje</i>
	Concrete	Steel	Timber / EWPs	Other	Timber applied to the façade
2020	67 %	33 %	0 %	0 %	11 %
2021	43 %	57 %	0 %	0 %	29 %
2022	43 %	14 %	43 %	0 %	57 %
2023	50 %	29 %	21 %	0 %	50 %
2024	22 %	56 %	22 %	0 %	56 %
2025	11 %	56 %	33 %	0 %	56 %

% in 2024 and 2025), which may reflect both the emphasis in the curriculum and the country's dominant construction practices. Timber-based systems, while present, are used less consistently as primary structural solutions.

In contrast, the use of wood or wood-based products in façade design shows a more stable and higher prevalence across the analysed period, particularly from 2022 onwards, when more than half of the projects have incorporated wood as a façade material. In 2024 and 2025, the percentage of projects that include timber in the façade was 56. This suggests that students are more likely to adopt wood in non-structural roles, where its aesthetic and design qualities are more directly expressed.

Selected student projects further illustrate the potential of engineered wood products in architectural design. Figures 2 and 3 present projects that apply cross-laminated timber in the main structural system, demonstrating an understanding of its spatial and structural capabilities. Furthermore, these projects demonstrate a high level of creativity in their structure, with interesting shapes and connections among the structural elements. The CLT remains visible, further enriching the overall design aesthetics. The project for the pavilion presented in Figure 3 demonstrates a strong understanding of the structural system using EWPs, as evidenced by the technical drawings and connection details for the separate elements.

**Figure 2** Student project for Botanical Garden in Skopje – application of a CLT structure, designed by Faton Kalisi**Slika 2.** Studentski projekt Botaničkog vrta u Skoplju – primjena konstrukcije od križno lameliranog drva (CLT); autor Faton Kalisi

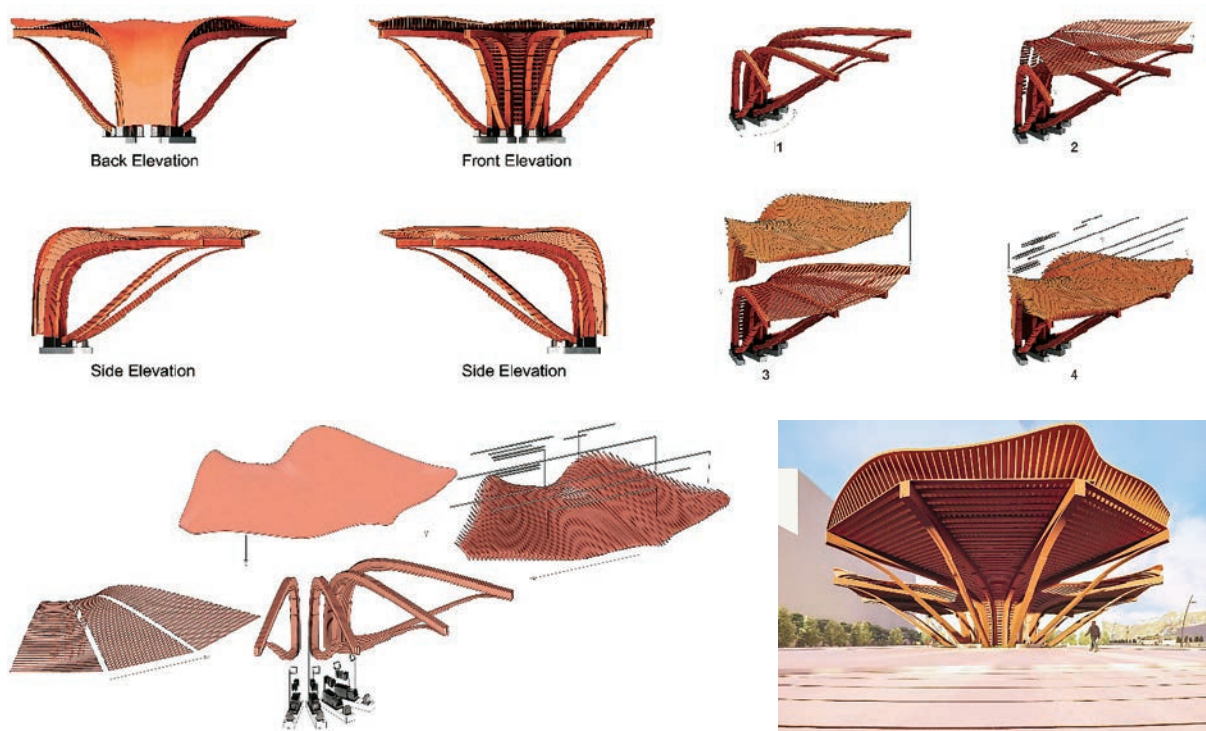


Figure 3 Student project for the Pavilion in Skopje – application of a CLT structure, designed by Eldin Fazliu

Slika 3. Studentski projekt paviljona u Skoplju – primjena konstrukcije od križno lameliranog drva (CLT); autor Eldin Fazliu



Figure 4 Students' project for the Pavilion in City Park, Skopje – designed by Qani Saiti, Arman Kačaniku, and Seadin Zendeli

Slika 4. Studentski projekt paviljona u Gradskom parku u Skoplju; autori Qani Saiti, Arman Kačaniku i Seadin Zendeli

Additional examples (Figures 4 and 5) show the use of wood in pavilion structures and lightweight design solutions, highlighting its flexibility and suitability for smaller-scale interventions. Both projects are designed in natural settings, demonstrating the choice of materials in relation to their contexts. The project in Figure 4 demonstrates a combined structure in which the organic columns are made of wood-based materials. The roof is made from a lightweight composite material in a wavy shape that compliments the wooden columns. The overall organic shape blends with the natural setting, following the nearby river course.

The pavilion shown in Figure 5 is entirely constructed from EWPs. The main structure consists of

parabolic carriers made of cross-laminated timber, strengthened and stiffened with secondary, smaller carriers in the horizontal direction. Between the secondary carriers, small segments of wood-plastic composite are added to create a semi-transparent pattern for the pavilion. This does not block the view of the natural setting, and it also creates interesting shadows on the base, which is a perfect example of a biophilic design pattern.

Overall, analyses of students' projects show a gradual, slow integration of wood and wood-based materials, especially in recent years. However, their application remains mostly limited to aesthetic elements in facades or small-scale structures such as pavilions, rather than complex load-bearing systems. These findings reflect the opportunities and limitations of the current educational framework and align with the survey and curriculum analyses.

4 CONCLUSIONS

4. ZAKLJUČAK

The holistic approach in this study yields similar results across three methods used during the research. There is a clear discrepancy between the relatively high level of theoretical knowledge and awareness of EWPs among students and their practical application in design practice, particularly within structural systems. Students demonstrate familiarity with key timber-based materials and express interest in their use. Nevertheless, the use of timber and EWPs as structural

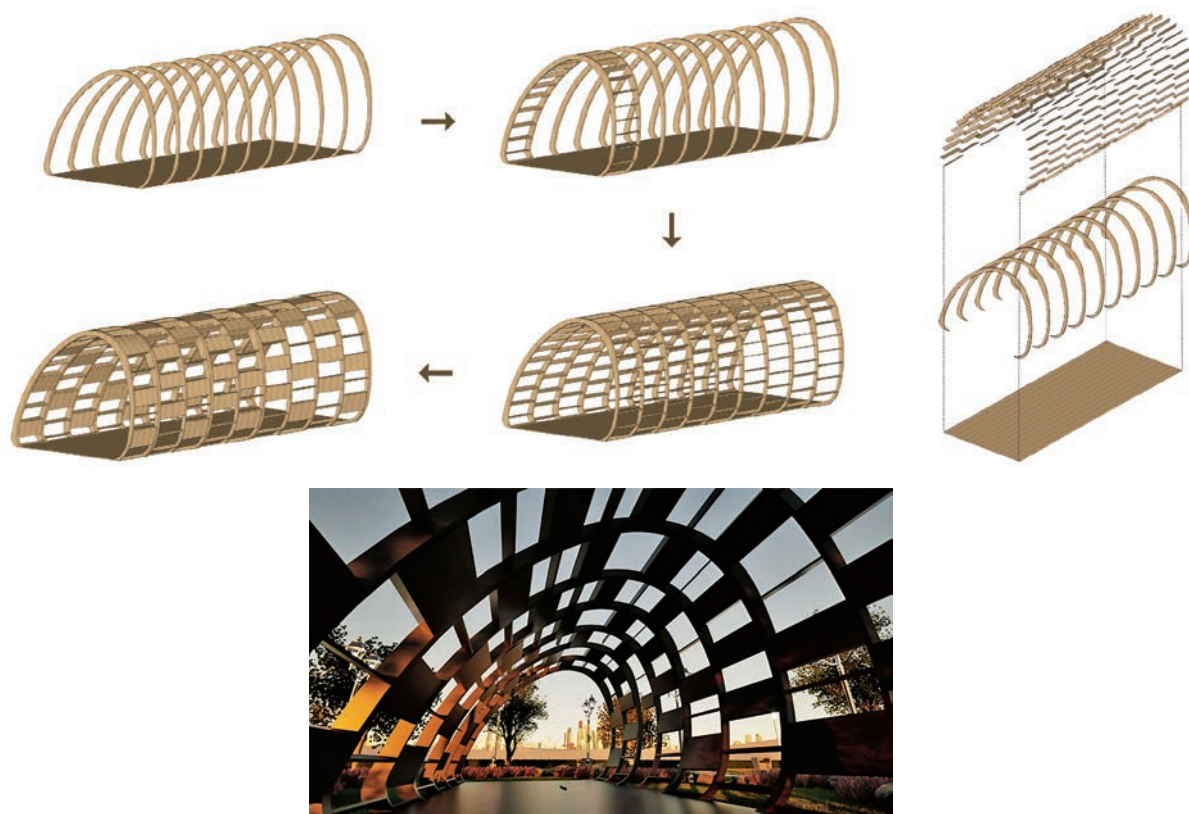


Figure 5 Students' project for the Pavilion in Skopje – designed by Ivona Atanasoska and Devleta Shabani
Slika 5. Studentski projekt paviljona u Skoplju; autorice Ivona Atanasoska i Devleta Shabani

materials in the students' projects remains relatively low. This can be concluded from both the survey questionnaire and the analyses of the student projects, where wood-based products are mostly used as decorative materials in the exterior or interior of the building.

The architectural curriculum analyses demonstrate that there is a solid theoretical foundation in materials, structural systems and construction technologies during the studies. Still, there is insufficient depth and focus on timber construction. The absence of dedicated courses and limited opportunities for hands-on experience appear to be key factors influencing students' design decisions and material preferences. However, despite this absence, there has been a gradual increase in the use of timber-based systems in recent student projects, which is a positive shift.

The novelty of this study lies in its integrated approach, which combines three methods to allow results to be viewed from different perspectives. Although the approaches differ, they indicate the same gaps in architectural education. Another important aspect of this research is that these analyses have not been conducted in North Macedonia to date. By combining students' perceptions, curriculum analysis, and students' projects, this study compares educational backgrounds with design practices. It provides valuable insights into how the situation in North Macedonia can be improved.

The results show that the application of EWPs in architectural education can be strengthened through targeted curriculum development, including dedicated courses focused on timber structures, practical training, hands-on experience and exposure to contemporary timber construction and production facilities. This can significantly enhance students' competencies and confidence, and support a broader transition towards more sustainable design practices in the country.

Finally, the proposed methodology can be applied in other academic contexts to evaluate students' knowledge and perceptions of timber-based materials, identify existing gaps, and support the development of more effective educational strategies.

Acknowledgements – Zahvala

The author of this paper would like to thank the students from the Department of Architecture, at International Balkan University in Skopje, North Macedonia, for their participation in the survey and for their valuable contributions through their projects analysed in this study. A great appreciation is extended to Faton Kalisi, Eldin Fazliu, Qani Saiti, Arman Kaçaniku, Seadin Zendeli, Ivona Atanasoska, and Devleta Shabani for their remarkable projects that applied timber-based materials.

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Design and Construction of Multifunctional Upholstered Furniture from *Cocos nucifera* (Coconut) for a University Hall of Residence

Dizajn i izrada višenamjenskoga ojaštuenog namještaja od drva kokosove palme (*Cocos nucifera*) za sveučilišni studentski dom

ORIGINAL SCIENTIFIC PAPER

Izvorni znanstveni rad

Received – prispjelo: 2. 4. 2026.

Accepted – prihvaćeno: 11. 6. 2026.

UDK: 684.4.05; 684.4.07

<https://doi.org/10.5552/drvind.2026.0347>

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ABSTRACT • Due to limitation of space in university residence halls, need for multifunctional furniture that promotes space utilisation, flexibility and convenience for user(s) has increased compared to single-function furniture that is costly and occupies more space. This study aimed to design and construct a multifunctional upholstered furniture unit from *Cocos nucifera* (coconut) for a university hall of residence. Specifically, it investigates the composition of a single unit that combines all functions of a bed, chair and drawer to achieve improved spatial efficiency, ergonomics and functional versatility. The study adopted Research and Development (R&D) research design involving information gathering, planning, prototyping development, testing and product refinement. Coconut timber, fabricated iron-framework, upholstery materials and transformation mechanisms were utilised in the construction of the prototype. Fourteen participants were involved in the preliminary evaluation which comprised assessment of space availability and usability survey. Descriptive statistics, reliability analysis, normality tests and Spearman rank correlation analysis were used to analyse data. Results revealed that the multifunctional furniture occupied significantly less space (182 cm × 26 cm × 29 cm) compared to single-function furniture arrangements (267 cm × 90 cm × 81 cm). The reliability analysis indicated acceptable internal consistency of ergonomic performance ($\alpha = 0.721$) and space-saving effectiveness ($\alpha = 0.785$). A significant positive correlation was found between space-saving performance and ergonomic performance ($r_s = 0.654$, $p < 0.05$). Cost analysis further indicated a higher cost of 52.3 % of single-function furniture as against the developed multifunctional furniture. Hence, this study presents a new approach to provide an affordable ergonomic, space-saving multifunctional upholstered furniture using *Cocos nucifera*.

KEYWORDS: *Cocos nucifera*; design and construction; multifunctional; upholstered furniture

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SAŽETAK • Zbog ograničenog prostora u studentskim domovima povećala se potreba za višenamjenskim namještajem koji pridonosi boljoj iskorištenosti prostora, fleksibilnosti i praktičnosti za korisnike u usporedbi s jednonamjenskim namještajem koji je skup i zauzima više mjesta. Cilj ovog istraživanja bio je dizajnirati i izraditi višenamjenski ojasučen namještaj od drva kokosove palme (*Cocos nucifera*) za sveučilišni studentski dom. Konkretno, istraživao je sastav jedne jedinice koja objedinjuje sve funkcije kreveta, stolice i ladičara kako bi se postigla veća prostorna iskoristivost, bolja ergonomska svojstva i funkcionalna svestranost namještaja. U radu je primijenjen istraživačko-razvojni (R&D) pristup koji je obuhvatio prikupljanje informacija, planiranje, izradu prototipa, ispitivanje i doradu proizvoda. U izradi prototipa upotrijebljeno je drvo kokosove palme, izrađeni su željezni okvir, materijali za ojasučenje i mehanizmi za transformaciju. U preliminarnoj evaluaciji, koja je obuhvatala procjenu raspoloživog prostora i anketu o upotrebljivosti namještaja, sudjelovalo je četrnaest ispitanika. Za analizu podataka primijenjeni su deskriptivna statistika, analiza pouzdanosti, testovi normalnosti i Spearmanova analiza korelacijskog ranga. Rezultati su pokazali da je višenamjenski namještaj zauzeo znatno manje prostora ($182\text{ cm} \times 26\text{ cm} \times 29\text{ cm}$) u usporedbi s jednonamjenskim namještajem ($267\text{ cm} \times 90\text{ cm} \times 81\text{ cm}$). Analiza pouzdanosti pokazala je prihvatljivu unutarnju konzistentnost ergonomskih svojstava ($\alpha = 0,721$) i učinkovitost uštede prostora ($\alpha = 0,785$). Utvrđena je značajna pozitivna korelacija između učinkovitosti uštede prostora i ergonomskih svojstava ($r_s = 0,654$, $p < 0,05$). Analiza troškova dodatno je potvrdila da je jednonamjenski namještaj 52,3 % skuplji od razvijenoga višenamjenskog namještaja. Stoga je rad primjer novog pristupa osiguranju pristupačnoga, ergonomskoga i višenamjenskoga ojasučenog namještaja kojim se štedi prostor, uz upotrebu drva kokosove palme (*Cocos nucifera*).

KLJUČNE RIJEČI: *Cocos nucifera*; dizajn i konstrukcija; višenamjenski ojasučen namještaj

1 INTRODUCTION

1. UVOD

In spatial design, saving space is important to optimise energy usage and thermal and visual comfort especially for tiny homes that emphasise smaller spaces for more sustainable lifestyles. Flexible and efficient, foldable, modular, space-saving and/or multifunctional equipment or furniture may considerably reduce the environmental impact of low-spaced dwellings (Oyewole *et al.*, 2010; Bonvoisin *et al.*, 2016; Lim and Ng, 2021). One of the trends of modern-day furniture design is multifunctional furniture items (Lim and Ng, 2021). Over 90 % of people in the densest populated cities live in small buildings or flats due to lack of space (Knauf, 2015). Thus, when multifunctionality is accounted for in the design of a furniture piece paired with ergonomics and anthropometric considerations, it can become less bulky and thus portable as well as convenient to use in small spaces.

The rate at which Nigerian institutions invest in construction of hall of residence, in part to fulfil the third cardinal function of establishing a university, which is to provide community service, is on a high side. For any hall of residence to achieve an optimum efficiency, the type and design of furniture to be adopted is one of the key components that needs proper attention. A multifunctional upholstered furniture in the context of this study is a single unit with functionality of bed, chair and drawer in smart design comprise of safety, comfort, ease of use, productivity/ performance and aesthetics. Upholstery-making, however, is the craft of designing practical cushioned or padded sitting furniture for homes and offices. Upholstery furniture

making simply requires the expertise in designing upholstery patterns, skills in using the hand tools to shape wood in building carcasses that fit a platform for sitting and backing; webbing with specific felts of strength, cording the edges of the carcass for aesthetics purposes; padding with foam materials for comfort and covering with fabrics for beauty and style (Utuk *et al.*, 2019). Wood is the main raw material of the furniture industry, and it mainly consumes natural resources from forests (Lins *et al.*, 2020).

Single-function furniture becomes wasted, and the multifunction process device maintains its utilisation for an extended timeframe since it has additional features and serves an expanded range of requirements (Andrews, 2021; Lim and Ng, 2021). In Nigeria, there are basically three categories of forests based on the type of vegetation within the country such as coastal mangrove and freshwater forest, tropical rainforest in the south humid zone and drier forest of the middle and north region (Salami and Balogun, 2016; Akinbami *et al.*, 2023; Ayeni *et al.*, 2023). Also, furniture is made with mainly two kinds of wood: naturally sourced solid wood and engineered wood. Solid wood is then categorised into two types: hardwood and softwood. Hardwood comes from deciduous trees that also produce seeds and are generally slower growing and often of a higher density than softwoods. They are used for high-end furniture decorative woodwork, desk, flooring among others. Examples are ash, beech, birch, cherry, oak, maple, walnut, mahogany, rosewood, teak and coconut trees.

The coconut tree (*Cocos nucifera*) is one of the most widely grown and important palms. However, in the case of furniture construction, the tree has been less

appealing compared with other hardwoods making it a generally accepted burning wood. Humans have been cultivating a wide range of coconut trees around the world. The average air dry and oven dry density of coconut stem is 400 and 460 kg/m³, respectively. The modulus of elasticity in bending (MOE) and the modulus of rupture in bending (MOR) values for air dry and oven dry conditions are 2374 and 2633 N/mm² and 27.30 and 30.44 N/mm². The compression strength parallel to grain and perpendicular to grain for air dry and oven dry conditions are 12.41 and 12.85 N/mm² and 9.28 and 9.64 N/mm², respectively (Rana, Das and Ashaduzzaman, 2015; Lamidi *et al.*, 2021). This validates the possibility to use the stem of *Cocos nucifera* for different structural purposes. The under-utilisation of this wood can be described as a colossal waste. Meanwhile, government attention has been drawn to wealth from waste. Therefore, this prompted the researchers' curiosity to reconsider the tree in constructing multifunctional furniture. Hence, the study has been made on design and construction of multifunctional upholstered furniture from *Cocos nucifera* (Coconut) for a university hall of residence.

1.1 Concept of multifunctional furniture

1.1. Koncept višenamjenskog namještaja

Most challenges encountered in small spaces can be solved through some smart solution approaches, like investment in multifunctional furniture and modular furniture as well as space design which can also contribute to enhancing the efficiency of small spaces (Estaji, 2017). Multifunctional furniture is referred to by many names: space-saving furniture, transformable furnishing and multifunctional furniture; design of a single piece that serves multiple activities or purposes at the same time. Such furniture has been manufactured and used for years but until now the significance of these multifunctional pieces has not been fully acknowledged (Canepa, 2017).

Multifunctional furniture denotes pieces of furniture that adjust with different applications by transforming spatial relationships of their pieces. Sometimes modification needs skill; such kinds of furniture can be quite costly as it adapts to different applications at the same time. Multifunctional items like foldable, stackable and transformable furniture are great solutions for maximizing small spaces (Farjami, 2014). Various types of such versatile furnishing are available on the market, for example, multipurpose furniture that can work as a table, chair, bookshelf and a wardrobe at the same time.

A university hall of residence is a shelter and home for its students; hence, it must provide conditions in which students feel comfort, wellbeing and live healthily (Gomes *et al.*, 2015). In residence halls,

where space is scarce, it is an issue how to fit basic furniture into cramped dormitories. Due to this spatial restriction, multifunctional furniture needs to be employed because neighbouring their living quarters people must adapt single quadrants for several tasks. Moreover, modern lifestyle trends promote efficiency while minimizing superfluity in everyday life and contribute to the increased desirability for flexible living solutions. With housing area becoming smaller, furniture that can offer maximum utility in the least space is increasingly preferred. This is where multifunctional furniture comes into play, as it combines uses into a single piece of furniture which provides optimal space efficiency.

1.2 Aim of paper

1.2. Cilj rada

The aim of this study is to design and construct a piece of multifunctional upholstered furniture from *Cocos nucifera* (Coconut) for a university hall of residence. Specifically, the study sought to design a furniture unit that integrates the functions of a bed, chair and drawer within a single structure in order to improve space utilisation and functionality in compact student dormitories.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

2.1 Research design

2.1. Dizajn istraživanja

The study adopted Research and Development (R&D) design. Research and development design is defined as an industry-based development model in which the findings of research are used to design new products and procedures, which are systematically tested in the field, evaluated and refined until they meet specified criteria of effectiveness, quality or similar standards (Cheng *et al.*, 2021; Gall *et al.*, 2007). Figure 1 depicts the flow of the entire design process entailed within the methodology, analysis, results and discussion.

Research and development model consists of ten primary stages:

- i. Research and information collection – literature review and needs analysis
- ii. Planning – product development planning
- iii. Developing the preliminary form of product – prototype creation
- iv. Preliminary field testing – small scale field testing
- v. Main product revision – revision based on preliminary testing
- vi. Main field testing – major field testing

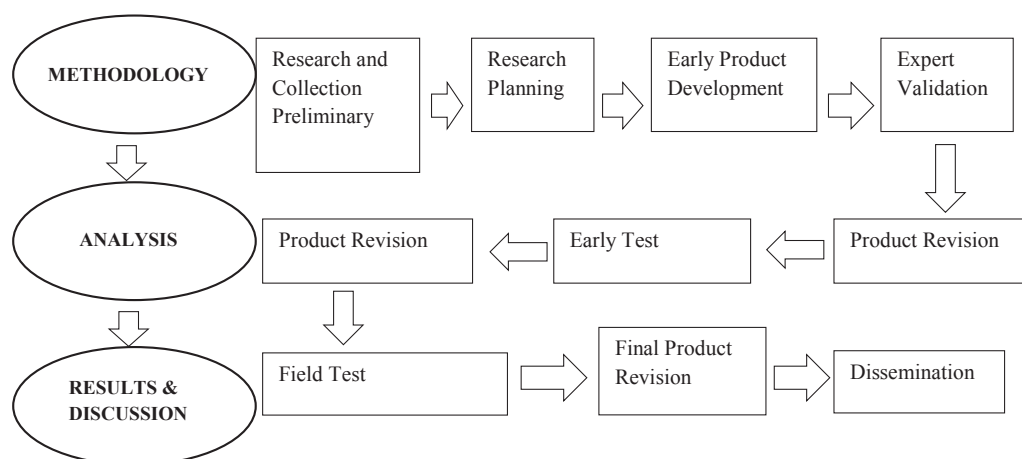


Figure 1 Research and development design process

Slika 1. Proces dizajna proizvoda i istraživanja

- vii. Operational product revision – subsequent refinement
- viii. Operational field testing – operational-scale testing
- ix. Final product revision – final refinement
- x. Dissemination and implementation – product dissemination and implementation

This model emphasises formative evaluation and repeated revision, making it particularly suitable for producing valid and reliable educational products. It has been extensively applied in the development of learning materials, media, curricula and instructional models.

2.2 Research and information collection

2.2. Istraživanje i prikupljanje informacija

Research and information collecting on multifunctional articles are essential in understanding the important features and functions that make such products effective and adaptable for modern use. Multifunctional articles are intended to provide two or more functions within a single unit as a means for increasing space utilisation, convenience, flexibility and cost effectiveness. The compactness, transformability traits, durability, ergonomic suitability and aesthetic appeal are key features underlying their insets into houses, institutions and commercial settings. A review of related literature, patent design and self-creative perspectives was conducted to collect materials that could be informative and representative on the selected themes allowing for a deeper comprehension.

Figures 2 – 9 show a few illustrative samples of some furniture that have been designed to enhance space and functionality. Figure 2 shows a multifunctional table with an integrated structure on which the user can perform various activities and user-controllable input functions (Furniture Design Magazine, 2022). Figure 3 shows an adaptive multifunctional furniture

chair that provides flexibility in support usage (IKEA Catalogue, 2023). Figure 4 depicts a multifunctional wardrobe with built-in storage and additional utility functions, while Figure 5 represents a multifunctional centre table aiming to merge the surface functionality with storage capacity (Furniture Design Magazine, 2022). A foldable bed-chair which tries to provide freedom of use and makes best use of limited space is shown in Figure 6 (Estaji, 2017). An example of an intervention in this area is shown in Figure 7, where a convertible storage furniture combining both seating and compartmentalised storage functions is provided for practical access to commonly used items and clothes, aiding item retrieval programming upon awakening smoothly with less physical effort involved (Gomes *et al.*, 2015). Figure 8 shows an example of a compact convertible furniture developed for relaxation and mobility as well as multipurpose use inside small areas (Mazlan *et al.*, 2021), whereas Figure 9 is an example of multifunctional study desk with shelves and storage that could serve both academics and residential purposes (IKEA Catalogue, 2023). Thus, these designs illustrate how multifunctional furniture can make it easier to utilise space in a residence hall effectively and to the user benefit.

2.3 Planning

2.3. Planiranje

Three tentative furniture concepts identified as Self-proposed Ideas A, B and C (Figure 10 – 12) were initially developed to explore different approaches for integrating the functions of a bed, chair and drawer within a single multifunctional furniture unit. Each concept possessed unique structural and functional characteristics aimed at improving space utilisation, transformability, ease of fabrication and user convenience. To determine the most suitable design for development, a subjected scoring process was conducted using selected evaluation criteria which included ease



Figure 2 Multifunctional table (Furniture Design Magazine, 2022)

Slika 2. Višenamjenski stol (Furniture Design Magazine, 2022.)



Figure 3 Multifunctional chair (IKEA Catalogue, 2023)

Slika 3. Višenamjenska sofa (IKEA Catalogue, 2023.)



Figure 4 Multifunctional wardrobe (Furniture Design Magazine, 2022)

Slika 4. Višenamjenski ormar (Furniture Design Magazine, 2022.)



Figure 5 Multifunctional centre table (IKEA Catalogue, 2023)

Slika 5. Višenamjenski središnji stol (IKEA Catalogue, 2023.)



Figure 6 Multifunctional bed (Estaji, 2017)

Slika 6. Višenamjenski krevet (Estaji, 2017.)



Figure 7 Multifunctional storage system (Gomes *et al.*, 2015)

Slika 7. Višenamjenski namještaj za odlaganje (Gomes *et al.*, 2015.)



Figure 8 Multifunctional chair (Mazlan *et al.*, 2021)

Slika 8. Višenamjenska stolica (Mazlan *et al.*, 2021.)



Figure 9 Multifunctional study desk (IKEA Catalogue, 2023)

Slika 9. Višenamjenski radni stol (IKEA Catalogue, 2023.)

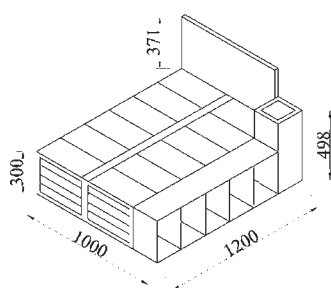


Figure 10 Self-proposed idea A

Slika 10. Vlastito dizajnersko rješenje A

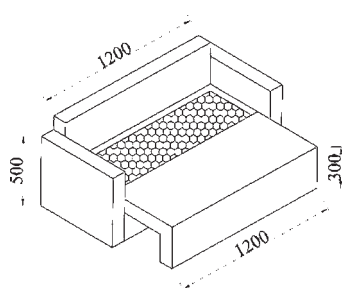


Figure 11 Self-proposed idea B

Slika 11. Vlastito dizajnersko rješenje B

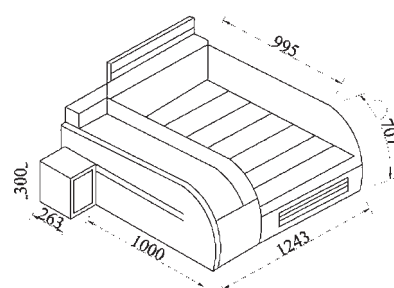


Figure 12 Self-proposed idea C

Slika 12. Vlastito dizajnersko rješenje C

of transformation, multifunctionality, ease of fabrication and space-saving effectiveness (Cheng *et al.*, 2021). Each criterion was assigned equal weighting, and the proposed concepts were rated using a five-point scale. The weighted scores obtained from the evaluation revealed that Self-proposed Idea B achieved the highest overall score and was therefore selected as the final design concept for further development and construction (Table 1).

2.4 Working drawing for self-proposed Idea B

2.4. Tehnički crtež vlastite dizajnerske ideje B

Based on the scoring, Self-proposed Idea B was chosen as the best design concept, thus allowing for

the development of a working drawing. It contains necessary visual and dimensional information for the construction and assembly of the multifunctional furniture. To facilitate a comprehensive understanding of the design, the drawing was sectioned according to each functional configuration, namely the chair position (Figure 13), drawer position (Figure 14) and bed position (Figure 15). For each function, plan, side and pictorial views were presented to clearly depict the dimensions, form and operational features of the furniture. In addition, an exploded view (Figure 16) was included to illustrate the individual components, assembly sequence and interconnections within the structure.

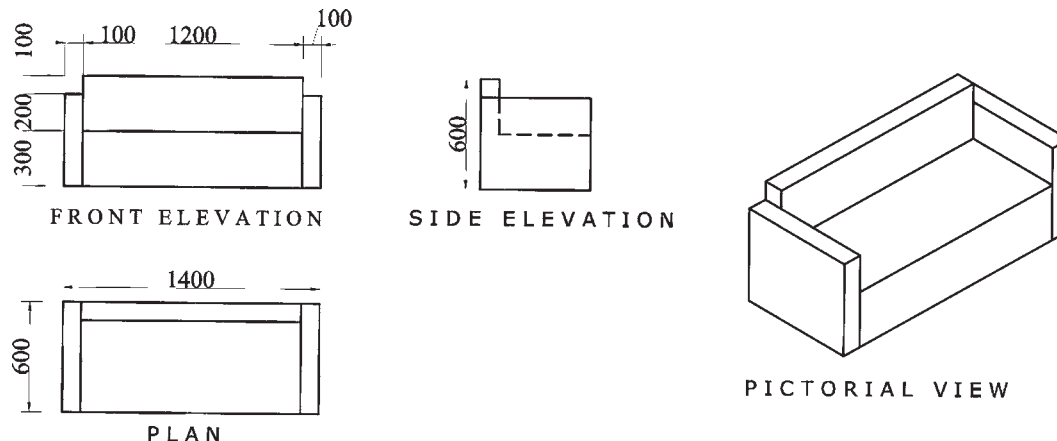


Figure 13 Multifunctional furniture in chair position

Slika 13. Višenamjenski namještaj u funkciji naslonjača

Table 1 Self-proposed idea A, B and C table of scoring

Tablica 1. Tablica vrednovanja vlastitih dizajnerskih rješenja A, B i C

Selection criteria Kriteriji vrednovanja	Weight, % Ponder, %	Self-proposed ideas / Vlastita dizajnerska rješenja					
		A		B		C	
		R	WS	R	WS	R	WS
Ease of transformation / jednostavnost transformacije	25	4	0.8	5	1.0	4	0.9
Multifunctionality / multifunkcionalnost	25	5	1.2	5	1.2	4	0.8
Ease of fabrication / jednostavnost proizvodnje	25	3	0.6	4	1.2	3	0.6
Space-saving / ušteda prostora	25	3	0.6	5	0.8	4	1.2
Total score / ukupan broj bodova		3.2		4.2		3.5	
Rank / poredak		3		1		2	

Note: R – Rating; WS – Weighted score; Rating scale: 5-excellent, 4-good, 3-neutral, 2-poor, 1-worst

Napomena: R – ocjena; WS – ponderirana ocjena; ljestvica ocjenjivanja: 5 – izvrsno, 4 – dobro, 3 – neutralno, 2 – loše, 1 – najgore

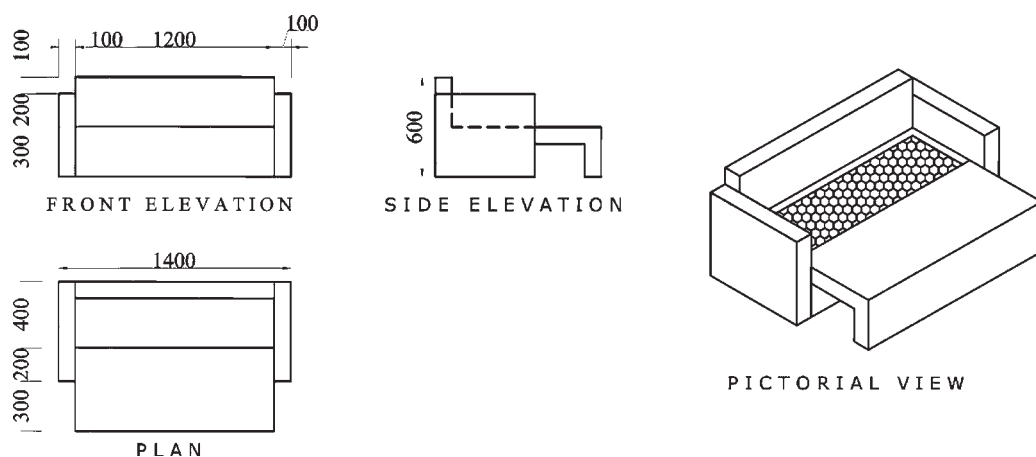


Figure 14 Multifunctional furniture in drawer position

Slika 14. Višenamjenski namještaj u funkciji ladice

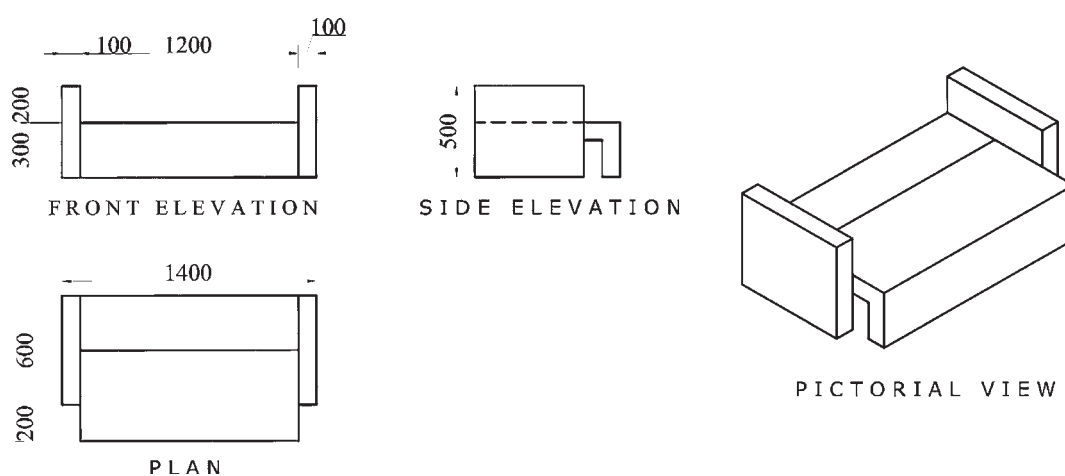


Figure 15 Multifunctional furniture in bed position

Slika 15. Višenamjenski namještaj u funkciji kreveta

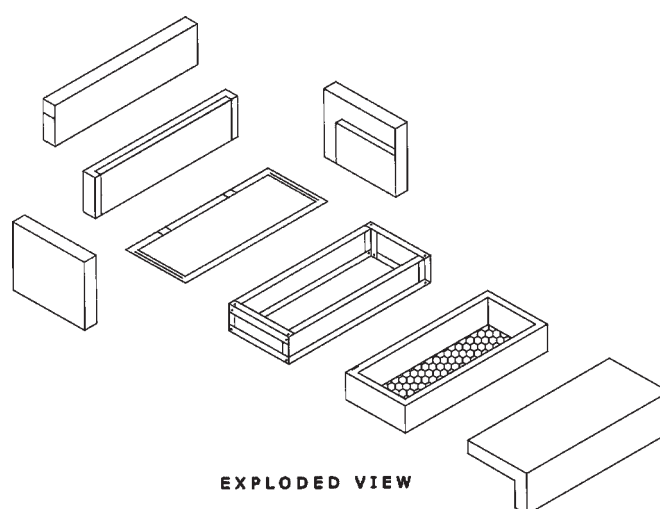


Figure 16 Exploded view of the developed multifunctional furniture

Slika 16. Prikaz rastavljenoga razvijenog višenamjenskog namještaja

2.5 Preparation of coconut timber

2.5. Priprema drva kokosove palme

The primary wood material used in this furniture is coconut timber derived from *Cocos nucifera*. Coconut trees were collected from Fashola town located in the Oyo West Local Government Area of Oyo State, Nigeria, along the Oyo – Iseyin Road. It is situated in the South-West geopolitical zone of the country, with coordinates approximately at 6.83333° N and 3.28333° E. The sampled trees were 50 – 60 years old, fairly



Figure 17 Coconut trunks
Slika 17. Debla kokosove palme



Figure 18 Conversion of coconut timber
Slika 18. Prerada drva kokosove palme



Figure 20 Bolts and nuts
Slika 20. Vijci i matice

straight and free from defects (Figure 17). These coconut trunks were converted into pieces with dimensions of 100 mm (width) × 25 mm (thickness) × 1000 mm (length) at a nearby sawmill (Figure 18). After conversion, the boards were air-seasoned to reduce the moisture content of wood (Figure 19).

2.6 Metal fasteners and hardware

2.6. Metalni spojni elementi

Timber contains various metal fasteners for putting the pieces of furniture together and fixing it on wooden panels with the iron frames. These range from bolts, nuts, screws and washers to metal brackets (Figure 20 and 21). Hardware pieces make sure that the furniture structure is proper and stable while in practical use.

2.7 Transformation mechanisms

2.7. Okov

This has to do with specific characteristics that the furniture needs to have in order to fulfil its design purpose. The furniture will include hierarchical or convertible items, which can serve multiple purposes without taking up too much ground area. The fixture was combined with a foldable mechanism (butterfly hinges) for



Figure 19 Seasoning of coconut timber
Slika 19. Sušenje drva kokosove palme

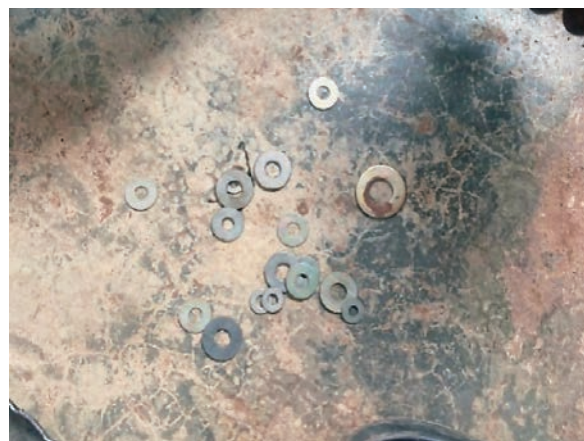


Figure 21 Washers
Slika 21. Podložne pločice



Figure 22 3D butterfly hinges
Slika 22. 3D leptir-spojnice



Figure 23 Drawer runner
Slika 23. Vodilica ladice

converting a chair to bed and a sliding mechanism (drawer runner) for providing storage compartments for personal belongings (Figure 22 and 23). All of the features are well defined in a way that ensures that the end design is practical and convenient for students.

2.8 Upholstery materials

2.8. Materijali za ojašćenje

Some areas of the design encompass utilizing upholstery materials to induce comfort and aesthetics into the furniture. High-density foam was used as cushioning material for seating surfaces and backrests (Figure 24). Upholstery fabric covered the foam for a soft and comfortable feel (Figure 25). Furniture design technique was enhanced within the developed multifunctional furniture by merging upholstery materials, where ergonomic comfort, structural support, durability and aesthetic level of quality score were improved. The upholstery system was composed of padded foam and covering fabric applied to the seat, backrest and touch surfaces of the furniture. Material selection was based on factors such as user comfort, load bearing capacity, deformation resistance, durability and extended usability in a university hall of residence.



Figure 24 High-density polyurethane foam
Slika 24. Poliuretanska spužva velike gustoće



Figure 25 Polyester upholstery fabric
Slika 25. Poliesterska tkanina za ojašćenje

The high-density polyurethane foam was chosen as the padding material for its capacity to provide sufficient body support and distribute pressure properly while sitting and reclining. The foam in this study had a density of 35 kg/m^3 and a stiffness value of 4.5 kPa , which were regarded as ideal for medium-duty furniture applications that require both comfort and dimensional stability (Figure 24). The chosen values of foam properties were satisfactory for limiting over-compression while maximizing resilience and more generally for prolonging the service life of upholstered elements under repeated use conditions.

The foam was enveloped with polyester upholstery fabric with the grammage of 320 g/m^2 (Figure 25). It was chosen for its texture, tensile strength, abrasion resistance, ease of maintenance/cleaning properties among others. The upholstery fabric not only provided a soft and comfortable surface but also enhanced the visual appearance and overall finishing quality of the furniture developed. The combination of high-density foam and durable upholstery fabric was therefore considered suitable for multifunctional furniture intended for intensive use in university hostel environments.



Figure 26 Fabricated iron
Slika 26. Obradeni željezni element



Figure 27 Fabricated iron
Slika 27. Spojeni željezni elementi

2.9 Fabricated iron for structural framework

2.9. Obradeni željezni elementi za nosivu konstrukciju

The main support structure of the furniture is made from fabricated iron. Angle irons are cut, welded and shaped together into a stiff supporting frame for the wooden panels and upholstery components (Figure 26 and 27). So, the iron frame gives additional strength for stability and load-bearing capacity, especially used in furniture like beds that support the sleeping function and sofas that support seating as well as compartment functionality.

3 PROJECT IMPLEMENTATION

3. PROVEDBA PROJEKTA

The project implementation phase involved the systematic transformation of the developed concept into a functional multifunctional upholstered furniture unit designed for use in a university hall of residence. This phase was about iteration and developing the design intentions to a point where it can be practically built, selecting materials for different parts of the furniture, as well as assembling these materials step by step. Emphasis was placed on integrating the chair, drawer and bed functions within a single compact framework while ensuring structural stability, ergonomic suitability and efficient space utilisation. Folding, sliding and conversion mechanisms were continuously refined throughout the implementation process to optimise operational smoothness, increase durability and provide better user safety. In addition, careful attention was given to joint placement, upholstery integration and dimensional accuracy to ensure that the final product achieved both functional adaptability and aesthetic coherence.

3.1 Concept development

3.1. Razrada koncepta

This demonstrated the fundamental functional features of the furniture, such as folding, sliding or

converting between different uses. This stage allows designers to examine the practicality, structural stability and aesthetic qualities of the design before subjecting it to user evaluation (Figure 28 – 32). The concept development phase involved the systematic translation of the preliminary furniture idea into a functional multifunctional prototype capable of integrating chair, drawer and bed functions within a single compact structure. This stage was essential for assessing the operational feasibility, structural behaviour, transformation efficiency, ergonomic suitability and aesthetic characteristics of the proposed furniture prior to final fabrication. An iterative design approach was adopted throughout the development process, allowing progressive modifications and refinements to improve functional performance, user convenience and spatial efficiency. Particular attention was given to dimensional coordination, load distribution, mechanical transformation, structural stability and material compatibility during the various stages of development.

To give a better insight into how the idea of furniture can change and evolve into an actual working model, stages of development can be seen in Figures 28-32. These stages show how the structural framework, transformation mechanisms, upholstery support system and final functional assembly of the developed furniture have been successively refined. Illustrated in Figure 28, Development Stage A shows the initial design structure for the furniture idea. At this point the main supporting members and dimensional arrangement was set out to give the furniture overall shape, balance and load-bearing arrangement. Anthropometric considerations relating to sitting and reclining dimensions were incorporated to ensure user comfort and functionality. Development Stage B, Figure 29, shows how the mechanical transformation system was integrated into the structural framework. At this stage, mobile and adjustable parts required to transform the furniture between chair, drawer and bed positions were



Figure 28 Development stage A
Slika 28. Faza razvoja A



Figure 29 Development stage B
Slika 29. Faza razvoja B



Figure 30 Development stage C
Slika 30. Faza razvoja C



Figure 31 Development stage D
Slika 31. Faza razvoja D

implemented. Folding and sliding mechanisms were also added to allow for smooth transformation while reducing load on the structure during operation. Also, the placement of joints, hinges and connecting parts was adjusted to give it more flexibility, durability and make use easier but safer. The furniture structure at the later development stage C including upholstery support systems, reinforcement members and storage components is shown in Figure 30. Further structural changes were made not only to improve rigidity but also to ease the use and functionality. Reinforcement components were placed in critical load-bearing areas to reduce deformation and enhance structural performance at service loading situations. Ergonomic considerations such as seating posture, body support, and accessibility of storage compartments were also evaluated and integrated into the design.

Development Stage D, presented in Figure 31, represents the advanced assembly before finalizing the end form of the furniture. At this point, the structural frame, mechanisms, upholstery and storage systems were combined into a single multifunctional unit. Functional evaluation was carried out to determine transformation efficiency, operational convenience,

structural stability and aesthetic quality. The furniture was redesigned, including minor changes related to dimensional alignment and finishing details for better performance. The final outcome of the concept development process is presented in Figure 32; it shows the completed multifunctional upholstered furniture in bed position. The developed prototype demonstrates the successful integration of seating, storage and sleeping functions within a single furniture unit designed spe-



Figure 32 Developed multifunctional furniture in bed position
Slika 32. Razvijeni višenamjenski namještaj u funkciji kreveta

cifically for compact living environments such as university residence halls. The concept development process therefore validates the practicality of multifunctional furniture systems in improving space management, functional adaptability and user convenience within restricted residential spaces.

3.2 Test plan: Space availability

3.2. Plan ispitivanja: iskoristivost prostora

This is performed to compare the area occupied by three single-function furniture pieces (bed, chair and drawer) and the developed multifunctional furniture. The furniture items with single function are grouped in one space area, then researchers move on to measure the occupied area. Researchers then put the proposed invention at a different space and measure how much of the space it occupies. The data are then recorded for comparative analysis.

3.3 Test plan: Usability survey and feedback

3.3. Plan ispitivanja: anketa o upotrebljivosti i povratne informacije

The participants for this study included fourteen (14) users who were briefed on how to fill out a questionnaire consisting of variables such as ergonomic performance and space-saving effectiveness. The questionnaire items were based on constructs adapted from Davis (1989) and the items about space saving effectiveness were drawn from Husein (2020). For this study, a seven-point Likert scale was adopted as it is more precise, reliable and simple to use than other scales, and provides better reflection on the interviewee's true evaluation.

4 ANALYSIS PLAN

4. PLAN ANALIZE

The data generated were analysed by comparing the corresponding area occupied in case of single functional furniture with the area occupied in case of developed multifunctional furniture. IBM SPSS Statistics version 21 was used to analyse ergonomic performance and space saving effectiveness data, including descriptive, reliability, normality and Spearman's correlation analyses.

5 RESULTS AND DISCUSSION

5. REZULTATI I RASPRAVA

5.1 Results for space availability

5.1. Rezultati iskoristivosti prostora

The results for space availability are shown in Table 2, where the measures of a single-function furniture dimensions and the dimensions of developed multifunctional furniture (cm) are expressed as length $\times$ width $\times$ height ($L \times W \times H$). Storage space required for the single function furniture arrangement was (237 cm $\times$ 26 cm $\times$ 42 cm), which was larger compared to the storage space required for multifunctional furniture (182 cm $\times$ 26 cm $\times$ 29 cm).

5.2 Results for usability survey and feedback – Descriptive analysis

5.2. Rezultati ankete o upotrebljivosti i povratne informacije – deskriptivna analiza

Results presented in Table 3 revealed that most respondents were 21 to 25 years old (64.3 %), then between 18-20 years old (28.6 %) and lastly, only a small percentage came from ages of 26-30 years old (7.1 %). Results also showed that there was a higher percentage (64.3 %) of male respondents as compared to female gender (35.7 %). The participants (30.5 %) agreed that the proposed invention does a good job ergonomically but 59.7 % of them strongly agreed that the invention is ergonomic. Most of the respondents (81.4 %) indicated strongly agree and only 18.6 % indicated agree in response to functionality as space-saver furniture.

5.3 Reliability and normality analysis

5.3. Analiza pouzdanosti i normalnosti

The reliability of the instrument was evaluated using the Cronbach's alpha coefficient. Data from Table 4 indicted that the internal consistency of the survey instrument was acceptable ($\alpha > 0.6$) for all the variables.

According to Table 5, the distribution of the questionnaire data does not statistically significant differ from a normal distribution ($p > 0.05$), as evidenced by the Shapiro-Wilk and Kolmogorov-Smirnov tests of normality. The data were analysed with the Spearman's rank correlation test (non-parametric analysis). This

Table 2 Result on space availability
Tablica 2. Rezultati iskoristivosti prostora

	Item / Element	Length, width and height, cm Dužina, širina i visina, cm ($L \times W \times H$)
Single-function furniture, cm Jednofunkcijski namještaj, cm	Bed / krevet	190 $\times$ 90 $\times$ 50
	Chair / stolica	42 $\times$ 45 $\times$ 81
	Drawer / ladičar	35 $\times$ 40 $\times$ 55
	All items / svi elementi	267 $\times$ 90 $\times$ 81
Developed multifunctional furniture, cm Razvijeni višenamjenski namještaj, cm		182 $\times$ 26 $\times$ 29

Table 3 Participant demographics by age and gender (No. of Participants = 14)**Tablica 3.** Demografska obilježja ispitanika prema dobi i spolu (broj ispitanika: 14)

S/N Red. br.	Items Stavka	Level (with scale) Razina (skala)	No. of scores Frekvencija odgovora	Mean Srednja vrijednost	Standard deviation Standardna devijacija
1	Age dob	1: 18 – 20 years old	4 (28.6 %)	4.52	0.312
		2: 21 – 25 years old	9 (64.3 %)		
		3: 26 – 30 years old	1 (7.1 %)		
2	Gender spol	1: Male	9 (64.3 %)	2.70	0.467
		2: Female	5 (35.7 %)		
3	Ergonomic performance (11 items) <i>ergonomska svojstva</i> (11 stavki)	1: Strongly disagree	0	4.32	0.264
		2: Disagree	10 (6.5 %)		
		3: Somewhat disagree	5 (3.3 %)		
		4: Neutral	0		
		5: Somewhat agree	0		
		6: Agree	47 (30.5 %)		
		7: Strongly agree	92 (59.7 %)		
4	Space-saving effectiveness (5 items) <i>učinkovitost uštede prostora</i> (5 stavki)	1: Strongly disagree	0	3.81	0.401
		2: Disagree	0		
		3: Somewhat disagree	0		
		4: Neutral	0		
		5: Somewhat agree	0		
		6: Agree	13 (18.6 %)		
		7: Strongly agree	57 (81.4 %)		

Table 4 Cronbach's alpha values for survey instrument**Tablica 4.** Vrijednosti Cronbachova alfa-koeficijenta za anketni upitnik

S/N Red. br.	Variable / Varijabla	Cronbach's alpha (α) Cronbachov alfa-koeficijent (α)	No. of items Broj stavki
1	Ergonomic performance (EP) / <i>ergonomska svojstva</i>	0.721	11
2	Space-saving effectiveness (S) / <i>učinkovitost uštede prostora</i>	0.785	5

test measures the strength and direction of association between two ranked variables. The full distribution of Spearman's rho is derived for small samples and would be suitable for the survey data analysis of this study.

Based on Table 6, it was found that space-saving effectiveness strongly, positively and significantly correlated with ergonomic performance ($rs = 0.645$, $p < 0.05$).

5.4 Cost analysis

5.4. Analiza troškova

Table 7 shows the material costs needed to produce a unit of the developed multifunctional furniture, while

Table 8 indicates the cost price of each piece of furniture. The sales cost per unit was estimated at Nigeria Naira (₦) and it revealed that the total cost for the three single furniture units was about 52.3 % higher than the material cost for the developed multifunctional furniture.

5.5 Discussion

5.5. Rasprava

The developed multifunctional furniture requires considerably less space ($182 \times 26 \times 29$ cm) than classical single function furniture with dimensions of $267 \times 90 \times 81$ cm, which proves its usability in the confined

Table 5 Kolmogorov-Smirnov and Shapiro-Wilk tests of normality**Tablica 5.** Kolmogorov-Smirnovljev i Shapiro-Wilkov test normalnosti distribucije

Variables / Varijabla	Kolmogorov-Smirnov			Shapiro-Wilk		
	Statistic	df*	P	Statistic	df*	p
Ergonomic performance (EP) / <i>ergonomska svojstva</i>	0.311	13	0.200	0.737	13	0.289
Space-saving effectiveness (S) / <i>učinkovitost uštede prostora</i>	0.243	13	0.200	0.845	13	0.461

* df – Degree of freedom / stupnjevi slobode

Table 6 Correlation between space-saving effectiveness and ergonomic performance**Tablica 6.** Korelacija između učinkovitosti uštede prostora i ergonomske svojstava

Variable relationship / Odnos među varijablama	r_s^*	p
Space-saving effectiveness and ergonomic performance <i>učinkovitost uštede prostora i ergonomska svojstva</i>	0.654	0.011
N	14	

* r_s – Correlation coefficient for Spearman's test / Spearmanov koeficijent korelacije

Table 7 Sales cost of the material per unit of multifunctional furniture**Tablica 7.** Trošak materijala po jedinici proizvoda za višenamjenski namještaj

S/N Red. br.	Material / Materijal	Unit Jedinica	Price Cijena, ₦
1	Coconut wood <i>drvo kokosove palme</i>	1	82,250
2	½" Plywood <i>furnirska ploča, 12 mm</i>	2	46,300
3	Iron angle / <i>željezni okvir</i>	1	67,300
4	Hinges / <i>spojnice</i>	1	2,500
5	Washer / <i>podložne pločice</i>	5	1,200
6	Screws / <i>vijci</i>	5	2,700
7	Bolts and nuts / <i>vijci i matice</i>	6	4,150
8	Drawer runner <i>vodilice ladice</i>	1	7,000
9	Foam / <i>poliuretanska pjena</i>	1	62,100
10	Fabric / <i>tkanina</i>	1	31,200
11	Labour / <i>rad</i>		12,500
	Total / <i>ukupno</i>		319,450

Table 8 Sales cost of a single furniture**Tablica 8.** Prodajna cijena jednog komada namještaja

S/N Red. br.	Description / Opis	Unit Jedinica	Price Cijena, ₦
1	Bed / <i>krevet</i>	1	375,200
2	Chair / <i>stolica</i>	1	87,150
3	Drawer / <i>ladičar</i>	1	24,300
	Total / <i>ukupno</i>		486,650

space of a university hall of residence. By embedding transformation functions such as bed, chair and drawer into one body significantly improved its spatial efficiency and functional performance. Moreover, these pieces of furniture showed desirable traits including built-in storage space, aesthetic appeal and adaptability to answer the challenges that enable optimal use of the living space. Thus, doubtlessly these results underpin the claim of Cheng *et al.*, (2021) and Husein (2021) who suggested that multifunctional furniture is a practical solution for environments that are limited in space and financially oriented because users can increase utilisation without extra furniture. Likewise, Canepa (2017) and Rajan *et al.*, (2019) indicated that multifunctional furniture design is especially beneficial for users having limited budgets. The results of this study are also in line with previous research on multifunctional furniture design (Mazlan *et al.*, 2021; Pricillia and Mutiara, 2021), which identified storage integration, transformability and spatial compatibility as major performance indicators for compact living space.

The results indicated that enhancements of furniture space optimisations were associated with greater comfort, utility and more positive ergonomic assessments. The outcomes indicated that multifunctional

furniture designed to facilitate efficient spatial utilisation could improve convenience for users and functional operation in small living spaces at the same time. This observation supports the position of Estaji (2017) and Vlaovic *et al.*, (2022) who argue that sustainable and flexible interior spaces require furniture designs that provide multiple functionalities with spatial requirements adaptable to the changing demands. This finding is also in agreement with that of Mazlan *et al.* (2021) and Vlaovic *et al.*, (2022) who concluded that flexibility, adaptability and efficient spatial configuration were the most significant influencing factors of usability and ergonomic satisfaction in multifunctional furniture systems.

6 CONCLUSIONS

6. ZAKLJUČAK

The findings of this study demonstrated the successful development of multifunctional upholstered furniture integrating bed, chair and drawer functions from *Cocos nucifera* timber for use in space-constrained environments. The novelty of the study lies in the effective combination of multifunctionality, ergonomic suitability and space optimisation within a single furniture unit produced from coconut timber. The developed furniture exhibited satisfactory ergonomic compatibility and enhanced user comfort, confirming its suitability for a contemporary university hall of residence.

Acknowledgements – Zahvala

The authors wish to thank the Tertiary Education Trust Fund under its Institutional Based Research (IBR) intervention (EAUED/Y/R/DRMIP/IBR/IBR&ACA/VOL.1/20/97) for the financial support provided to carry out this research work.

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Investigation of Noise Exposure Levels in Furniture Industry: The Impact of Enterprise Scale and Machine Operational States

Istraživanje razina izloženosti buci u industriji namještaja: utjecaj veličine poduzeća i radnih stanja strojeva

ORIGINAL SCIENTIFIC PAPER

Izvorni znanstveni rad

Received – prispjelo: 5. 4. 2026.

Accepted – prihvaćeno: 29. 5. 2026.

UDK: 331.432.6; 684.4

<https://doi.org/10.5552/drind.2026.0348>

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ABSTRACT • *The furniture industry is characterized by the intensive use of cutting, shaping, and surface-treating machinery, which naturally generates high noise levels. This study aimed to assess noise exposure levels in furniture manufacturing facilities by examining the effects of enterprise scale, machine types, and working conditions (loaded and unloaded) on occupational health and safety (OHS). The study was conducted in a total of 30 enterprises, 10 at each enterprise scale level. Physical risk factor data for noise were recorded using on-site measurements for the machines and production lines used at each enterprise level, depending on various variables. ANOVA, T-test, and Correlation analyses were performed to determine the relationships between the variables. The results revealed that small-scale businesses were the riskiest group in terms of noise levels. Generally, although measured noise levels in workplaces remain below the highest exposure action value of 85 dB, critical levels have been detected under specific machinery and working conditions. In machine-based assessments, the critical machines exceeding the highest exposure value of 85 dB are: In small-scale businesses – planing machine (95.26 dB), circular saw (88.08 dB) and band saw (86.81 dB); in micro-scale businesses – CNC drilling machine (91.13 dB), CNC sizing machine (88.01 dB) and band saw (85.95 dB); and in medium-scale businesses – circular saw (85.24 dB). As a result of the study, it has been emphasized that long-term noise exposure poses a risk to employees' hearing health and that preventive measures are therefore mandatory.*

KEYWORDS: *noise pollution; furniture industry; machinery; occupational safety and health*

SAŽETAK • *Industriju namještaja obilježava intenzivna primjena strojeva za rezanje, oblikovanje i obradu površina drva, što posljedično uzrokuje visoke razine buke. Cilj ovog istraživanja bio je procijeniti razine izloženosti*

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buci u pogonima za proizvodnju namještaja ispitivanjem utjecaja veličine poduzeća, vrste strojeva i radnih uvjeta (pod opterećenjem i bez njega) na zaštitu na radu. Istraživanje je provedeno u ukupno 30 poduzeća, odnosno u deset poduzeća za svaku kategoriju veličine poduzeća. Podatci o fizičkim čimbenicima rizika od buke prikupljeni su mjerenjem u blizini strojeva i proizvodnih linija u poduzećima različitih veličina, ovisno o različitim varijablama. Za utvrđivanje odnosa između varijabli provedeni su ANOVA, t-test i korelacijska analiza. Rezultati su pokazali da su mikropoduzeća i mala poduzeća rizičnije skupine s obzirom na razinu buke. Općenito, iako su izmjerene razine buke na radnim mjestima ispod gornje granične vrijednosti izloženosti od 85 dB, kritične razine zabilježene su za specifične strojeve i radne uvjete. Procjenama pojedinih strojeva ustanovljeno je da su kritični strojevi koji prelaze gornju graničnu vrijednost izloženosti od 85 dB sljedeći: u malim poduzećima blanjalica (95,26 dB), kružna pila (88,08 dB) i tračna pila (86,81 dB); u mikropoduzećima CNC bušilica (91,13 dB), CNC raskrajač (88,01 dB) i tračna pila (85,95 dB) te u srednje velikim poduzećima kružna pila (85,24 dB). Kao rezultat istraživanja naglašeno je da dugotrajna izloženost buci nosi rizik od oštećenja sluha radnika te da su stoga preventivne mjere obvezne.

KLJUČNE RIJEČI: onečišćenje bukom; industrija namještaja; strojevi; zaštita na radu

1 INTRODUCTION

1. UVOD

The furniture manufacturing sector holds an important position in national economies in terms of economic growth and employment potential (Grzegorzewska, 2020). However, the sector also involves significant hazards that directly affect employee health due to physical risk factors present in the working environment (Turan and Yıldız Töre, 2021; Özdemir and Albayrak, 2024). Among these physical risk factors, noise stands out as one of the most common and critical occupational health and safety (OHS) problems in the furniture industry (Yaşar *et al.*, 2024). Particularly in furniture production facilities where cutting, drilling, shaping, and surface-processing machines are intensively used, high levels of noise threaten workers' hearing health, hinder communication, cause distraction, and indirectly increase the risk of occupational accidents (Beljo Lučić and Goglia, 1995; Hasan *et al.*, 2024).

Machines commonly used in furniture production processes – such as circular saws, milling machines, CNC units, sanding lines, air compressors, and various assembly machines – generate high noise levels due to their operating principles (Owoyemi *et al.*, 2016; Serin *et al.*, 2017). The level of noise emitted from these machines may vary depending on several factors, including machine type, maintenance condition, production line layout, the worker's proximity to the machine, and production intensity (Serin *et al.*, 2013; Dimou, 2014). Previous studies have shown that noise levels in carpentry lines and high-speed cutting machines often exceed 85 dB(A), and in some enterprises this level may rise to 95–100 dB(A) (Rathipe and Raphela, 2022), which indicates that legal limits are exceeded (MLSS, 2013). According to OHS regulations, exposure above 85 dB(A) requires employees to use hearing protection, while exposure above 87 dB obliges employers to implement technical and organizational improvements (Directive 2003/10/EC, 2003; MLSS, 2013; Official Gazette, 2013).

Noise is also known to affect more than just hearing health. Long-term exposure to high noise levels can lead to stress, sleep disorders, fatigue, decreased performance, concentration problems, and communication difficulties (Mehrotra *et al.*, 2024). Furthermore, noise can increase the likelihood of accidents by making it more difficult for workers to hear emergency warnings (Diviani *et al.*, 2019).

Across Türkiye, the distribution of enterprise scales in furniture manufacturing is as follows: 23,372 micro-scale enterprises (86 %), 3,238 small-scale enterprises (11 %), and 490 medium-scale enterprises (1.8 %). In terms of total employment in the sector, 32 % (62,859 workers) are employed in small-scale enterprises, 33 % (65,449 workers) in medium-scale enterprises, and 23 % (44,363 workers) in micro-scale enterprises (SSI, 2022).

This study aims to analyze noise, a physical risk factor, in the furniture industry, which, due to its small-scale business structure and location far from industrial zones, has a high risk of occupational accidents and diseases. Within this scope, the study identifies and compares noise levels among different sizes of businesses in the furniture sector, at varying levels of machinery and equipment, and in terms of operational activities. Based on the data obtained, improvement suggestions have been developed for different variables.

Studies on noise exposure in the furniture industry in the literature have generally focused either on specific machine types or on general operational data. However, this study differs from previous literature and the authors' past works by combining and analyzing the scale of the operation (micro, small, medium), machine operating conditions (loaded/unloaded), and measurement locations (operator location/environment) within the same dataset. This multivariate approach offers a unique contribution not only by identifying noise risk through measurement but also by holistically revealing how this risk interacts with the business structure and operational dynamics.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

This study aimed to examine noise pollution in furniture manufacturing firms operating in the central district of Bursa across different enterprise scales (small, medium, and large). The research was conducted as a field study in furniture production facilities. For this work, the enterprise scale classification of the Small and Medium Enterprises Development Organization (SMEDSA) for the year 2023, which is based on the number of employees, was adopted. Accordingly, companies with less than 10 employees are defined as micro-sized, companies with 10-50 employees are defined as small-sized, and companies with 50-250 employees are defined as medium-sized (SMEDSA, 2023).

To ensure reliable results in the variance analyses applied to the data obtained from this study, it was essential that sample sizes across groups were not significantly different. For this reason, a minimum of 10 enterprises per scale group (small, medium, and large) was targeted, and measurements were conducted in at least 30 enterprises in total. Enterprises were selected using a convenience sampling method based on their accessibility, availability, and ability to reflect industry activity.

Noise measurements were conducted using a digital sound level meter (brand: EXTECH, model: EN300-5). This device is an “Integrated Mean Field Sound Level Meter” conforming to IEC 61672-1 Class 2 standards. The measurement process was carried out in accordance with the device measurement sensitivity of 1.5 dB(A). The sound level meter is also capable of performing frequency analysis, allowing the frequency range of each decibel value to be determined.

Noise measurements of workers operating in indoor environments in furniture manufacturing enterprises were carried out using a digital sound level me-

ter, as illustrated in the noise measurement algorithm shown in Figure 1. In this study, the noise measurement device was calibrated to 104 dB(A) prior to measurements. Noise measurements were performed using A-weighting and slow response mode, at the workers’ ear level (160 cm). Measurements were conducted on workers operating different machines in each enterprise, with approximately 10 minutes of measurement duration and three repetitions per measurement. All measurements were taken during day shifts and while the facility was in active production.

Noise level measurements in the furniture manufacturing facility were conducted in accordance with the ‘Task-Based Measurement Strategy’ outlined in the ISO 9612 standard. To satisfy and exceed the minimum duration requirements specified by the standard, three independent measurement repetitions (samples) were recorded for each task, with each sampling period lasting 10 minutes. The measurements were converted to an eight-hour working period using Equation 1. Using Equation 2, the maximum allowable working durations for workers were calculated (Directive 2003/10/EC, 2003; Noise Regulation, 2003).

$$L_{ED,d} = L_{eq} + 10 \cdot \log(t/8)$$

$$L_{ED,d} = L_{eq} + 10 \cdot \log(0.5/8) \quad (1)$$

L_{eq} – noise level, t – measurement duration (hours).

$$L_{ED,d} = 10 \cdot \log_{10} \left(\frac{t_1 \cdot 10^{\frac{L_1}{10}}}{8} \right) \quad (2)$$

L_1 – noise level at time t_1 , t_1 – exposure duration, $L_{ED,d}$ – hazard limit.

The measurements to be conducted in the enterprises were evaluated within the scope of continuous noise exposure. Measurements were carried out along the furniture production line, primarily at the workers’ operating positions and movement routes, in a manner

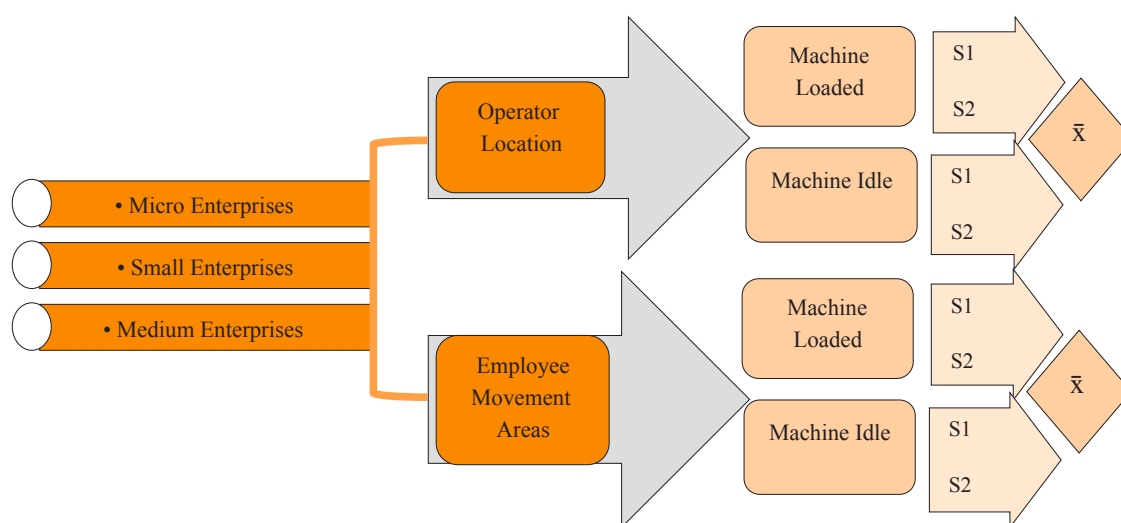


Figure 1 Noise measurement algorithm
Slika 1. Algoritam za mjerenje buke

that covered the entire working environment. The noise levels transmitted from the machines to the workers were compared among enterprises in accordance with the relevant regulations (ILO, 1993). The aim of these measurements was to determine the personal noise exposure of furniture industry workers.

Descriptive statistical values for the dust data were calculated, and summary tables and graphs were prepared for each enterprise and machine type. To determine whether there were statistically significant differences among dust measurement data from different enterprises and machines, variance analysis (ANOVA) was performed. The collected data were analyzed using statistical methods, and all analyses were conducted with the SPSS (Statistical Package for the Social Sciences) software, after which the results were interpreted.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

In the study, three different measurements were conducted for each variable in the enterprises within the measurement scope. The reliability (internal consistency) of the data obtained from the measurements was calculated using the Cronbach's Alpha Reliability Coefficient (α) as 0.716. The fact that the reliability coefficient satisfied the condition of $0.60 < \alpha < 0.80$ indicated that the data were reliable (Kalaycı, 2010; Yıldız and Uzunsakal, 2018). The Kolmogorov-Smirnov test was applied to the data, and it was determined that the data showed a normal distribution. Therefore, parametric tests were used in the analyses.

Data obtained from micro, small, and medium-sized enterprises where noise levels were measured were subjected to a general evaluation (using a One-Sample T-Test) according to the highest exposure ac-

tion value of 85 dB (Directive 2003/10/EC, 2003; MLSS, 2013; Official Gazette, 2013). The findings revealed that the measured values showed statistically significant differences ($p < 0.05$) from the determined limit value. It was determined that the average noise level in the businesses was 3.949 dB below the specified limit value (Table 1). In a general evaluation conducted in small and medium-sized furniture businesses, it was determined that the average noise level was below 85 dB (Yaşar *et al.*, 2024). However, another study reported that the highest exposure action value of 85 dB was exceeded in 70 % of the enterprises (Hasan *et al.*, 2024). The high noise risk in small-scale enterprises is driven by cumulative noise from closely spaced, older machinery, poor building acoustics, and low PPE compliance.

The results of the variance analysis showed statistically significant differences ($p < 0.05$) among the measured noise levels according to the enterprise scale variable (Table 2). This difference was found to be between small-scale and medium-scale enterprises. In a study conducted in the woodworking and furniture sector, it was reported that the development of OHS culture in small and medium-sized enterprises was insufficient (Komut *et al.*, 2023). In another study focusing on the furniture industry, it was determined that noise levels remained below the highest exposure action value 85 dB. (Taşdemir *et al.*, 2024). General assessments in the furniture sector indicate that OHS measures in the sector are insufficient (Yaşar and Komut, 2018; Taşdemir *et al.*, 2024).

The relationship between the measured average noise levels and enterprise scale and measurement location was examined through correlation analysis. The Pearson correlation coefficient was calculated as -0.110 for the business scale and -0.259 for the measurement

Table 1 One-sample *t*-test results for noise data

Tablica 1. Rezultati *t*-testa za podatke o buci

Enterprise scale <i>Veličina poduzeća</i>	<i>N</i>	Mean, dB <i>Srednja vrijednost, dB</i>	Standard deviation <i>Standardna devijacija</i>	<i>t</i>	Degrees of freedom <i>Stupnjevi slobode</i>	Mean differences <i>Razlike srednjih vrijednosti</i>	Sig. (2-tailed) <i>Značajnost (dvosmjerna)</i>
Whole / <i>sve veličine</i>	828	81.051	14.223	-7.990	827	-3.949	0.000*
Micro / <i>mikro</i>	148	82.062	9.236	-3.870	147	-2.938	0.000*
Small / <i>mala</i>	232	84.036	22.864	-0.643	231	-0.964	0.521
Medium / <i>srednja</i>	448	79.171	8.220	-15.009	447	-5.829	0.000*

* $p < 0.05$

Table 2 One-way ANOVA test results for noise data according to the enterprise scale variable

Tablica 2. Rezultati jednosmjernje analize varijance (ANOVA) za podatke o buci prema varijabli veličine poduzeća

Variation source <i>Izvor varijacije</i>	Sum of squares <i>Suma kvadrata</i>	Degrees of freedom <i>Stupnjevi slobode</i>	Mean of squares <i>Srednji kvadrat</i>	<i>F</i> -value <i>F-vrijednost</i>	Sig. (2-tailed) <i>Značajnost (dvosmjerna)</i>
Between groups / <i>među skupinama</i>	3800.909	2	1900.455	9.589	0.000*
Within groups / <i>unutar skupina</i>	163499.982	825	198.182		
Total / <i>ukupno</i>	167300.892	827			

* $p < 0.05$

Table 3 *T*-test results for noise data according to the measurement location variable**Tablica 3.** Rezultati *t*-testa za podatke o buci prema varijabli mjernog mjesta

Enterprise scale <i>Veličina poduzeća</i>	Location <i>Lokacija</i>	<i>N</i>	Mean, dB <i>Srednja vrijednost, dB</i>	Standard deviation <i>Standardna devijacija</i>	<i>F</i>	<i>t</i>	<i>df</i>	Mean differences <i>Razlike srednjih vrijednosti</i>	Sig. (2-tailed) <i>Značajnost (dvosmjerna)</i>
Whole <i>sve veličine</i>	Operator Position <i>položaj operatora</i>	414	84.734	17.880	5.214	7.710	826	7.366	0.000*
	Movement Area <i>područje kretanja</i>	414	77.368	7.628					
Micro <i>mikro</i>	Operator Position <i>položaj operatora</i>	74	83.184	9.319	0.593	1.484	146	2.245	0.140
	Movement Area <i>područje kretanja</i>	74	80.940	9.077					
Small <i>mala</i>	Operator Position <i>položaj operatora</i>	116	89.861	30.352	2.376	4.006	230	11.652	0.000*
	Movement Area <i>područje kretanja</i>	116	78.210	7.766					
Medium <i>srednja</i>	Operator Position <i>položaj operatora</i>	224	82.591	8.336	8.660	9.674	446	6.839	0.000*
	Movement Area <i>područje kretanja</i>	224	75.752	6.517					

* $p < 0.05$

location. In the analysis, the Sig. (2-tailed) value was calculated as 0.020 for the business scale and 0.000 for the measurement location. The results showed that the average measured noise level decreased as the enterprise scale increased.

Statistically significant differences were detected between the position where the machine operator controls the machine and the operator's movement area. For all three enterprise scale groups, the average noise level at the operator's position was 84.734 dB, approaching the limit value, whereas this value was determined as 77.368 dB in the operator's movement area (Table 3).

The difference in noise exposure observed between the operator's fixed position and the movement area is directly linked to workplace acoustics and expo-

sure dynamics. The operator's close proximity to the machine minimizes distance-induced sound attenuation, thereby elevating direct exposure.

Statistically significant differences were found in noise levels between the idle and loaded operating conditions of the machines. In all three plant sizes, the average noise level, which was 77.920 dB during idle operation, approached the limit value, reaching 84.182 dB when the machines were under load (Table 4). The significantly higher noise levels observed under operational loads compared to idle states are directly linked to technical process variables. The escalation of noise emissions under load is primarily driven by increased cutting and contact resistance between the cutting tool and the wood, alongside material type, density, and

Table 4 *T*-test results for noise data according to the machine operating status variable**Tablica 4.** Rezultati *t*-testa za podatke o buci prema varijabli radnog stanja stroja

Enterprise scale <i>Veličina poduzeća</i>	Location <i>Lokacija</i>	<i>N</i>	Mean, dB <i>Srednja vrijednost, dB</i>	Standard deviation <i>Standardna devijacija</i>	<i>F</i>	<i>t</i>	<i>df</i>	Mean differences <i>Razlike srednjih vrijednosti</i>	Sig. (2-tailed) <i>Značajnost (dvosmjerna)</i>
Whole <i>sve veličine</i>	Loaded <i>pod opterećenjem</i>	414	84.182	17.910	3.263	6.489	826	6.262	0.000*
	Idle / u praznom hodu	414	77.920	8.041					
Micro <i>mikro</i>	Loaded <i>pod opterećenjem</i>	74	84.251	9.280	0.009	2.959	146	4.379	0.004*
	Idle / u praznom hodu	74	79.873	8.715					
Small <i>mala</i>	Loaded <i>pod opterećenjem</i>	116	88.528	30.635	2.442	3.046	230	8.986	0.003*
	Idle / u praznom hodu	116	79.543	8.415					
Medium <i>srednja</i>	Loaded <i>pod opterećenjem</i>	224	81.908	8.178	1.968	7.464	446	5.473	0.000*
	Idle / u praznom hodu	224	76.435	7.316					

* $p < 0.05$

Table 5 One-way ANOVA test results for noise data according to the machine variable**Tablica 5.** Rezultati jednosmjernje analize varijance (ANOVA) za podatke o buci prema varijabli vrste stroja

Enterprise scale <i>Veličina poduzeća</i>	Variation source <i>Izvor varijacije</i>	Sum of squares <i>Suma kvadrata</i>	Degrees of freedom <i>Stupnjevi slobode</i>	Mean of squares <i>Srednji kvadrat</i>	F-value <i>F-vrijednost</i>	Sig. (2-tailed) <i>Značajnost (dvosmjerna)</i>
Micro <i>mikro</i>	Between groups <i>među skupinama</i>	4501.490	17	264.794	4.282	0.000*
	Within groups <i>unutar skupina</i>	8039.088	130	61.839		
	Total / <i>ukupno</i>	12540.578	147			
Small <i>mala</i>	Between groups <i>među skupinama</i>	9286.772	18	515.932	0.986	0.477
	Within groups <i>unutar skupina</i>	111467.633	213	523.322		
	Total / <i>ukupno</i>	120754.404	231			
Medium <i>srednja</i>	Between groups <i>među skupinama</i>	6579.111	37	177.814	3.086	0.000*
	Within groups <i>unutar skupina</i>	23625.889	410	57.624		
	Total / <i>ukupno</i>	30205.000	447			

* $p < 0.05$

tool wear. Additionally, the heightened motor load during processing, combined with aerodynamic and mechanical forces generated at high rotational speeds, provides the technical causal framework for these quantitative findings.

The results of the variance analysis regarding the machine variable for the noise levels observed in micro-scale enterprises revealed statistically significant differences ($p < 0.05$) in noise levels among the machines used in these enterprises. The results of the variance analysis regarding the machine variable for the noise levels observed in small-scale enterprises showed that there were no statistically significant differences ($p > 0.05$) among the machines used in these enterprises in terms of noise levels. It was determined that there were statistically significant differences in the measured noise levels among the machines used in medium-scale enterprises (Table 5).

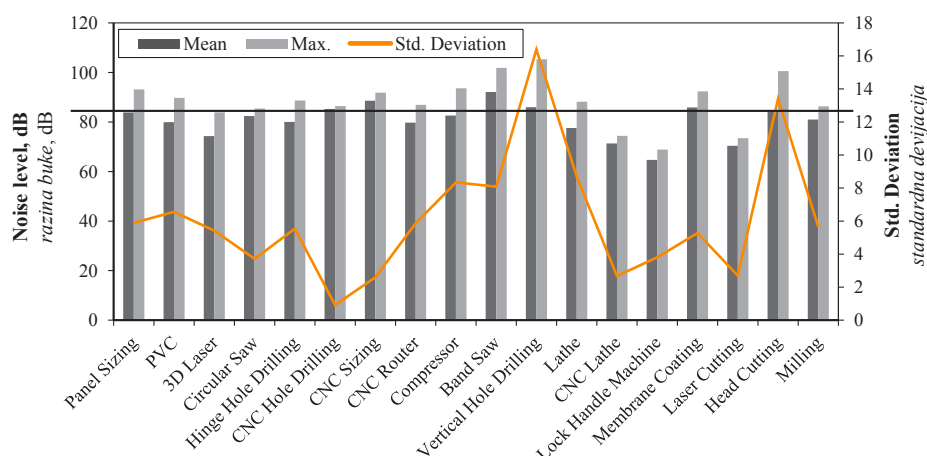
In micro-scale businesses where measurements were taken, the average noise levels of CNC drilling,

CNC sizing, band saw, vertical drilling, and membrane pressing machines were found to be above 85 dB. On the other hand, the measured maximum values of all machines except 3D laser, CNC lathe, door handle drilling, and laser cutting machines exceeded 85 dB (Figure 2).

The values related to the machine variable for noise levels in small-scale enterprises are presented in Figure 3. Accordingly, the machine with the highest average noise level was the planer machine, while the lowest value was measured in the fabric cutting machine.

The measurement values related to the machine variable for noise levels in medium-scale enterprises are presented in Figure 4. Accordingly, the machine with the highest average noise level was the circular saw machine, while the machine with the lowest measured value was the horizontal drilling machine.

Similarly, studies conducted in the forest products industry sector have reported that the noise levels of band saw machines, planer machines, and multi-rip machines exceed the legal limit value and that the sec-

**Figure 2** Measurement values at the machine level in micro-scale enterprises**Slika 2.** Izmjerene vrijednosti na razini strojeva u mikropoduzećima

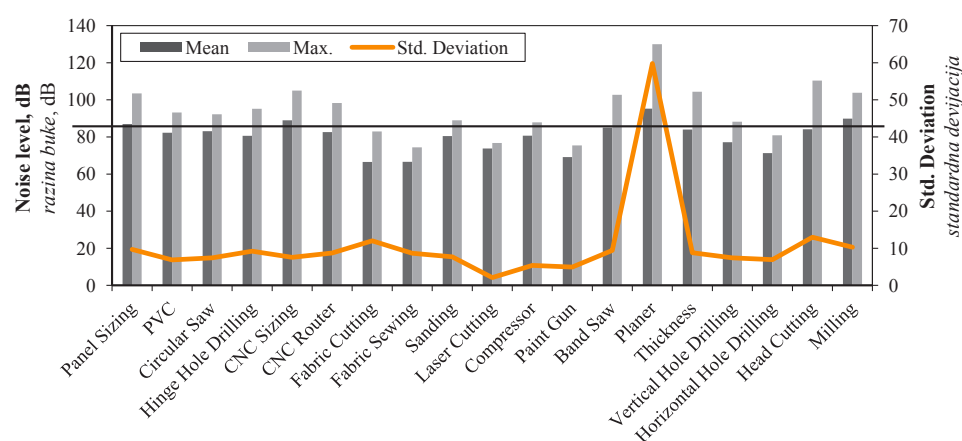


Figure 3 Measurement values at the machine level in small-scale enterprises

Slika 3. Izmjerene vrijednosti na razini strojeva u malim poduzećima

tor generally requires precaution in terms of workplace noise levels (Fidan *et al.*, 2020). On the other hand, in the furniture industry sector, it was measured that the miter cutting machine and the circular saw machine produce noise levels above the limit value (Yaşar *et al.*, 2024). Another study reported that the 85 dB highest exposure action value was exceeded especially in machines located in raw material and semi-finished material cutting and drilling lines in the furniture sector (Turan and Yıldız Töre, 2021; Özdemir and Albayrak, 2024). However, it has been observed that employee complaints continue even in cases where the noise limit value is not exceeded (Helmy and Dwi Sanrani, 2025). In the sector, circular saws, milling machines, CNC units, sanding lines, air compressors, and various assembly machines generate high noise levels due to their operating principles (Owoyemi *et al.*, 2016; Serin *et al.*, 2017). It is also reported that all machines used in wooden furniture production exceed the limit value (Hasan *et al.*, 2024). On the other hand, in workplaces where noise levels are measured below the limit value

in this sector, it has been reported that personal protective equipment should still be used due to instantaneous increases in noise levels (Corlan *et al.*, 2022).

Statistically significant differences were detected among production lines in medium-scale enterprises in terms of noise levels (Table 6).

In medium-scale enterprises, the highest noise level was detected in the carpentry line, whereas the lowest noise level was observed in the upholstery line (Table 7). Noise levels above the limit value have been reported in production lines where wood processing machines are predominantly used (carpentry workshops) (Hasan *et al.*, 2024). On the other hand, welding processes used in metal component production lines have also been reported to exceed the threat threshold for employee health (Özdemir and Albayrak, 2024).

The findings reveal the inadequacy of a purely PPE-focused approach to noise control and highlight the necessity of an occupational safety and health control hierarchy. Therefore, noise should be controlled primarily at the source (insulation, damping) and sec-

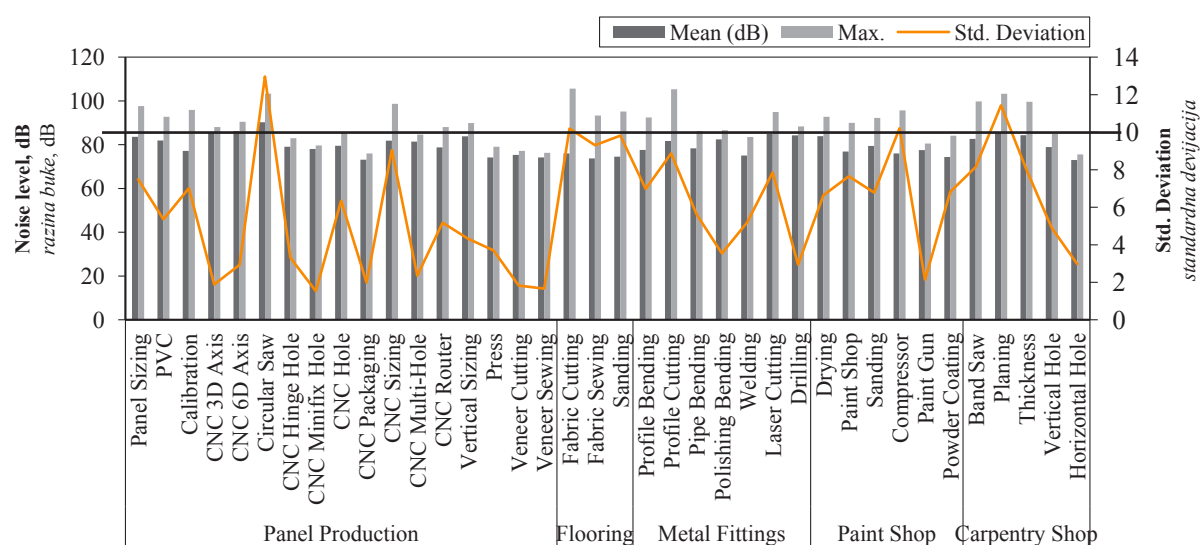


Figure 4 Measurement values at the machine level in medium-scale enterprises

Slika 4. Izmjerene vrijednosti na razini strojeva u srednje velikim poduzećima

Table 6 One-way ANOVA test results for noise data according to the production line variable in medium-scale enterprises
Tablica 6. Rezultati jednosmjerne analize varijance (ANOVA) za podatke o buci prema varijabli proizvodne linije u srednje velikim poduzećima

Variation source <i>Izvor varijacije</i>	Sum of squares <i>Suma kvadrata</i>	Degrees of freedom <i>Stupnjevi slobode</i>	Mean of squares <i>Srednji kvadrat</i>	F-value <i>F-vrijednost</i>	Sig. (2-tailed) <i>Značajnost (dvosmjerna)</i>
Between groups / među skupinama	2780.927	4	695.232	11.231	0.000*
Within groups / unutar skupina	27424.073	443	61.905		
Total / ukupno	30205.000	447			

* $p < 0.05$

Table 7 Descriptive statistics of measurements conducted according to the production line variable in medium-scale enterprises for noise data

Tablica 7. Deskriptivna statistika mjerenja provedenih prema varijabli proizvodne linije u srednje velikim poduzećima za podatke o buci

Production line <i>Proizvodna linija</i>	N	Mean, dB <i>Srednja vrijednost, dB</i>	Standard deviation <i>Standardna devijacija</i>	Std. Error <i>Standardna pogreška</i>	Min.	Max.
Panel production / linija pločastog namještaja	172	80.377	6.782	0.517	53.93	103.33
Upholstery line / linija za ojaštavanje	84	74.754	9.706	1.059	54.83	105.60
Metal parts / strojna obrada metala	64	79.302	6.927	0.866	64.20	105.30
Painting shop / lakirnica	68	78.183	7.765	0.942	50.73	95.70
Carpentry shop / stolarska radionica	60	82.878	8.904	1.150	55.30	103.30
Total / ukupno	448	79.171	8.220	0.388	50.73	105.60

only along its propagation path (acoustic panels, layout) through engineering measures; administrative measures and technically supported PPE applications should be used only as a last resort.

4 CONCLUSIONS

4. ZAKLJUČAK

This study comprehensively analyzed noise exposure in the furniture industry sector based on enterprise scale, machine type, and operational variables (loaded/idle operation and measurement location). The study utilized empirical data obtained from furniture enterprises operating at different enterprise scales.

This study has demonstrated that noise control strategies in the furniture industry cannot be uniform. Findings presented for the first time in this scope show that as the scale of the operation decreases, the impact of operational variables (such as load conditions) on noise exposure increases exponentially. This holistic analysis offers a new perspective to occupational safety and health professionals, enabling them to create risk maps not only based on machines but also related to the scale of the operation.

The findings confirmed an inverse relationship between enterprise scale and noise levels. As the scale of the enterprise increased, the average noise levels decreased. In particular, small-scale enterprises were found to have significantly higher noise risk compared to medium-scale enterprises. This situation can be associated with the more modern machinery infrastructure and better-structured OHS management systems in larger-scale facilities.

Although the overall average noise level across all enterprises remained below the highest exposure action value of 85 dB, machine-based analyses revealed that the risk exhibited a heterogeneous distribution. Especially in micro-scale enterprises, it was found that critical machines such as CNC drilling, CNC sizing, band sawing, and membrane pressing machines exceeded 85 dB. On the other hand, there was a statistically significant difference in noise emissions between machines operating under load and those operating idle. When machines operated under load, the average noise levels approached the limit value. Furthermore, the operator's fixed working position posed a significantly higher risk compared to the operator's movement area.

The finding that the highest risk in medium-scale enterprises occurred in carpentry production lines, while the lowest risk was observed in upholstery lines, indicates that sectoral improvement strategies should be developed specifically for different production departments.

Acknowledgements – Zahvala

This study is derived from a part of Erhan ÖZTÜRK's master's thesis titled "Examination of Certain Physical Risk Factors in the Furniture Manufacturing Sector at Different Enterprise Scale Levels: The Case of Bursa/TÜRKİYE", conducted in 2025 at the Graduate Education Institute, Department of Forest Industrial Engineering, Bursa Technical University. In addition, this study was supported as a scientific research project (Project Number: 240Y007) by Bursa Technical University, Bursa, 2025 (in Turkish).

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***1997: "Guide to Punctuation" (online), University of Sussex, www.informatics.sussex.ac.uk/departments/docs/punctuation/node00.html. First published 1997 (pristupljeno 27. siječnja 2010).

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Discussion and conclusion may, if desired by authors, be combined into one chapter. This text should interpret the results relating to the problem outlined in the introduction and to related observations by the author(s) or other researchers. Repeating the data already presented in the "Results" chapter should be avoided. Implications for further studies or application may be discussed. A conclusion shall be expressed separately if results and discussion are combined in the same chapter. Acknowledgements are presented at the end of the paper. Relevant literature shall be cited in the text according to the Harvard system ("name – year"), e.g. (Badun, 1965). In addition, the bibliography shall be listed at the end of the text in alphabetical order of the author's names, together with the title and full quotation of the bibliographical reference. The list of references shall be selective, and each reference shall have its DOI number (<http://www.doi.org>) (check at <http://www.crossref.org>):

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Example:

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Books:

Author's second name, initial(s) of the first name, year: Title. (ev. Publisher/editor): edition, (ev. volume). Place of publishing, publisher (ev. pages from – to).

Examples:

Krpan, J. 1970: Tehnologija furnira i ploča. Drugo izdanje. Zagreb: Tehnička knjiga.

Wilson, J.W.; Wellwood, R.W. 1965: Intra-increment chemical properties of certain western Canadian coniferous species. In: W. A. Cote, Jr. (Ed.): Cellular Ultrastructure of Woody Plants. Syracuse, N.Y., Syracuse Univ. Press, pp. 551-559.

Other publications (brochures, studies, etc.):

Müller, D. 1977: Beitrag zur Klassifizierung asiatischer Baumarten. Mitteilung der Bundesforschungsanstalt für Forst- und Holzwirtschaft Hamburg, Nr. 98. Hamburg: M. Wiederbusch.

Websites:

***1997: "Guide to Punctuation" (online), University of Sussex, www.informatics.sussex.ac.uk/departments/docs/punctuation/node00.html. First published 1997 (Accessed Jan. 27, 2010).

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