Laminated Wood Material Reinforced with Bacterial Cellulose (Kombucha SCOBY) Part 2: Selected Mechanical Properties

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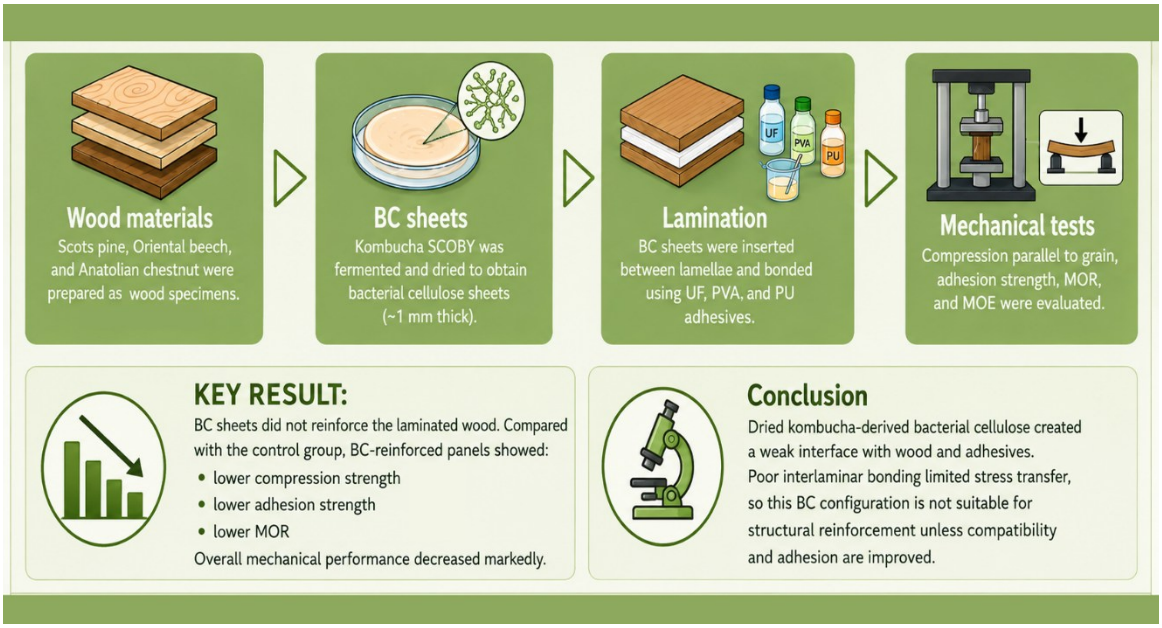
GRAPHICAL ABSTRACT



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Kombucha pellicles (Kombucha microbial culture) were evaluated as a source of bacterial cellulose to use in the production of laminated wood material. The goal was to improve the mechanical properties. The Kombucha pellicles were produced at room temperature over an eight-week fermentation period, after which bacterial cellulose sheets approximately 1 mm thick were obtained by drying. These sheets were used in the production of laminated wood material together with Scots pine (*Pinus sylvestris* L.), Oriental beech (*Fagus orientalis* L.), and Anatolian chestnut (*Castanea sativa* Mill.) wood species, utilizing urea formaldehyde, polyurethane, and polyvinyl acetate adhesives. To evaluate the mechanical properties, the following tests were applied: compressive strength parallel to the grain, adhesive strength, bending strength, and modulus of elasticity in bending. The findings revealed that although bacterial cellulose displayed a mechanically strong structure, overall mechanical performance did not reach the desired level due to insufficient adhesion between lamina layers. The results indicated that further research is needed to improve structural compatibility and adhesion mechanisms for the use of this material in advanced mechanical applications.

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Keywords: Bacterial cellulose; Mechanical properties; Kombucha pellicle; Lamination; Sustainable materials

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INTRODUCTION

Wood is a renewable biomaterial that is abundant in nature, energy-efficient to process, and aesthetically appealing; furthermore, when combined with appropriate engineering approaches, it is capable of providing high mechanical performance (Budakçı *et al.* 2016; Korkmaz *et al.* 2025). Due to these qualities, wood has been utilized for centuries, particularly in structural applications such as load-bearing systems, flooring, roofing, and façade cladding (Kılınç *et al.* 2023; Küçüktüvek *et al.* 2023). However, as wood is a natural polymer composite, it inevitably has certain structural heterogeneities and defects. Factors, such as growth rings, variations in fiber orientation (anisotropy), knots, resin pockets, and reaction wood, complicate its mechanical behavior, rendering its performance under tension, compression, and bending loads relatively unpredictable (Fu *et al.* 2021; Grottesi and Coelho 2023). For instance, knots induce stress concentrations that diminish material strength, while the anisotropic nature results in significant discrepancies between strength and elasticity values measured parallel and perpendicular to the grain. Consequently, overcoming these limitations to fully realize the potential of wood as a structural material depends on enhancing the reliability of its mechanical properties, which remains a critical area of research.

One of the most significant engineering solutions developed to mitigate the impact of these natural defects and optimize mechanical performance is laminated wood technology (Keskin and Togay 2003; Çiftçi *et al.* 2024). This technology relies on bonding relatively thin wood layers—such as lamellae or veneers—under pressure using high-performance adhesives, with their grain orientations typically arranged parallel to one another. The lamination process enhances the overall homogeneity and mechanical resistance of the material by distributing the influence of natural defects inherent in solid wood, such as knots, across different layers and reinforcing weak zones (Gáborík *et al.* 2016; Ngadianto *et al.* 2023).

Furthermore, by engineering the quality and arrangement of the lamellae, it is possible to manufacture structural elements with optimized mechanical properties—such as modulus of rupture (MOR), tensile strength, compressive strength, and modulus of elasticity (MOE) tailored for specific loading conditions (Wu *et al.* 2023). To further enhance the mechanical capacity of laminated wood, reinforcement with high-strength synthetic composites, including glass fiber reinforced polymer (GFRP), carbon fiber reinforced polymer (CFRP), and aramid fiber reinforced polymer (AFRP), is frequently employed in critical stress zones (Borri *et al.* 2005; Yahyaei-Moayyed and Taheri 2011; Wei *et al.* 2013). While these hybrid systems offer superior mechanical performance, the high energy consumption associated with synthetic polymer production, coupled with recyclability challenges and environmental sustainability concerns, is driving researchers to seek more ecological and bio-based reinforcement alternatives (Dicker *et al.* 2014; Başeğmez 2025).

Biopolymers derived from renewable sources, which promise superior mechanical properties, have gained significant attention in recent years as eco-friendly reinforcement elements for composite materials (Ladero *et al.* 2017). Among these biopolymers, bacterial cellulose (BC) stands out due to its unique morphology and exceptional mechanical characteristics. Bacterial cellulose is synthesized extracellularly by certain bacterial species—such as those belonging to the genus *Gluconacetobacter*—through the fermentation of simple sugars such as glucose. It has a complex three-dimensional network structure. This network consists of ultra-fine cellulose fibrils with nanometer-scale diameters (20 to 100 nm) and a high aspect ratio (Tabarsa *et al.* 2017; Hervy *et al.* 2018). Such a fibrous architecture provides BC with a remarkable combination of properties, including a very high degree of crystallinity, a significantly higher Young's modulus compared to plant-based cellulose, high tensile strength, low density, and complete biodegradability (Chen *et al.* 2021). Furthermore, BC sheets, which can be produced through kombucha culture fermentation, represent a promising resource for potential applications of this material. However, it should be noted that the economic feasibility and sustainability of BC production depend on process optimization and the use of alternative low-cost substrates, and therefore require further investigation. In particular, the long time period for development of the cultured fiber mats appears to pose a barrier to industrial scale-up.

Previous studies have demonstrated that the integration of bacterial cellulose into various polymer matrices—both synthetic and bio-based—can result in composites with significantly enhanced mechanical properties (Mbituyimana *et al.* 2021; Li *et al.* 2022). For instance, even low concentrations of BC added to matrices, such as epoxy or polylactic acid, can increase tensile strength, flexural strength, and toughness (Chiciudean 2011). Furthermore, it has been reported that BC layers applied to the surface of wood veneers lead to substantial increases in both tensile strength and modulus of elasticity (Ananto *et* *al.* 2021). These findings suggest that BC possesses significant potential within laminated wood structures, either as an intermediate layer in the bond line or by being integrated directly onto the lamella surfaces. Such integration can improve stress transfer and prevent crack propagation, thereby increasing the load-bearing capacity and overall mechanical resistance of the final composite, facilitated by the ability of BC's nano-fibrillar structure to form a robust interface with wood cell walls.

Considering this information, the present study investigated the feasibility of utilizing bacterial cellulose layers derived from Kombucha pellicles in the production of laminated wood materials. To evaluate the mechanical performance of the manufactured specimens, density, compressive strength parallel to the grain (ISO 13061-17 2017), adhesion strength (TS EN 205 2017), modulus of rupture (TS 2474 1976), and modulus of elasticity in bending (TS 2478 1976) tests were conducted.

EXPERIMENTAL

This study is a continuation of the previously published work entitled "Laminated Wood Material Reinforced with Bacterial Cellulose Sheets Derived from Kombucha Pellicles: Part 1 – Some Physical Properties." Similar material preparation methods and experimental procedures were employed to ensure experimental consistency. However, the present study focuses on mechanical properties, and the related descriptions have been revised and restructured accordingly to ensure originality.

Materials

Preparation of wood specimens

In this study, wood from Scots pine (*Pinus sylvestris* L.), Oriental beech (*Fagus orientalis* L.), and Anatolian chestnut (*Castanea sativa* Mill.), all commonly utilized in the furniture industry, was employed. In accordance with TS 2470 (1976), first-grade, defect-free blanks with dimensions of 400 mm × 100 mm × 10 mm were prepared in the radial direction. The blanks were conditioned at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 3% until reaching a constant weight, following the TS 2471 (1976) standard. The wood materials were selected as first-grade, defect-free specimens in accordance with TS 2470 (1976), ensuring comparable density characteristics within each species. Under these controlled conditions, all specimens were assumed to reach equilibrium moisture content prior to lamination. The samples were reconditioned under the same environmental conditions. The moisture content of the BC sheets was not directly measured; however, under the specified conditioning conditions, it is expected to reach equilibrium with the ambient environment. Detailed physical and structural characteristics of the BC material have been reported in Part 1 of this study (Budakcı *et al.* 2025). After conditioning, the specimens were machined to final dimensions of 400 × 100 × 6.6 mm^3 for the control group and 400 × 100 × 6 mm^3 for the BC-reinforced group. All specimens were subsequently re-conditioned under the same environmental parameters prior to lamination.

Adhesive

Polyvinyl acetate (PVAc), polyurethane (PU), and urea-formaldehyde (UF) adhesives were utilized in the production of the laminated wood. The adhesives were applied at a spread rate of 170 g/m², monitored with a precision of 0.01 g, in accordance with the manufacturer's recommendations and procedures used for laminated wood bonding (ASTM D5751-99 2019). A constant adhesive spread amount per unit area was used for all adhesive types to ensure direct comparability among the experimental groups and to isolate the effect of BC reinforcement. The fundamental properties of the adhesives and the corresponding pressing parameters are summarized in Table 1.

Table 1. Adhesive Properties and Pressing Parameters Used in The Study

Parameter	UF	PVAc	PU
Solid content (%)	65	54	96.8
Density (g/cm³)	1.28	1.10	1.10
pH (at 20 °C)	7.3	6.7	7.0
Viscosity (cP)	3500	13500	4500
Application amount (g/m²)	170	170	170
Press pressure (N/mm²)	0.8	0.8	0.8
Pressing time (min)	10	120	120
Temperature (°C)	90	20	20

Kombucha Pellicle Production

Bacterial cellulose (BC), utilized as a reinforcing layer in this study, was obtained through the static fermentation of a kombucha-based culture medium. The medium was prepared by dissolving sucrose (90 g/L) and black tea (5 g/L) in distilled water. After the solution cooled to room temperature, previously fermented kombucha liquid (200 mL per L) and approximately 24 g of wet SCOBY were introduced as inoculum (Reiss 1994). All materials used during preparation were treated with hot water (~ 90 °C) to reduce contamination risk. Fermentation was conducted under static conditions for approximately 28 days at a temperature of 22 ± 4 °C and a relative humidity of 80 ± 5%.

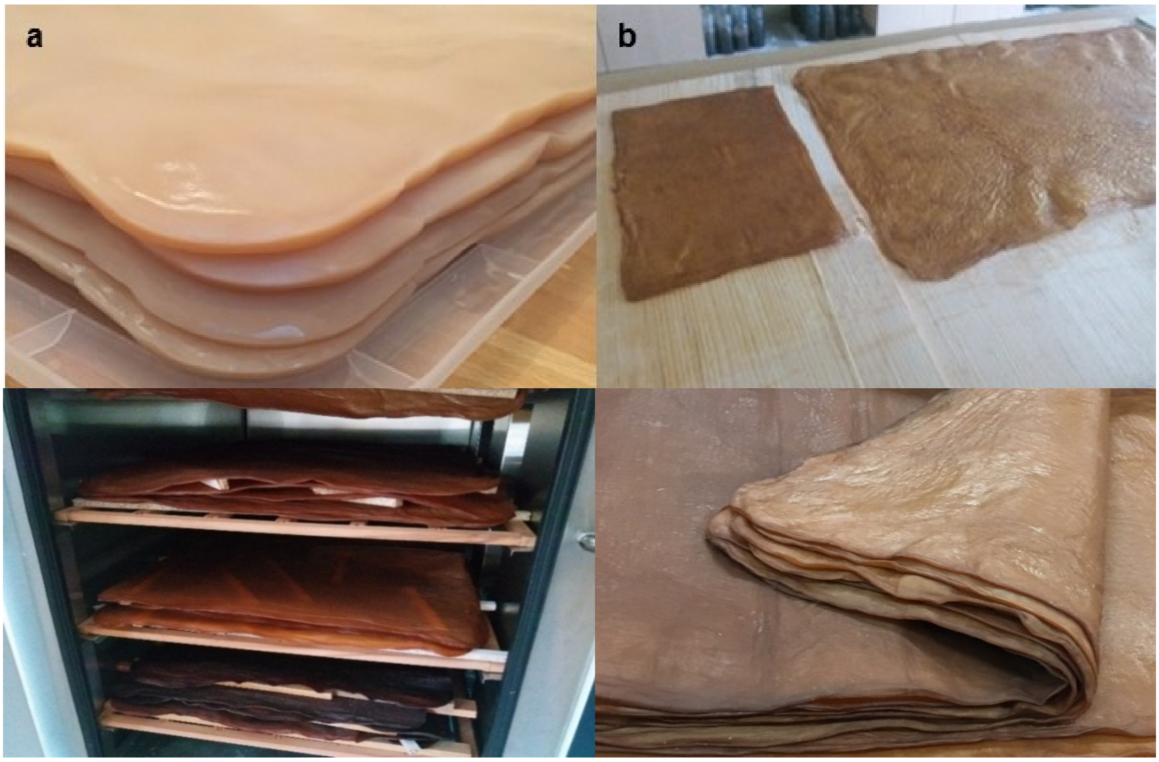


Fig. 1. Kombucha-derived BC pellicles: (a) air-drying and conditioning process; (b) stacked dried pellicles. Reproduced from Part 1 (Budakcı *et al*. 2025) to ensure experimental consistency

During fermentation, the acidity of the medium was monitored using a digital pH meter, and pH values were maintained within the range of 3.0 to 4.0. This condition may lead to pH-related incompatibilities between BC and adhesive systems, and its potential effects on bonding performance are discussed in the relevant section. At the end of the fermentation period, cellulose pellicles with an approximate thickness of 10 mm were formed. The pellicles were then rinsed repeatedly with distilled water to remove residual compounds from the fermentation medium. Drying was performed at room conditions by placing the pellicles on parchment paper and allowing moisture to evaporate naturally. The drying process continued for approximately 30 days, and the samples were periodically turned at two-day intervals to ensure homogeneous drying. Thickness measurements were taken from eight different locations (corners and edge midpoints) using a digital caliper, and average values were calculated. The final thickness of the dried sheets was found to be 1.0 mm with a standard deviation of 0.15 mm. Detailed physical, structural, and chemical characterization of the BC sheets (including density, surface morphology, crystallinity, and chemical composition) was not conducted in the present study. These properties have been comprehensively reported in Part 1 of this study (Budakcı *et al.* 2025). The current work focuses specifically on evaluating the mechanical performance of laminated wood composites incorporating BC layers. Prior to lamination, the samples were conditioned at 20 ± 2 °C and 65 ± 3% relative humidity.

Preparation of Test Samples

The conditioned wood layers were manufactured into three-layer laminated wood composites with dimensions of 400 × 100 × 20 mm^3 using a hydraulic press. The lamellae were arranged in a parallel (unidirectional) configuration, with the grain direction of all layers aligned parallel to the longitudinal axis of the specimens, and no cross-lamination was applied. This layering arrangement is illustrated in Fig. 2.

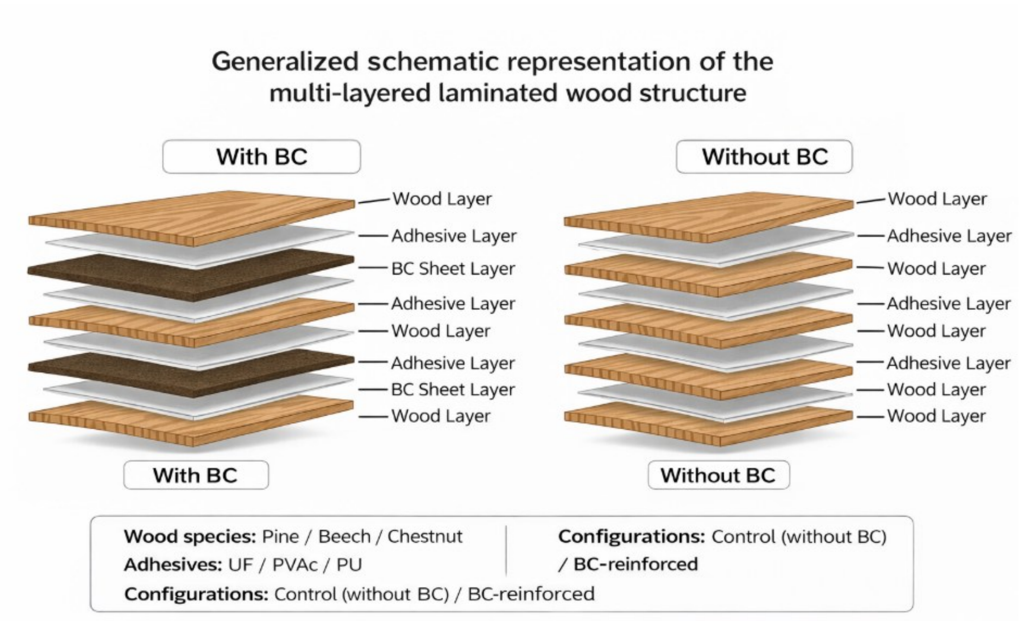


Fig. 2. Generalized schematic of the laminated wood structure, showing BC-reinforced and control configurations used in the study

The PVAc and UF adhesives were applied to the surfaces using a roller, whereas the PU adhesive was applied with a notched trowel. In the BC-reinforced laminated materials (Fig. 3), the dried BC sheets were integrated between the wood lamellae. In this study, the adhesive was applied only to the wood surfaces (single glue spread, SGS). The BC sheets were not directly coated with adhesive due to their dense and low permeability structure, which limits adhesive penetration. Additionally, the use of a double glue spread

(DGS) method was not adopted in order to maintain process consistency and to avoid excessive adhesive accumulation at the interface.

Fig. 3. Production stages of BC-reinforced laminated wood materials: (a) adhesive application, (b) layering, (c) pressing, and (d) conditioning. Reproduced from Part 1 (Budakcı *et al.* 2025) to ensure experimental consistency

The laminated specimens, initially produced at 400 × 100 × 20 mm^3, were subsequently dimensioned for mechanical testing in accordance with the relevant standards. For the compression strength parallel to the grain test, specimens were prepared with dimensions of 30 mm (length) × 20 mm (width) × 20 mm (thickness). For the bonding strength test, the dimensions were 150 × 20 × 10 mm^3. For the modulus of rupture (MOR) and modulus of elasticity (MOE) tests, specimens were sized to 320 × 20 × 20 mm^3. To eliminate moisture content variations arising from the gluing and machining processes, all specimens were conditioned at 20 ± 2 °C and 65 ± 3% relative humidity until reaching a constant weight, following the TS 13061-17 (2017) standard. For each experimental combination (wood species × adhesive type × configuration), 10 replicate specimens were prepared and tested for each mechanical property (compression strength, adhesion strength, MOR, and MOE).

Methods

Compressive strength parallel to grain test

The compressive strength parallel to the grain (σ_c) was determined according to the TS 13061-17 (2017) standard. The widths (a) and thicknesses (b) at the midpoints of the air-dry specimens were measured using a digital caliper with a precision of ± 0.01 mm. The loading rate of the universal testing machine was adjusted to ensure specimen failure within 1.5 to 2 min from the onset of loading, and the process continued until fracture occurred (Fig. 4). The compressive strength parallel to the grain was calculated using Eq. 1,

$$\sigma_c = \frac{F_{max}}{a.b} \tag{1}$$

where σ_c is the compressive strength parallel to grain (N/mm²), F_{max} is the maximum force at failure (N), *a* is the width of the specimen (mm), and *b* is the thickness of the specimen (mm).

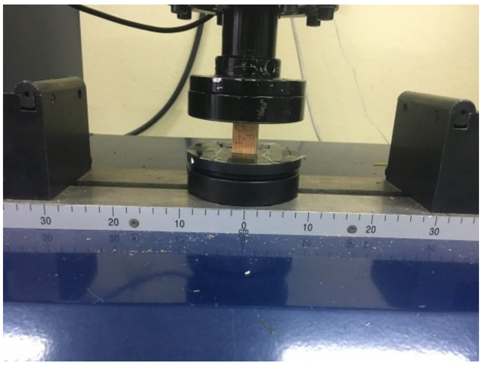


Fig. 4. Compressive strength test parallel to the fibers

Adhesion strength test

The adhesion strength (σ_a) was determined according to the TS EN 205 standard. Air-dry specimens, prepared in accordance with the standard, were subjected to a tensile force in a universal testing machine at a crosshead speed that induced failure at the adhesive line within 15 to 60 s (Fig. 5). The adhesion strength was calculated using Eq. 2:

$$\sigma_a = \frac{F_{max}}{A} \quad (2)$$

where F_{max} is the maximum force at failure (N) and A is the bonding surface area (mm²), calculated as $A = a \times l$, where a is the width (mm) and l is the length of the bonding surface (mm).

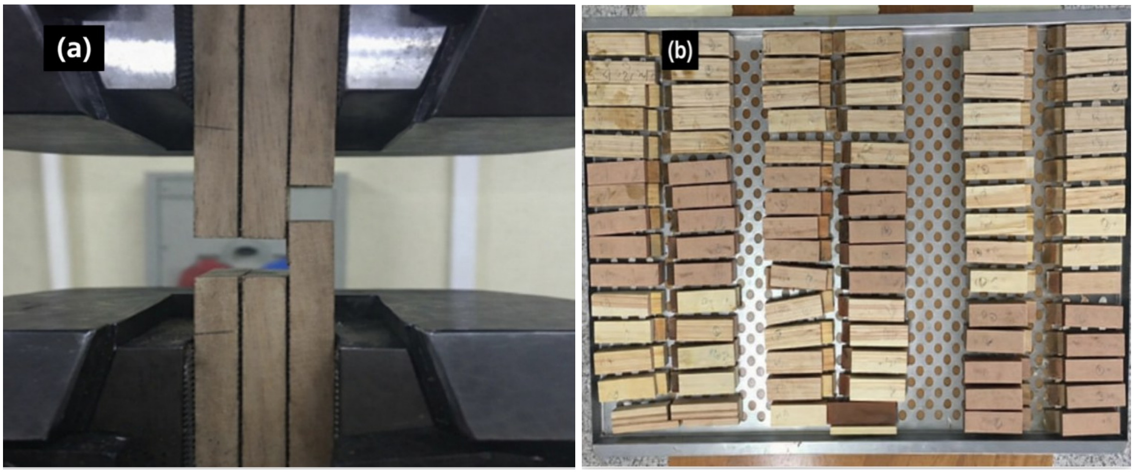


Fig. 5. Adhesion strength test: a: initial stage of the adhesion strength test; b: specimens after testing

Modulus of rupture and modulus of elasticity in bending

The MOR was determined in accordance with the TS 2474 (1976) standard. The width and thickness at the midpoints of the air-dry specimens were measured using a digital caliper with a precision of ± 0.01 mm. The loading rate of the universal testing machine was adjusted to ensure specimen failure within 1.5 ± 0.5 min from the onset of loading (Fig. 6). The modulus of rupture was calculated using Eq. 3,

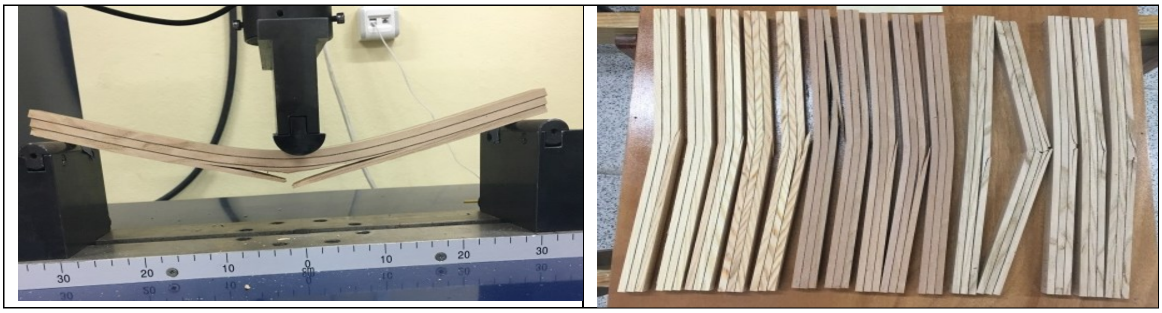
$$MOR = \frac{3.F_{max}.L_s}{2.b.h^2} \quad (3)$$

where MOR is the modulus of rupture (N/mm²), F_{max} is the maximum force at failure (N), L_s is the span length (mm), b is the width of the specimen (mm), and h is the thickness of the specimen (mm).

The MOE was determined according to the TS 2478 (1976) standard using the same specimens employed for the MOR test. The MOE was calculated using Eq. 4,

$$MOE = \frac{L^3 \Delta F}{4bh^3 \Delta w} \quad (4)$$

where MOE is the modulus of elasticity (N/mm²), ΔF is the difference between two force values within the elastic region (N), L is the span length (mm), b is the width (mm), h is the height (mm), and Δw is the deflection at the mid-span corresponding to ΔF (mm).



A B

Fig. 6. Experimental setup for the (a) MOR and (b) MOE in the three-point bending test

Statistical analysis

Statistical evaluations were performed using the MSTAT-C software package (University of Michigan, MI, USA). The effects of the experimental factors and their interactions were determined through Analysis of Variance (ANOVA). To identify significant differences between the variables, Duncan's Multiple Range Test (DMRT) was employed, utilizing the Least Significant Difference (LSD) critical value at a 95% confidence level.

RESULTS AND DISCUSSION

Compressive Strength Parallel to the Grain

The mean values of compressive strength parallel to the grain were analyzed to evaluate the influence of BC layers on the mechanical performance of the laminated wood composites.

The results indicated that compressive strength varied significantly, depending on the wood species, adhesive type, and lamination configuration (with or without BC). To determine the statistical significance of these factors and their interactions, a multi-way ANOVA was performed, the results of which are summarized in Table 2.

According to the ANOVA results, the compressive strength parallel to the grain was significantly influenced by wood species, adhesive type, lamination factors, and their respective interactions ($p \leq 0.05$). Notably, the interaction between wood species and lamination factors (AC interaction) was found to be statistically non-significant. To identify the specific factors and levels contributing to these differences, DMRT was performed based on the LSD critical values.

The resulting comparisons for wood species, adhesive types, and lamination configurations are presented in Table 3.

Table 2. ANOVA Results for Compressive Strength Parallel to the Grain (N/mm²)

Factors	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Level of Significance ($p \leq 0.05$)
Wood Species (A)	2	3036.093	1518.047	420.110	0.000*
Adhesive Type (B)	2	87.749	43.875	12.1421	0.000*
BC Reinforcement (C)	1	653.834	653.834	180.944	0.000*
Interaction (AB)	4	94.814	23.704	6.559	0.000*
Interaction (AC)	2	1.096	0.548	0.151	Ns**
Interaction (BC)	2	129.745	64.872	17.953	0.000*
Interaction (ABC)	4	42.714	10.678	2.9552	0.025*
Error	72	260.168	3.613		
Total	89	4306.214			

*Significant at 95% confidence level; Ns: Not significant

Table 3. DMRT Comparison Results for Wood Species, Adhesive Type, and Lamination Factor

Wood Species	**x̄**	**HG**
Pine	52.33	A*
Beech	48.38	B
Chestnut	38.52	C
LSD ± 0.9784		
Adhesive Type	**x̄**	**HG**
PVAc	45.38	B
PU	47.74	A*
UF	46.1	B
LSD ± 0.9784		
Lamination	**x̄**	**HG**
Control	49.1	A*
BC - reinforced	43.71	B
LSD ± 0.7988		

Note: x̄ = Arithmetic mean; HG = homogeneity group; and * = The highest compressive strength value parallel to the grain

According to Table 3, the highest compressive strength parallel to the grain at the wood species level was obtained in laminated samples produced from pine, whereas the lowest value was observed in chestnut. For adhesive type, PU adhesive resulted in the highest compressive strength, while PVAc and UF adhesives produced lower values. In terms of lamination factor, the control group exhibited higher compressive strength compared to the BC-reinforced samples.

In the evaluation based on wood species, the compressive strength of pine samples was 8.2% higher than that of beech and 35.8% higher than that of chestnut. These differences are attributed to variations in wood anatomy and chemical composition. The superior compressive strength of pine can be explained by its lignin content and the reinforcement provided by the regular arrangement of its tracheid cells (Li *et al.* 2021). In contrast, the porous structure of chestnut and variations in its cellulose-to-lignin ratio may have resulted in its relatively lower strength. Furthermore, the interaction of the PU adhesive with the wood cell walls and its varying degree of penetration across different species likely contributed to these results. Although some literature indicates that the compressive strength of beech is generally higher than that of pine and chestnut (Örs and Keskin 2008), other studies support the current study's findings, stating that pine can exhibit higher parallel compression values than beech (Çetin and Gündüz 2017). The superior performance of pine can be attributed to the radial orientation of the specimens and the presence of high-density latewood bands within its anatomical structure, which act as a natural reinforcement against axial loads. Furthermore, this regular cellular architecture, in conjunction with the adhesive and bacterial cellulose layers, facilitated a more balanced stress distribution and load transfer interface (Pereira *et al.* 2018). Conversely, the lower values observed in chestnut are due to structural weaknesses inherent in its ring-porous anatomy. Specifically, the wide and porous earlywood zones create irregular stress concentrations at the lamination interface, undermining the overall mechanical stability.

Regarding the adhesive type, the compressive strength parallel to the grain of laminated specimens produced with PU adhesive was 5.2% higher than those bonded with PVAc and 3.6% higher than those with UF. In the literature, the lowest compressive strength values for laminated pine specimens bonded with PVAc, PU, and UF were reported in samples using UF adhesive (Öztürk and Arıoğlu 2006). The relatively lower compressive strength exhibited by UF-bonded specimens can be attributed to the inherent brittleness of this resin's polymeric structure and its post-curing mechanical behavior (Luo *et al.* 2019; Wibowo *et al.* 2022). Because cured UF resin forms a highly cross-linked thermoset polymer network, it possesses a rather rigid and brittle structure (Antunes *et al.* 2018). Under axial compressive forces applied parallel to the grain, wood cell walls tend to buckle; however, the UF adhesive line, lacking sufficient flexibility, fails to accommodate this deformation. This deformation mismatch between the wood tissue and the adhesive layer leads to stress concentrations at the interface and ultimately to the premature formation of microcracks (Wang *et al.* 2019; Zhong *et al.* 2021). In contrast, the relatively more elastomeric structures of PU and PVAc adhesives allow them to absorb interfacial stresses, exhibiting a more stable deformation in tandem with the wood, which in turn enhances the overall axial load-bearing capacity of the material (Gadhave and Dhawale 2022; La Scala *et al.* 2024).

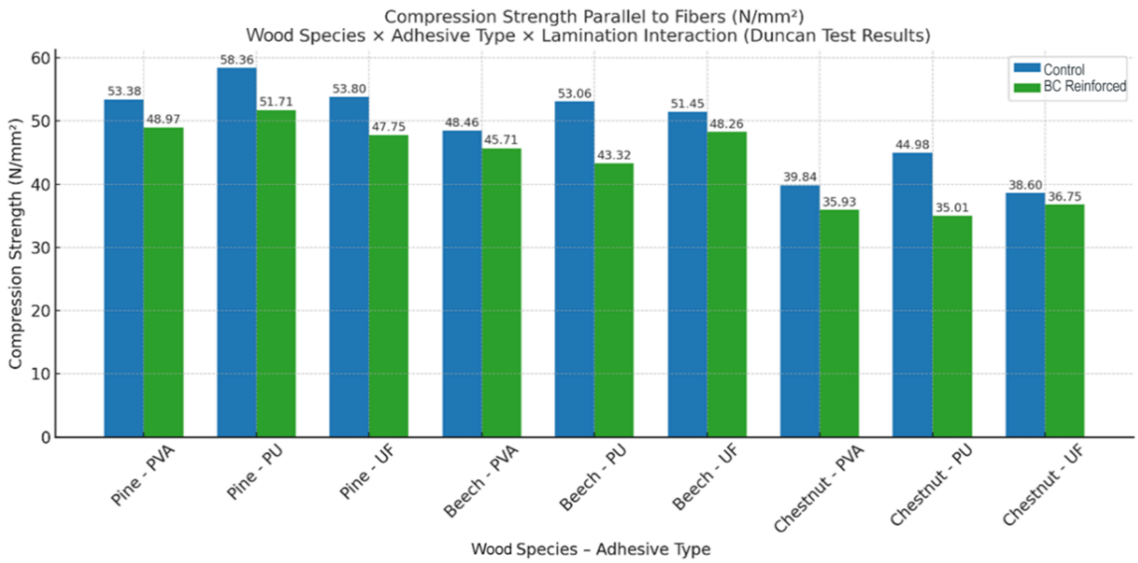


Fig. 7. DMRT comparison results for compressive strength values parallel to the grain based on the interaction level of wood species, adhesive type, and lamination factors

At the lamination factor level, the compressive strength of the BC-reinforced samples (43.7 N/mm²) was approximately 11% lower than that of the control group (49.1 N/mm²). This reduction suggests that the BC layers introduced a weak interface within the laminated structure, hindering uniform stress distribution under axial loads. Although the fibrous network of the BC sheet is individually robust (Illa *et al.* 2019), it may have functioned as a sliding plane due to insufficient interfacial adhesion with the wood substrate.

The DMRT results for the interactions among wood species, adhesive type, and lamination factors, alongside the comprehensive group comparisons, are illustrated in Fig. 7.

According to these results, the highest compressive strength parallel to the grain was achieved in pine specimens bonded with PU without BC reinforcement (58.4 N/mm²). In contrast, the lowest value was observed in chestnut specimens bonded with PU and integrated with a BC layer (35.01 N/mm²).

Adhesion Strength

The mean adhesion strength values of the laminated wood composites exhibited variations depending on the wood species, adhesive type, and the presence of the bacterial cellulose layer. To evaluate the statistical significance of these primary factors and their interactions on the bonding performance, an ANOVA was conducted, with the results summarized in Table 4.

Table 4. Results of the ANOVA for Adhesion Strength Values (N/mm^2)

Factors	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Level of Significance ($p \leq 0.05$)
Wood Species (A)	2	33.910	16.955	14.4381	0.0000*
Adhesive Type (B)	2	21.435	10.717	9.1266	0.0003*
BC Reinforcement (C)	1	1826.462	1826.462	1555.3537	0.0000*
Interaction (AB)	4	3.292	0.823	0.7008	Ns
Interaction (AC)	2	32.618	16.309	13.8880	0.0000*
Interaction (BC)	2	22.887	11.443	9.7448	0.0002*
Interaction (ABC)	4	2.215	0.554	0.4715	ns
Error	72	84.550	1.174		
Total	89	2027.368			

*Significant at 95% confidence level

According to the ANOVA results, the adhesion strength was significantly influenced by the wood species, adhesive type, lamination factor, and most of their interactions ($p \leq 0.05$). However, the interaction between wood species and adhesive type (AB), as well as the triple interaction between all factors (ABC), were found to be statistically insignificant. To identify the specific factors contributing to these differences, DMRT was performed at the levels of wood species, adhesive type, and lamination factors utilizing the LSD critical value. The comparison results are presented in Table 5.

According to Table 5, at the wood species level, the highest adhesion strength was obtained in laminated samples produced from beech wood (5.405), whereas the lowest values were observed in samples produced from chestnut and pine. Regarding adhesive type, the highest adhesion strength was obtained in samples bonded with PVAc and PU adhesives, while the lowest value was observed in samples bonded with UF adhesive. In terms of the lamination factor, the control group exhibited the highest adhesion strength, whereas the BC-reinforced laminated samples showed the lowest value.

Table 5. DMRT Comparison Results for Wood Species, Adhesive Type, and Lamination Factor

Wood Species	x̄	HG
Pine	4.45	B
Beech	5.40	A*
Chestnut	3.92	B
LSD ± 0.5577		
Adhesive Type	**x̄**	**HG**
PVAc	4.63	A*
PU	5.17	A*
UF	3.97	B
LSD ± 0.5577		
Lamination	**x̄**	**HG**
Control	9.09	A*
BC - reinforced	0.08	B
LSD ± 0.798		

Note: x̄ = Arithmetic mean; HG = homogeneity group; and * = the highest adhesion strength value

Evaluating the wood species, the adhesion strength of beech samples was 21.3% higher than that of pine. Conversely, the adhesion strength of chestnut samples was 12% lower than that of pine. The literature indicates that wood species, density, and surface quality significantly affect adhesion (Mahrdt *et al.* 2017; Rohumaa *et al.* 2021). In this study, the higher density of beech compared to pine and chestnut, coupled with the smoother surface obtained after machining, likely contributed to these results by facilitating superior adhesive penetration and bond formation. Furthermore, it has been reported that the diffuse-porous, homogeneous structure of beech, characterized by small vessels, is highly effective in promoting specific adhesion, leading to successful bonding at the interface (Budakçı 2003).

Regarding the adhesive types, the adhesion strength of samples bonded with PU was 11.7% higher than those bonded with PVAc. In contrast, the adhesion strength of UF-bonded samples was 23.1% lower than those using PU. Previous studies corroborate that adhesive formulation significantly impacts bonding performance (Ren and Frazier 2012). It is also noted that PVAc exhibits high adhesion strength because it forms an elastic polymer film at the interface. This characteristic allows it to perform well against internal or external stresses by distributing the load uniformly across the entire bonding area (Altınok 1995; Budakçı 2010). Furthermore, previous research reported that PVAc outperformed UF in adhesion performance and demonstrated a 45.5% superiority over contact adhesives (Kılıç 2006).

At the lamination factor level, the adhesion strength of the BC-reinforced samples (0.088 N/mm^2) was approximately 99.0% lower compared to the control group (9.10 N/mm^2). Bacterial cellulose has been reported to be inherently incompatible with non-polar environments due to its highly hydrophilic nature, resulting in poor interfacial adhesion with the hydrophobic surfaces of traditional polymeric matrices (Martínez *et al*. 2013). Additionally, it is emphasized that the strong crystalline structure of bacterial cellulose impedes the deep penetration of structural resins (Bach and Manh Vu 2020). Considering these studies, it can be concluded that the high density and lack of pore spaces within the BC layers utilized in this research physically prevented the adhesives from penetrating the substrate, thereby leading to catastrophic adhesion failure. Furthermore, the literature specifies that when bacterial cellulose is in a dry state, the hydroxyl groups of its cellulose chains form strong intra- and intermolecular hydrogen bonds, creating a tightly cross-linked network. Conversely, in the wet state, water molecules can participate in these hydrogen bonds, penetrate between the cellulose chains, and disrupt the cross-linked structure. It is reported that if wet bacterial cellulose wrinkles or folds during drying, the cellulose chains may slip irreversibly, making it highly difficult to obtain perfectly smooth, flat dry sheets (Bach and Manh Vu 2020). In the present study, the high capillary forces generated during the stagnant air-drying phase of the bacterial cellulose pellicles caused the nano-fibrils to aggregate tightly through irreversible hydrogen bonding. This phenomenon resulted in a dense, collapsed structure, commonly referred to as hornification. Consequently, the closure of surface pores and the drastic reduction in accessible reactive hydroxyl sites physically impeded the adhesive molecules from penetrating the cellulose network. This barrier effectively prevented the establishment of a strong mechanical interlock or chemical bonding at the wood-BC-adhesive interface, ultimately explaining the low adhesion strength.

The DMRT comparison results and the collective analysis of the interactions among wood species, adhesive types, and lamination factors are illustrated in Fig. 8.

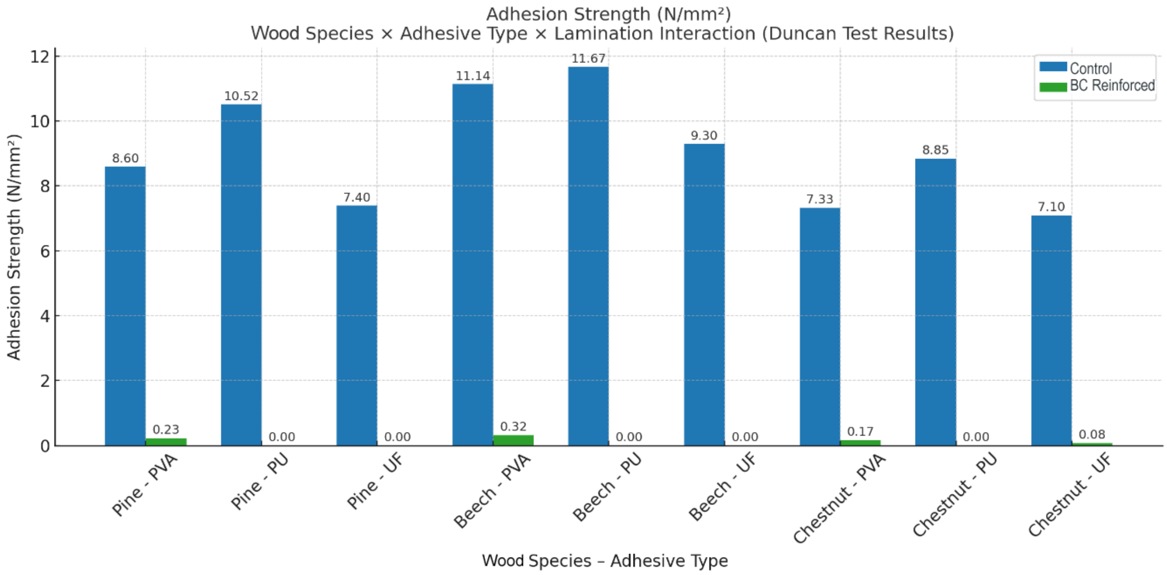


Fig. 8. DMRT comparison results for adhesion strength values regarding the interaction level of wood species, adhesive type, and lamination factors

According to these results, the highest adhesion strength was achieved in beech specimens (11.7 N/mm^2) bonded with PU without BC reinforcement. This finding demonstrates that the PU adhesive exhibits high compatibility with the anatomical structure of beech, facilitating robust bond formation. In contrast, the lowest adhesion strength values were observed across all specimens integrated with BC layers, ranging between 0 and 0.324 N/mm^2. It is suggested that the application of the BC layer significantly weakened the adhesive interaction by altering the surface topography and reducing the capacity for chemical bonding. Additionally, differences in pH between bacterial cellulose (BC) and the adhesives used may also influence bonding performance. The inherently slightly acidic nature of BC, compared to the neutral or alkaline character of certain adhesive systems, may lead to chemical incompatibilities at the interface. This mismatch can negatively affect adhesive penetration and bond formation, thereby contributing to the reduction in mechanical performance. When considered together with the surface characteristics of BC, this effect emerges as a significant factor explaining the weakening of interfacial adhesion. Specifically, the presence of the BC layer appears to act as an interfacial barrier, severely limiting the effectiveness of resins such as PU and UF. The general evaluation indicates that the BC-reinforcement process, as executed in this study, drastically reduces adhesion strength. This inhibitory effect varies depending on both the specific adhesive chemistry and the wood species utilized.

Modulus of Rupture

The mean MOR values of the laminated wood materials exhibited variations depending on the wood species, adhesive type, and lamination factors. To evaluate the statistical significance of these factors and their interactions on the flexural performance, an ANOVA test was conducted, with the results summarized in Table 6.

Table 6. ANOVA Results for MOR Values (N/mm²)

Factors	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Level of Significance ($p \leq 0.05$)
Wood Species (A)	2	2485.340	1242.670	55.6544	0.0000*
Adhesive Type (B)	2	99.862	49.931	2.2362	0.1142
BC Reinforcement (C)	1	68873.954	68873.954	3084.6009	0.0000
Interaction (AB)	4	147.566	36.891	1.6522	0.1706
Interaction (AC)	2	81.594	40.797	1.8271	0.1683
Interaction (BC)	2	337.429	168.715	7.5561	0.0010
Interaction (ABC)	4	357.473	89.368	4.0025	0.0055
Error	72	1607.639	22.328		
Total	89	73990.858			

*Significant at 95% confidence level

According to the ANOVA results, the MOR values were found to be statistically significant ($p \leq 0.05$) for wood species (Factor A), lamination factor (Factor C), the interaction between wood species and adhesive type (AB interaction), and the triple interaction (ABC interaction), while other factors and interactions were insignificant.

Table 7. DMRT Comparison Results for MOR According to Wood Species, Adhesive Type, and Lamination Factor

Wood Species	**$\bar{x}$**	**HG**
Pine	61.45	A*
Beech	62.39	A*
Chestnut	50.80	B
LSD ± 2.432		
Adhesive Type	**$\bar{x}$**	**HG**
PVAc	59.20	A*
PU	58.68	A*
UF	56.75	A*
LSD ± 2.432		
Lamination	**$\bar{x}$**	**HG**
Control	85.88	A*
BC - reinforced	30.55	B
LSD ± 1.986		

Note: $\bar{x}$ = Arithmetic mean; HG = homogeneity group; and * = The highest MOR value

To identify the specific levels contributing to these differences, DMRT was performed at the wood species, adhesive type, and lamination factor levels utilizing the LSD critical values. The resulting comparisons are provided in Table 7. As shown, the highest MOR values were obtained in specimens produced from beech (62.39 N/mm^2) and pine (61.45 N/mm^2), while the lowest MOR was observed in chestnut samples (50.80 N/mm^2). Regarding the adhesive type, the highest MOR was detected in samples bonded with PVAc (59.20 N/mm^2) and PU (58.68 N/mm^2). It is evident that these two adhesives effectively facilitate the bond strength within the laminated structures. Conversely, samples produced using UF adhesive exhibited a lower MOR (56.75 N/mm^2), demonstrating poor performance compared to the other adhesive types. When evaluated in terms of the lamination factor, the MOR was notably high in the control group specimens (85.88 N/mm^2), whereas this value significantly decreased in samples integrated with BC layers (30.55 N/mm^2).

In the evaluation according to wood species, the MOR of laminated beech specimens was approximately 1.5% higher than that of pine. Conversely, the MOR of chestnut samples was approximately 17.4% lower than that of pine. These differences are attributed to the anatomical structure and chemical composition of the respective wood species. Specifically, the homogeneous and dense fiber structure of beech is a primary factor enhancing MOR, whereas the more porous anatomy and irregular fiber organization of chestnut likely resulted in lower flexural resistance. According to the literature, MOR tests conducted on various solid wood materials consistently report that beech yields superior values (Gaff *et al.* 2017). Another study emphasizes that wood species is a critical factor influencing the MOR of wood-based panels (He *et al.* 2018). Furthermore, it is established that wood species with higher specific gravity tend to exhibit superior adhesion strength, which subsequently improves mechanical properties and increases MOR (Zhang 1997; Demirkır 2014). Thus, the higher density of beech compared to chestnut was likely instrumental in achieving the observed high MOR values.

In the evaluation based on adhesive type, a marginal difference of 0.88% was observed in MOR between samples bonded with PVAc and those with PU. Although this difference is not statistically significant, PU exhibited a slightly superior performance compared to PVAc. Conversely, the MOR of specimens using UF adhesive was 3.3% lower than those bonded with PU and 2.5% lower than those with PVAc. This relative underperformance can be attributed to the inability of the UF resin to establish a sufficiently robust bond within the laminated structure or its restricted penetration into the wood cell walls. Examining the literature, it is noted that while some studies report that adhesive type statistically affects MOR and the modulus of elasticity (MOE) (Togay *et al.* 2017; Kusnindar *et al.* 2018), others indicate no significant impact (Bal and Bektaş 2012).

Regarding the lamination factor, the MOR of BC-reinforced specimens was approximately 64.4% lower than that of the control group. This substantial discrepancy stems from the inability of the BC layers to maintain structural integrity between the wood lamellae during the lamination process. While the BC layers are individually flexible, their limited bonding affinity with the wood substrate likely compromised the overall mechanical performance. This lack of interfacial adhesion is proposed to lead to a sliding effect between layers under flexural load, preventing the composite from acting as a unified structural element (Mohd Yusof *et al.* 2019).

The significant three-way interaction (wood species × adhesive type × lamination factor) observed in MOR values indicates that the effect of BC reinforcement was not independent, but strongly influenced by both the anatomical structure of the wood and the bonding characteristics of the adhesive system. In particular, the presence of BC layers altered the stress transfer mechanism between lamellae, and this effect varied depending on the compatibility between the adhesive and the wood species. For example, in wood species with more porous structures, such as chestnut, the limited penetration of adhesive and the presence of BC as an interlayer may further weaken interfacial bonding, leading to a more pronounced reduction in MOR. In contrast, denser and more homogeneous wood structures, such as beech, may partially mitigate this effect due to improved load distribution. Therefore, the observed interaction confirms that the mechanical performance of BC-reinforced laminated composites is highly dependent on the combined influence of wood anatomy, adhesive behavior, and interlayer characteristics. The DMRT comparison results and collective analysis conducted at the interaction level of wood species, adhesive type, and lamination factors are illustrated in Fig. 9.

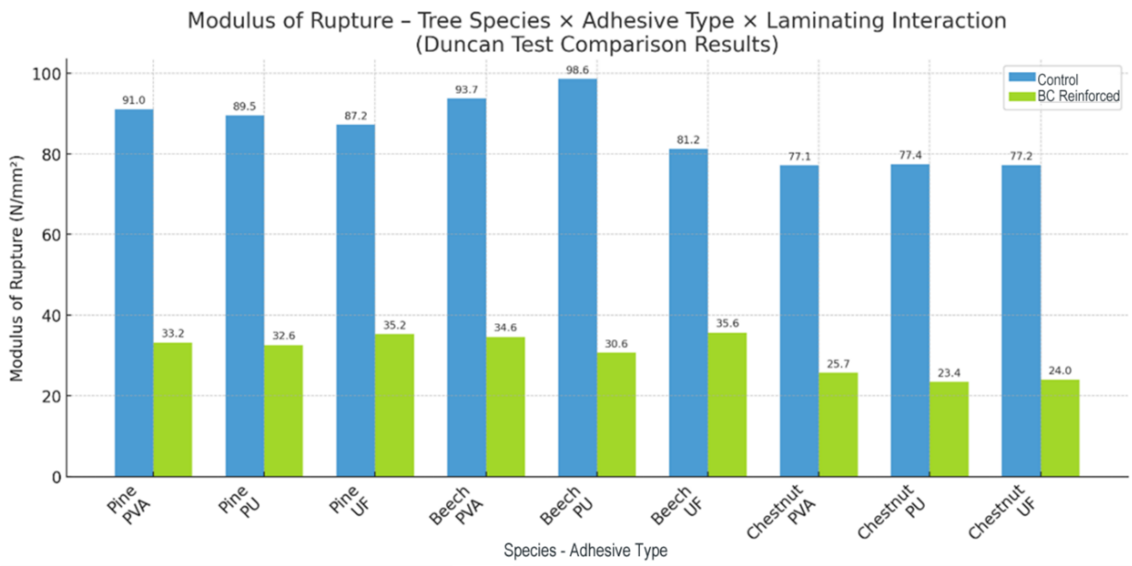


Fig. 9. DMRT comparison results for MOR values based on the interaction of wood species, adhesive type, and lamination factor

According to the results illustrated in Fig. 9, the highest MOR value was achieved in beech specimens (98.6 N/mm^2) bonded with PU without BC reinforcement. This peak performance reflects the superior interfacial bonding and high-density characteristic of the beech-PU combination. In contrast, the lowest MOR value was observed in chestnut samples (23.4 N/mm^2) bonded with PU and integrated with BC layers. This significant reduction in flexural strength underscores the detrimental effect of the BC interface, particularly when combined with the ring-porous anatomical structure of chestnut (Mohd Yusof *et al.* 2019; Li *et al.* 2023).

Modulus of Elasticity in Bending

The mean MOE in bending for the laminated wood composites exhibited variations depending on the wood species, adhesive type, and lamination factors. To evaluate the statistical significance of these factors and their interactions, an ANOVA test was performed, and the results are presented in Table 8.

The ANOVA results indicated that the MOE was significantly influenced by the wood species, adhesive type, lamination factor, and their respective interactions ($p \leq 0.05$). To identify the specific factors and levels contributing to these differences, DMRT was performed at the levels of wood species, adhesive type, and lamination factors utilizing the LSD value. The resulting comparison data are presented in Table 9.

Table 8. ANOVA Test Results for MOE in Bending (N/mm²)

Factors	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Level of Significance ($p \leq 0.05$)
Wood Species (A)	2	114457320.1	57228660.07	490.419	0.0000*
Adhesive Type (B)	2	2445043.7	1222521.87	10.476	0.0001*
BC Reinforcement (C)	1	1740921913.6	1740921913.60	14918.79	0.0000*
Interaction (AB)	4	3031221.1	757805.29	6.49	0.0002*
Interaction (AC)	2	66266523.8	33133261.90	283.93	0.0000*
Interaction (BC)	2	2493820	1246910.03	10.68	0.0001*
Interaction (ABC)	4	4576990.7	1144247.68	9.80	0.0000*
Error	72	8401910	116693.19		
Total	89	1942594743.2			

*Significant at 95% confidence level

Table 9. DMRT Comparison Results for MOE in Bending According to Wood Species, Adhesive Type, and Lamination Factor

Wood Species	$\bar{x}$	HG
Pine	6805	A*
Beech	5465	B
Chestnut	4043	C
LSD ± 175.8		
Adhesive Type	$\bar{x}$	**HG**
PVAc	5576	A*
PU	5532	A*
UF	5206	B
LSD ± 175.8		
Lamination	$\bar{x}$	**HG**
Control	9836	A*
BC - reinforced	1040	B
LSD ± 143.6		

Note: $\bar{x}$ = Arithmetic mean; HG = homogeneity group; and * = The highest in bending value

According to Table 9, at the wood species level, the highest MOE was obtained in specimens produced from pine. The MOE in beech specimens was measured as 5460 N/mm^2, which remained lower compared to pine. The lowest MOE was detected in chestnut samples (4040 N/mm^2). In the evaluation according to adhesive type, the highest MOE values were observed in samples bonded with PVAc (5580 N/mm^2) and PU (5530 N/mm^2) adhesives, while the lowest MOE was recorded for samples using UF (5210 N/mm^2). Regarding the lamination factor, the MOE reached a high level in the control group (9840 N/mm^2), whereas this value decreased dramatically to 1040 N/mm^2 in samples integrated with BC layers.

Evaluating the wood species, the MOE of laminated beech specimens was approximately 19.7% lower than that of pine. In chestnut samples, this value was approximately 40.6% lower than in pine. These differences are closely related to the fiber orientation, density, and cellular integrity of the respective wood species. While the dense and regular fiber structure of pine contributes to its high MOE, the more porous and irregular anatomy of chestnut limits its stiffness. According to the literature, MOE in bending tests for solid wood typically indicates that beech yields the highest values, followed by pine and chestnut (Efe and Kasal 2007). Furthermore, it is reported that wood density is a critical factor, and that MOE generally increases with increasing density (Bal and Bektaş 2012; Şenol 2018).

The finding that pine surpassed beech in MOE is inconsistent with some general literature trends but can be explained by specific anatomical factors. The superior performance of pine is attributed to its narrow annual rings and high latewood ratio, which significantly enhance local rigidity under radial bending loads (Barrios *et al.* 2017). Additionally, the surface morphology of pine, combined with the intercalated bacterial cellulose sheets and the adhesive line, demonstrated relatively more stable mechanical resistance against interfacial slippage during bending. In contrast, the diffuse-porous and homogeneous texture of beech was insufficient in providing the specific structural reinforcement offered by the dense latewood bands of coniferous species under radial loading, failing to effectively damp interlayer stresses.

In the evaluation according to adhesive types, the MOE of specimens using PVAc was only 0.8% higher than those bonded with PU. Although this difference is marginal, it indicates that both adhesives exhibit similar performance in terms of elasticity. Conversely, the MOE of specimens bonded with UF was approximately 6.6% lower than PVAc and 5.9% lower than PU. This relative underperformance can be attributed to the limited structural bonding capacity and inherent brittleness of the UF resin. It is reported in the literature that MOR and MOE in bending are often more significantly influenced by wood properties than by the specific characteristics of the adhesive (Kumar *et al.* 2015).

Regarding the lamination factor, the MOE of laminated specimens integrated with BC layers was approximately 89.4% lower than that of the control group. This substantial discrepancy demonstrates that the BC layers were insufficient in maintaining interlayer integrity. The fibrous but low-binding structure of the BC sheets failed to provide resistance against elastic deformation, leading to a severe degradation of mechanical properties. This approximately 89.4% reduction in MOE, when analyzed within the framework of beam bending theory, directly corresponds to interlayer shear and delamination mechanisms. The 99.0% loss in bond strength observed in BC-reinforced samples during adhesion tests prevented the material from behaving as a single integrated beam under flexural load. According to classical mechanics, while the area moment of inertia of a monolithic beam with complete bonding is proportional to the cube of its thickness (h^3), the total moment of inertia of a system consisting of three independent layers of equal thickness (each h^3) is theoretically equal to 1/9 of the integrated beam (3 x $(h/3)^3$ = $h^{3/}9$). This theoretical approach indicates a stiffness loss of approximately 88.8% in a system where interlayer slip is unrestrained. The 89.4% decrease in MOE observed in this study demonstrates an exceptionally high correlation with this theoretical expectation. Macroscopic examination of the fracture profiles after bending tests confirmed that the layers flexed independently and complete delamination occurred at the interfaces. Therefore, the measured decrease is judged to be a direct physical and mathematical consequence of the material's loss of load transfer capacity (Murakami 1984).

The DMRT comparison results and the collective analysis conducted at the interaction level of wood species, adhesive type, and lamination factors are illustrated in Fig. 10.

According to these results, the highest MOE in bending was achieved in pine specimens bonded with PVAc without BC layers (13.0 N/mm^2). This peak value highlights the synergistic effect of the regular tracheid structure of pine and the elastic film-forming capability of PVAc in the absence of interfacial interference. Conversely, the lowest MOE was observed in chestnut specimens integrated with BC layers and bonded with UF adhesive (633 N/mm^2). This extremely low stiffness value underscores the cumulative negative impact of the ring-porous anatomy of chestnut, the inherent brittleness of the UF resin, and the interfacial discontinuity introduced by the bacterial cellulose layer (Zhu *et al.* 2024).

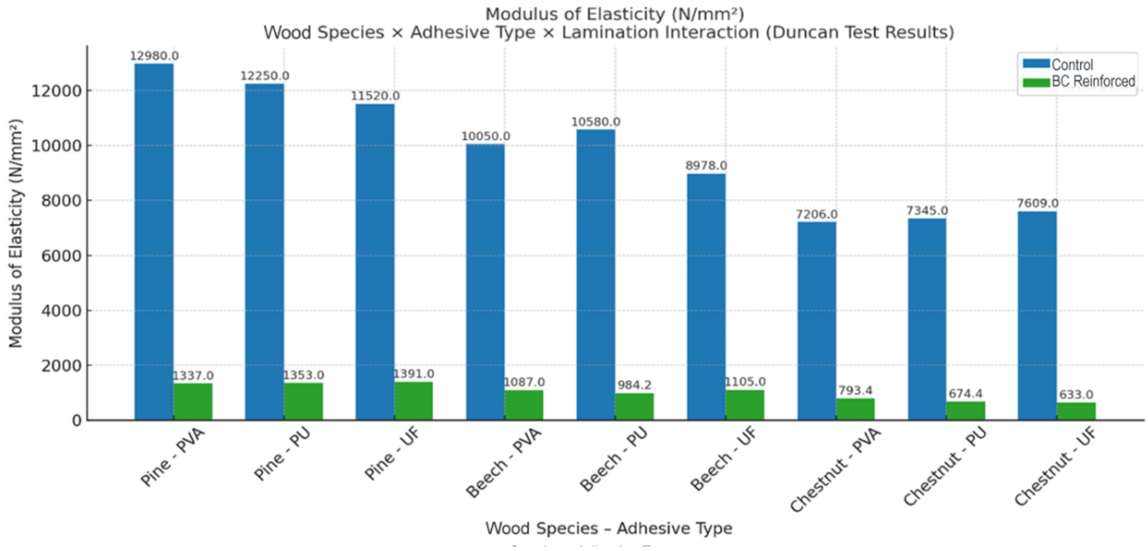


Fig. 10. DMRT comparison results for MOE in bending values based on the interaction of wood species, adhesive type, and lamination factor

CONCLUSIONS

This study investigated the effect of bacterial cellulose (BC) sheets derived from BC layers on the mechanical properties of laminated wood made from pine, beech, and chestnut, using poly(vinyl acetate) (PVAc), polyurethane (PU), and urea-formaldehyde (UF) adhesives. The following conclusions were reached:

1. The main finding of the research is that BC sheets, despite their high individual mechanical strength potential, significantly reduced the overall mechanical performance of the composite when integrated using current bonding techniques due to poor interlaminar adhesion.
2. Adhesion strength in BC-reinforced samples was almost completely eliminated (up to 99% reduction) compared to the control group. This indicates that sufficient bonding could not be formed. This was attributed to the irregular surface morphology of the BC. Its high density and lack of suitable pore structure restricted adhesive penetration, and it exhibited poor compatibility with hydrophobic adhesives.
3. Significant decreases were observed in modulus of rupture (MOR) and modulus of elasticity (MOE). This is because the weakness in the bond line prevents stress transfer, making the BC layer act as a defect rather than a reinforcement.
4. Compressive strength parallel to the grain was also lower in BC-reinforced samples. This confirms that the weak bond line prevents the material from behaving as an integrated unit under load, leading to premature failure.
5. The findings of this study indicate that in its current untreated form and when applied using the air-dried sheet insertion method, BC is not suitable as a structural reinforcing material for wood laminates. Future research should focus on optimizing

the interfacial bonding through surface modifications of BC or by exploring alternative bonding strategies to overcome these mechanical limitations.

6. The findings of this study are limited to the specific BC preparation method used, namely air-dried sheet insertion. Beyond structural use, BC demonstrates potential as a functional interlayer for specialized applications such as vibration damping and acoustic insulation. However, the economic feasibility of required secondary treatments and surface modifications must be critically evaluated to ensure practical applicability in industrial furniture production.

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