

Article

Laminated Veneer Lumber (LVL) from Hungarian Underutilized Hardwood Species

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Abstract

This study evaluated the potential of two abundant but underutilized hardwood resources in Hungary—Turkey oak (*Quercus cerris*) and grey poplar (*Populus canescens*)—for laminated veneer lumber (LVL) production. The widely used hybrid poplar (*Populus × euramericana* cv. I-214) was included as a reference. LVL panels were manufactured using rotary-cut veneers bonded with melamine urea formaldehyde (MUF) and phenol formaldehyde (PF) adhesives. Mechanical performance was assessed through bending strength (MOR), apparent modulus of elasticity (MOE_{app}), internal bond strength (IB), and density. Turkey oak exhibited high mechanical performance, with group mean MOR values ranging from 114.70 to 149.73 MPa and MOE_{app} values from 12.68 to 14.63 GPa, while PF-bonded panels generally showed improved mechanical and bonding performance. Grey poplar LVLs achieved group mean MOR values of 64.29–80.68 MPa and MOE_{app} values of 7.14–8.17 GPa. Hybrid poplar LVLs achieved group mean MOR values of 62.56–68.91 MPa and MOE_{app} values of 6.66–8.25 GPa. Group mean internal bond strength ranged from 0.59 to 1.02 MPa for poplar-based LVLs and from 1.21 to 1.94 MPa for Turkey oak LVLs. The findings provide preliminary evidence of the potential of Turkey oak and grey poplar for LVL production and provide a basis for further investigation.

Keywords: LVL; Turkey oak; poplar; MUF; PF; bending stiffness; bending strength; mechanical behaviour; low-value-added lumber

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1. Introduction

One of the major challenges of the 21st century is managing the various processes triggered by climate change, which affect Central Europe among other regions. These processes include changes in temperature and in the amount and distribution of precipitation, the appearance of new pests, and overall shifts in living conditions. Their impacts are already visible, such as the large-scale decline of pine and ash forests across Europe. In many cases, the adaptability of certain tree species is too slow relative to the pace of environmental change [1]. As a result, some native species are expected to disappear from certain areas, directly influencing the wood industry that relies on them. As climate zones shift northward, it becomes necessary to identify tree species from more southern regions that could be introduced into Central Europe [2].

In Europe, LVL production is traditionally based on softwood species [3], primarily Norway spruce and Scots pine. Norway spruce is especially favoured due to its excellent strength-to-weight ratio and low resin content, which is advantageous for manufacturing. Scots pine veneers have higher density, resulting in slightly improved mechanical properties in the final product. In North America, LVL manufacturers use a wider range of species, including Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), yellow poplar (*Liriodendron tulipifera*), and red maple (*Acer rubrum*) [3,4]. In Australia, LVL is produced from various pine species and eucalyptus, while in Japan it is manufactured from larch (*Larix kaempferi*, *Larix leptolepis*) and Japanese cedar (*Cedrus*). In China, LVL production and research have increasingly focused on the high-value utilization of fast-growing plantation resources, particularly poplar, with recent studies extending from material characterization and performance enhancement toward structural applications such as timber frames and trusses [5–7]. Ongoing research explores additional species that meet the required mechanical and bonding properties for LVL production [8]. The LVL manufacturing method successfully utilizes small-diameter logs and poorer-quality timber that would otherwise be deemed trash or crushed and used to produce lower-grade wood products such as fibreboards or particleboards [9].

In Europe, some LVL manufacturers have already introduced hardwood species such as beech and birch. Due to their higher density, hardwood-based LVL products exhibit superior mechanical performance; however, they require additional processing steps, such as pre-drilling for screw connections. Hardwood LVL products also show varying resistance to fungal decay, making proper species selection and surface treatment essential. Experimental studies are currently investigating oak, black locust, poplar, and mixed-species LVL to develop new, potentially underutilized hardwood-based products [10–12]. Research confirms that suitable LVL can be produced from hardwoods, provided that appropriate veneer-processing facilities are available. At present, market demand in Hungary is limited, and existing needs are largely met by softwood-based LVL. Moreover, the production and use of dense hardwood veneers pose additional challenges, particularly regarding fungal resistance; for example, beech-based LVL is primarily suitable for interior applications [13,14].

After the Second World War, the poplar stands (*Populus* spp.) in Hungary were established through several poplar planting programmes. Cultivation technologies suitable for domestic conditions were developed, along with hybrid poplar varieties optimized for local environments [15,16]. As low-density hardwoods, hybrid poplars have been used in a variety of products, including packaging materials (e.g., pallets, crates), plywood (e.g., for furniture), and fibre production [16]. Over the past decade, as forest-management priorities have been reassessed, harvesting of hybrid stands has begun, and renewed interest has emerged in planting native poplar species—white poplar, grey poplar, and trembling poplar (*Populus alba*, *Populus canescens*, and *Populus tremula*, respectively). These species are characterized by a density of 450–490 kg/m³, MOR of 52–62.5 MPa, compression strength parallel to the grain of 35.0–40.0 MPa, tensile strength of 77.0–83.3 MPa, and MOE of 7800–8000 MPa. Poplars are typically diffuse-porous species, with libriform fibres (comprising 56%–63% of the cross-section) that are 1.0–1.3 mm long, featuring large lumina and thin cell walls. Major defects and failures include knots, frost cracks, false heartwood, and very low decay resistance [17]. During processing—such as sawmilling—domestic poplar species often present issues such as cracking, twisting, and cupping. Because of these characteristics, native poplars, unlike hybrid poplars, have not been widely used for industrial applications.

Another underutilized species is Turkey oak. The native range of Turkey oak extends across southeastern Europe—including Turkey, Greece, Italy, and Albania—and into parts of western Asia with moderate climates. In Hungary, it is the most abundant oak

species, representing approximately 11.4% of the country's forested area [18]. Turkey oak wood has excellent strength properties: tensile strength ranges from 100 to 139 MPa, bending strength from 94 to 136 MPa, and compression strength from 44 to 71 MPa at 12% moisture content and air-dry conditions. Its density ranges from 570 to 850 kg/m³ when oven-dry and 1000 to 1100 kg/m³ when green, making it well suited for load-bearing construction applications [18]. In contrast to diffuse-porous poplar, Turkey oak has a heterogeneous ring-porous structure with large earlywood vessels. This anatomical structure results in more direction-dependent machining behaviour, with surface quality influenced by the cutting direction related to the grain and growth rings [19,20]. Turkey oak timber is widely used for beams, posts, and other structural elements due to its mechanical performance and reliability. Its attractive grain pattern also makes it popular in furniture production, where it can be easily stained and treated for enhanced appearance. In addition, Turkey oak is used in veneer production, contributing to the manufacture of plywood and laminated veneer lumber (LVL) panels [21]. Therefore, Turkey oak is a strong candidate for LVL production in Hungary due to its wide availability and favourable mechanical characteristics [17,21].

Poplar (*Populus* spp.) is a fast-growing deciduous species with strong potential for LVL manufacturing in Hungary due to its adaptability and favourable wood traits. Poplar trees typically have tall, straight stems and triangular serrated leaves. The I-214 hybrid (*Populus deltoides* × *Populus nigra*) is characterized by rapid growth and high productivity. Under favourable site conditions, I-214 plantations may reach a diameter at breast height (DBH) of approximately 28 cm and a height of 23 m by the age of 8 years, although growth rates depend strongly on site conditions, spacing, and silvicultural management [22]. For the production of high-quality veneer logs, rotation periods are approximately 12–25 years [15,17].

In Hungary, I-214 is widely planted in timber-oriented plantations, agroforestry systems, and environmental projects, valued for its high biomass productivity [16]. The I-214 hybrid exhibits typical poplar characteristics: light colour, straight grain, and uniform texture. With a density of 300–480 kg/m³, its mechanical properties at 12% moisture content include tensile strength of approximately 60 MPa, bending strength of approximately 70 MPa, and compression strength of approximately 40 MPa. Hybrid I-214 is used in construction, furniture making, papermaking, packaging, and bioenergy production. Its uniform structure makes it particularly suitable for veneer, plywood, and LVL products, improving overall quality and manufacturing efficiency [16,17].

Figure 1 presents the availability of the wood species. Grey poplar (*Populus canescens*) also holds significant potential for higher-value applications and was therefore included in the present study [23].

Recent studies by Réh, Sedliačik and coworkers have also demonstrated the potential of veneer-based engineered wood products, with particular emphasis on the effects of adhesive formulation and manufacturing conditions on their mechanical and bonding properties [24,25]. To investigate the effect of the applied adhesive type on LVL performance, two widely used adhesives were selected to evaluate their suitability for the manufacture of laminated veneer lumber (LVL): melamine–urea–formaldehyde (MUF) and phenol–formaldehyde (PF). These adhesives were chosen due to their extensive industrial application and their importance in the production of wood-based composites [26].

MUF adhesive is a thermosetting resin composed of melamine, urea, and formaldehyde, and is characterized by excellent bonding performance and good water resistance, depending on its melamine content. Its ability to form strong bonds between wood veneer layers makes it particularly suitable for LVL production. Moreover, MUF formulations can be adjusted to meet specific industrial requirements, such as curing rate and

formaldehyde emission levels, ensuring compatibility with a wide range of manufacturing processes [26].

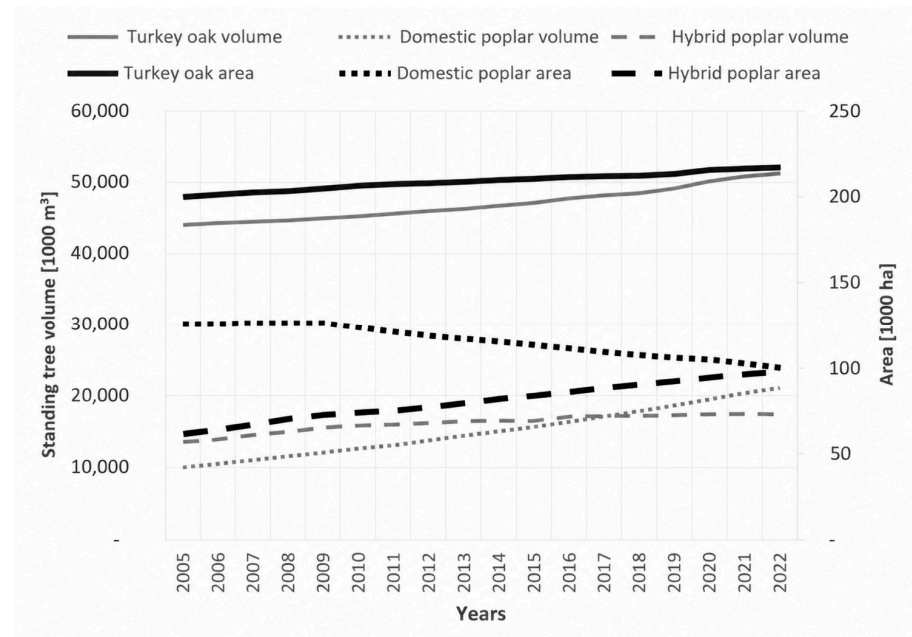


Figure 1. Volume of Turkey oak, domestic poplars and hybrid poplars in Hungary in the last two decades.

To ensure sustainable resource use, the future availability and industrial applicability of these wood species must be assessed. Several funded research projects are currently focused on characterizing their fundamental properties—including physical, chemical, anatomical, mechanical, and processing attributes—and on developing technologies and products capable of upgrading these raw materials into higher value-added forms. Our research groups are contributing to those research projects through fibre-based product development [27] and by exploring their suitability for laminated strand lumber (LSL) production [18,28].

Therefore, the main objective of our experimental comparative study series is to evaluate the suitability of underutilized Hungarian hardwood species for LVL production by assessing the effects of wood species and adhesive type on the selected mechanical performance of the manufactured panels. Selected experimental series included in this study were previously reported separately in student theses [29–32], while preliminary results of the joint study were presented at the 12th Hardwood Conference [33], which was related to this special edition.

2. Materials and Methods

2.1. Materials—Wood

Three wood species were investigated: Turkey oak (*Quercus cerris*), grey poplar (*Populus canescens*), and I-214 hybrid poplar (*Populus × euramericana* cv. I-214). Logs of the investigated species were supplied by NEFAG Zrt. (Nagykunság Forestry and Wood Industry Co., Szolnok, Hungary). Veneers were produced from the logs by rotary peeling at Bek-Holz Ltd. (Újkígyós, Hungary). The radial position of individual veneers within the logs was not recorded. Therefore, no distinction between juvenile and mature wood was made during panel manufacturing. Veneers of Turkey oak, I-214 poplar and grey poplar were trimmed using a circular saw to dimensions of approximately 400 × 420 mm. The veneer thickness

and average moisture content were 1.6 mm and 4% for Turkey oak, and 2.8 mm and 5% for the poplars, respectively. The difference in veneer thickness is attributable to the markedly different characteristics of the two wood species. Turkey oak is a dense and high-strength hardwood, whereas poplar is a low-density hardwood with a less compact anatomical structure. Consequently, Turkey oak cannot be rotary peeled to the same veneer thickness as poplar while maintaining acceptable veneer quality. Since the intended application was LVL production, relatively thick veneers were preferred. For Turkey oak, the selected thickness represented the maximum veneer thickness that could be reliably produced by the industrial partner while maintaining suitable quality. All the veneers were dried in a Memmert UFB 400 drying oven (Memmert GmbH + Co. KG, Schabach, Germany) for 4 h at 60 °C. The final moisture content was 4.8%. No additional grading or systematic removal of natural defects was performed prior to LVL manufacturing.

2.2. Materials—Adhesives and Other Chemicals

The MUF adhesive used in this study had a dry matter content of 66% and was supplied by Kronospan-MOFA Hungary Ltd. An ammonium nitrate catalyst with a concentration of 35% was applied in combination with the MUF resin; both materials were provided by Kronospan-MOFA Hungary Ltd. (Mohács, Hungary).

Phenol–formaldehyde (PF) resin is particularly well suited for structural applications due to its well-established performance characteristics. It exhibits high mechanical strength under both dry and wet conditions. In its liquid form, PF resin requires hot pressing, resulting in relatively short curing times of only a few minutes. Furthermore, PF resins demonstrate excellent resistance to heat, moisture, steam, and chemical degradation, often exceeding the durability of wood itself, which makes them especially suitable for exterior and load-bearing wood-based products [34,35]. The PF adhesive used in this study had a dry matter content of 49% and was supplied by KremsChem Austria GmbH (Krems, Austria). The main technical information on the adhesives used is presented in Table 1. Information about the pot life of the adhesive system was not available and is therefore not reported.

Table 1. Technical specifications of the adhesives used in LVL manufacturing.

Component	Density [g/cm ³]	Solid Content [%]	Viscosity (mP·s at 20 °C)	Adhesive Composition	Mixing Ratio
PF resin	1.21	48–49	280–400	PF resin	Single component
MUF resin	1.27–1.33	66	300–650	MUF resin + hardener	Resin: hardener = 100:2 (by mass)
Hardener for MUF (ammonium nitrate-based)	N.A.	35	N.A.	N.A.	N.A.

2.3. Methods—Experimental Panel Production

All experimental LVL panels were fabricated with parallel grain orientation. The adhesive was manually applied to one side of the veneers and evenly distributed using a putty knife. LVL panels with a target thickness of 16 mm were designed; therefore, 11 layers of 1.6 mm thick oak veneers and 6 layers of 2.8 mm thick grey poplar and I-214 poplar veneers were used. The glued veneer assemblies were placed between steel protective plates, and the final thickness was controlled using 16 mm thick steel spacer bars (Figure 2). Two independently manufactured LVL panels were produced for each material configuration.

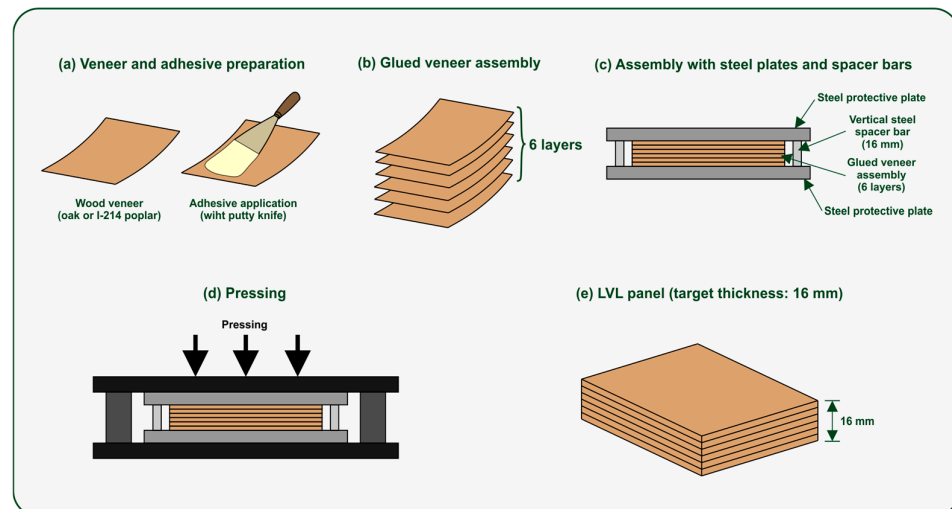


Figure 2. Panel production in laboratory conditions.

According to Németh et al. [8], an adhesive spread of 70 g/m² (based on dry matter content) was applied between each layer; however, due to the higher absorbency and surface roughness of poplar, a spread rate of 80 g/m² was determined to be sufficient to ensure complete surface coverage without over-penetration. For measuring the necessary amount of adhesive, a KERN GAB 12K0.1 laboratory scale (KERN & SOHN GmbH, Balingen, Germany) was used.

In the case of the MUF adhesive, 2% ammonium nitrate catalyst (based on dry matter content) was used.

Hot pressing was carried out at 140 °C in two steps: the initial high-pressure stage lasted for ~40% of the total pressing time at a specific pressure of 3.8 MPa, followed by a reduced pressure of 0.8 MPa for the remaining pressing period. For the 6-layer panels, the total pressing time was 13 min, consisting of 5 and 8 min for the first and second stages, respectively. For the 11-layer panels, the total pressing time was 18 min, divided into 6 and 12 min for the respective stages. The pressing times were calculated using an empirical formula [35]:

$$Z = f + \left(\frac{d}{2}\right) \quad (1)$$

where

Z = press time,

f = number of adhesive layers,

d = nominal thickness of the panelboard.

The nominal thickness was ensured by two square steel spacers with a thickness of 16 mm. For board production, a Siempelkamp Laborpresse laboratory hot press was used (G. Siempelkamp GmbH & Co. KG, Krefeld, Germany). Table 2 presents the marking and pressing parameters of different LVL products.

Table 2. Experimental LVL panel configurations and manufacturing parameters.

Species	Adhesive	Marking	Veneers	Pressure 1.stage/2.stage ¹ [MPa]	Time 1.stage/2.stage ¹ [min]
I-214 poplar	MUF	IP-MUF	6-layer	3.8/0.8	5/8
I-214 poplar	PF	IP-PF			
Grey poplar	MUF	GP-MUF	6-layer	3.8/0.8	5/8
Grey poplar	PF	GP-PF			

Turkey oak	MUF	TO-MUF	11-layer	3.8/0.8	6/12
Turkey oak	PF	TO-PF			

¹: Stage 1 and Stage 2 refer to the first and second consecutive phases of the pressing cycle.

2.4. Methods—Testing

The produced panels were evaluated by determining bending strength and modulus of elasticity based on the general testing procedure of EN 310:1999, internal bond strength (according to EN 319:1998), density (according to EN 323), and moisture content (EN 322) for veneers. Due to the dimensions of the experimental LVL panels, deviations from the standard specimen sizes were necessary for the determination of bending properties.

The bending test specimens had the following dimensions and were therefore cut with a square cross-section: 16 mm in thickness and 16 mm in width for both flatwise (veneers horizontally) and edgewise testing (veneers vertically). The length of all specimens was 220 mm, and the support span was 200 mm (Figure 3).

Multiple bending test specimens were obtained from the manufactured panels. However, panel identification was not retained for the individual specimens during specimen preparation and testing. Consequently, the specimens reported in the results cannot be retrospectively assigned to the individual panels, and the allocation of flatwise and edgewise specimens between the two panels cannot be reconstructed.

The span-to-thickness ratio is 12.5 therefore it differs from the standard specimen geometry prescribed in EN 310. Thus, the test is not fully compliant with EN 310. The modulus calculated from the load-deflection relationship is reported herein as the apparent bending modulus MOE_{app} . Owing to the relatively low span-to-thickness ratio, the measured midspan displacement contains a greater contribution from shear deformation than would occur using the standard EN 310 span. Regarding bending strength, the relatively low span-to-thickness ratio increases the contribution of shear stresses, which may influence the measured MOR as well. Bending tests were carried out both parallel and perpendicular to the plane of the panel.



Figure 3. Edgewise bending test of an I-214 poplar test piece with PF adhesive.

Bending properties were determined using an Instron IN5566s universal testing machine (Instron Corporation, Norwood, MA, USA). The density of the experimental panels was also determined using the same specimens. Internal bond strength (tensile strength perpendicular to the plane of the board) was measured on 50 × 50 mm specimens in accordance with the relevant standards. The measurements were carried out using a Bizerba SL 2100 M precision balance (Bizerba SE & Co. KG, Balingen, Germany), a Mitutoyo calliper, and a Mitutoyo micrometre (Mitutoyo, Corporation, Kawasaki, Japan).

Due to the lack of specimen-level panel identification, the results were analyzed descriptively at the specimen level, and the comparisons between the investigated configurations should be regarded as exploratory. Data processing, descriptive statistical analysis, and graphical visualization were performed using Python (version 3.14.2), with the pandas (version 2.3.3) and Matplotlib (version 3.10.8) packages. The study was treated as exploratory and descriptive, and no inferential statistical analysis was performed. Parts of the experimental dataset were previously reported in student theses [29–32], which addressed individual material configurations separately. The present study combines these experimental series for joint comparative evaluation. The complete dataset and its integrated analysis have not previously been published as a full research article. The MOR and MOE_{app} values are used in this study for comparative evaluation of the investigated experimental configurations and should not be interpreted as demonstrating compliance with structural design requirements.

3. Results and Discussion

Table 3 presents the mean and coefficients of variation in values for bending strength, modulus of elasticity, and density.

Table 3. Results of bending tests of the experimental LVLs made from different wood species.

Species	Adhesive	Orientation	N [pcs]	MOR [MPa]		MOE _{app} [MPa]		Density [kg/m ³]	
				Mean	CoV (%)	Mean	CoV (%)	Mean	CoV (%)
GP	MUF	horizontal	5	80.68	10.8	8168.93	5.8	512.9	1.7
GP	MUF	vertical	5	77.17	9.2	8069.63	3.4	517.6	2.1
GP	PF	horizontal	6	66.37	15.9	7409.87	19.8	505.1	5.8
GP	PF	vertical	6	64.29	11.9	7139.68	8.4	501.7	4.1
I-214	MUF	horizontal	6	68.91	16.1	8254.33	7.6	458.7	3.9
I-214	MUF	vertical	6	63.80	6.8	7919.06	4.7	456.5	2.1
I-214	PF	horizontal	6	62.56	16.9	6655.31	12.7	473.5	1.2
I-214	PF	vertical	6	64.63	11.1	6937.81	6.6	465.9	3.0
TO	MUF	horizontal	6	118.39	2.9	14,022.5	2.3	798.3	0.6
TO	MUF	vertical	8	114.70	3.6	12,680.46	3.0	706.8	1.6
TO	PF	horizontal	6	149.73	5.6	14,629.07	1.9	855.4	1.1
TO	PF	vertical	6	136.30	8.2	13,138.47	3.8	855.0	0.4

The bending properties, including MOR and MOE_{app}, are presented in Figures 4 and 5, respectively. The boxplots show the distribution and descriptive statistics of the measured values of MOR and MOE_{app} for I-214 poplar, grey poplar, and Turkey oak samples produced with MUF and PF adhesives, under both vertical and horizontal loading conditions.

All investigated LVL configurations exhibited mean MOR values above 60 MPa. I-214 poplar LVL demonstrated MOR values between 62 and 69 MPa, indicating adequate mechanical performance despite its relatively low density (Figure 4). Grey poplar (GP) showed further improvement, particularly with MUF adhesive, reaching values up to approximately 81 MPa. The highest MOR values were observed in Turkey oak specimens, with TO-MUF reaching up to 123 MPa and TO-PF achieving 150 MPa. These values demonstrate the high bending strength potential of Turkey oak LVL, highlighting the potential of high-density hardwood species.

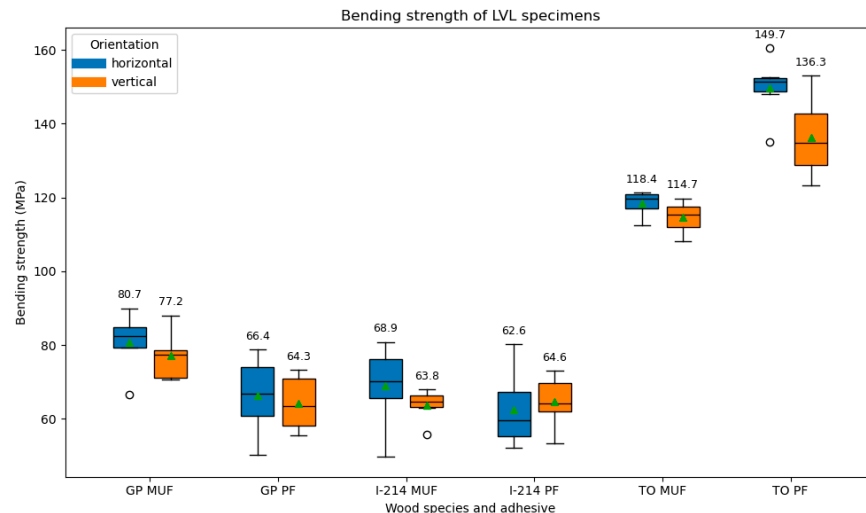


Figure 4. Bending strength of the experimental LVLs (horizontal—flatwise, vertical—edgewise).

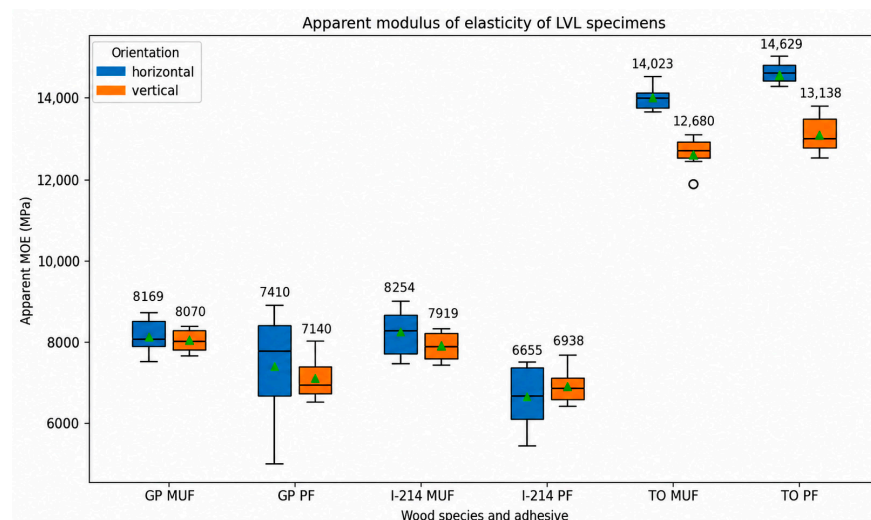


Figure 5. Apparent modulus of elasticity of the experimental LVLs (horizontal—flatwise, vertical—edgewise).

In contrast to MOR, stiffness values revealed a clear limitation for poplar-based materials (Figure 5). Both I-214 poplar and GP exhibited MOE_{app} values in the range of 6.5–8.2 GPa

Turkey oak LVL performed better, particularly when bonded with PF adhesive. The TO-PF variant reached MOE_{app} values up to 14.6 GPa; TO-MUF also showed high stiffness (~12.5 GPa).

As Table 4 and Figure 6 shows, internal bond strength was influenced by both wood species and adhesive type. PF adhesive consistently resulted in higher IB values compared to MUF across all species. I-214 poplar specimens bonded with MUF exhibited the lowest IB (0.59 MPa), whereas PF improved this value to 0.94 MPa. Grey poplar showed moderate to good bonding performance (0.95–1.02 MPa), while Turkey oak exhibited the highest IB values, reaching 1.94 MPa with PF adhesive. Within the investigated materials, the higher-density Turkey oak combined with PF adhesive exhibited the highest bonding performance. However, the better bonding performance of PF LVL should be interpreted cautiously because of the limited number of specimens and the lack of the failure mode information, and the lack of wet-bond or durability testing.

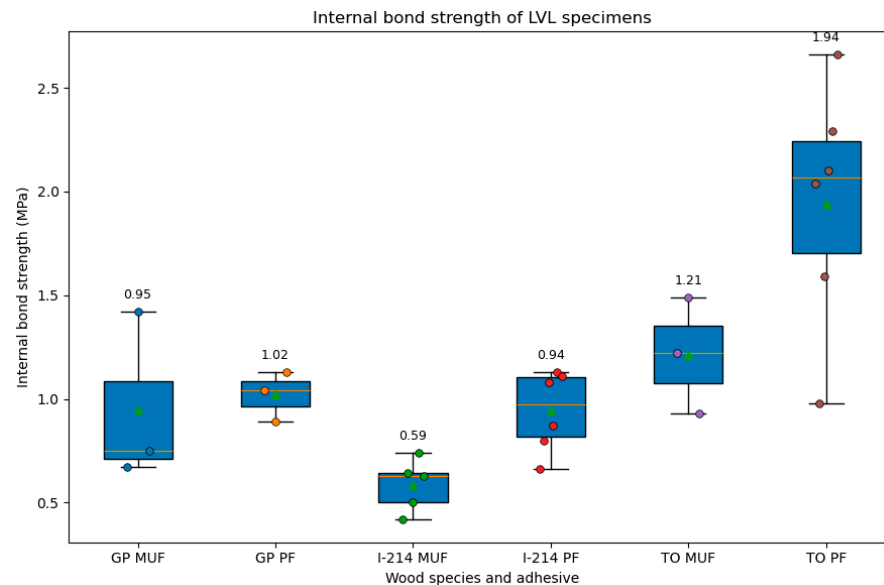


Figure 6. Internal bond strength of the experimental LVLs.

Table 4. Results of internal bond (IB) strength tests of the experimental LVLs made from different wood species.

Species	Adhesive	N [pcs]	Internal Bond (IB) Strength	
			Mean [MPa]	CoV [%]
GP	MUF	3	0.95	43.5
GP	PF	3	1.02	11.9
I-214	MUF	5	0.59	21.5
I-214	PF	6	0.94	20.6
TO	MUF	3	1.21	23.1
TO	PF	6	1.94	30.2

I-214 poplar exhibited the lowest density, with mean values ranging from 458.7 to 473.5 kg/m³ across the test sets. Grey poplar was slightly denser, with mean values ranging from 502 to 518 kg/m³. Turkey oak exhibited the highest density, with mean values ranging from 706.8 to 855.4 kg/m³.

Differences in density were observed between the TO-MUF flatwise and edgewise specimen groups. Therefore, differences in bending properties between these groups should be interpreted carefully, as the potential contribution of density cannot be separated from that of testing orientation. The choice of adhesives had an effect on bond strength and a moderate influence on mechanical properties. PF adhesive yielded higher internal bond strength and improved stiffness (especially in hardwoods). Although MUF occasionally resulted in slightly higher MOR for certain poplar and grey poplar configurations, its lower bonding performance should be investigated further. Despite their widespread industrial use and established performance, MUF and PF adhesives raise environmental and health concerns due to potential formaldehyde emissions. Therefore, lower emissions of formaldehyde-free adhesive alternatives should be considered in future LVL research.

Although both wood species and adhesive type influenced the results, the observed differences reflect the investigated LVL manufacturing configuration rather than the independent effects of wood species or adhesive type. Furthermore, due to non-standard span-to-thickness ratio used in the three-point bending tests, the reported apparent MOE_{app} and MOR values should be interpreted as comparative measures among the

investigated LVL configurations rather than as directly comparable structural design properties. A further limitation of the present experimental design is that the individual veneers were not nondestructively characterized prior to panel manufacturing. Such pre-characterization could enable a more balanced allocation of veneers among experimental groups and reduce variability associated with the inherent heterogeneity of wood.

4. Conclusions

The results of our exploratory study indicate differences in mechanical and bonding performance among the LVL configurations investigated. However, the effects of wood species cannot be separated from the associated differences in veneer geometry and manufacturing parameters.

Among the tested combinations, Turkey oak with PF adhesive showed the most promising overall performance, with high bending strength, stiffness and internal bond strength. These results indicate that Turkey oak, an underutilized hardwood species, has potential as a raw material for LVL and warrants further investigation for LVL production. The poplar-based LVL variants exhibited lower stiffness, which may limit their direct application in stiffness-critical load-bearing structures.

Overall, the study indicates the potential of locally available underutilized hardwood species for LVL production. However, the current evidence does not allow definitive conclusions regarding isolated species effects, compliance with structural requirements, or general suitability for load-bearing applications. The findings serve as a basis for the further development of resource-efficient LVL through appropriate species and adhesive selection, while future research should focus on optimized lay-ups, hybrid configurations, and structural validation.

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Data Availability Statement: Experimental data for individual specimens are available upon request from József Garab at garab.jozsef@uni-sopron.hu.

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