Laminated Wood Material Reinforced with Bacterial Cellulose Sheets Derived from Kombucha Pellicles: Part 1 — Some Physical Properties

Mehmet Budakçı,[a] Diğdem Şağban,[a] Mustafa Korkmaz,[a] and İzham Kılınç [b,*]

In this study, the usability of kombucha pellicles as a source of bacterial cellulose (BC) in the production of laminated wood was investigated to improve its physical properties. Within this scope, the kombucha culture was produced at room temperature through a fermentation process of approximately 25 days and then dried to obtain BC sheets with a thickness of approximately 1 mm. These sheets were used in the production of laminated wood material, along with wood species of Scots pine (*Pinus sylvestris* L.), Oriental beech (*Fagus orientalis* L.), and Anatolian chestnut (*Castanea sativa* Mill.), using urea-formaldehyde, polyurethane, and polyvinyl acetate adhesives. To evaluate the physical properties of the manufactured samples, density, thickness swelling, and water absorption tests were performed. Furthermore, the structural and thermal properties of the BC were analyzed using scanning electron microscopy and thermogravimetric analysis techniques. The findings indicated that BC is a high-performance biomaterial for lamination. The results unveiled BC's remarkable potential for developing eco-friendly materials, though certain technical challenges remain to be addressed before its full capabilities can be realized.

DOI: 10.15376/biores.20.4.8976-8992

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

*Contact information: a: Department of Wood Products Industrial Engineering, Faculty of Forestry, Düzce University; Düzce, Türkiye; b: Department of Design, Interior Design, Vocational School of Technical Sciences, Batman University, Batman, Türkiye; *Corresponding author: izham.kilinc@batman.edu.tr*

INTRODUCTION

Wood material, because of its numerous advantages, such as unique aesthetic qualities, workability, a high strength-to-weight ratio, and its nature as a renewable resource, has maintained its place as a fundamental material throughout human history across a wide range of applications, from architecture to everyday objects (Budakci *et al.* 2016; Asdrubali *et al.* 2017; Guenther *et al.* 2024). However, the hygroscopic nature of wood, *i.e.*, its tendency to absorb and release moisture from its surroundings, is one of its most significant disadvantages. Due to the presence of hydrophilic groups in polymers, such as cellulose, hemicellulose, and lignin, that constitute the cell wall, wood is highly sensitive to changes in atmospheric humidity (Báder and Németh 2019; Grottesi and Coelho 2023; Kılınç *et al.* 2023). This characteristic causes the material to swell as a result of water absorption, shrink as a result of water loss, and consequently undergo undesirable deformations, such as cracking and warping, following these repeated dimensional changes (Brischke and Alfredsen 2020; Zhan *et al.* 2021). Furthermore, a high moisture content can shorten its service life by increasing the risk of degradation by biological agents such as fungi and insects. Therefore, enhancing the dimensional stability of wood, reducing its water absorption, and improving its overall durability are fundamental and ongoing research topics in the fields of material science and forest products engineering.

To overcome these limitations arising from the natural hygroscopic behavior of wood material, and particularly to enhance its resistance to water, various modification techniques and composite production methods have been developed. These methods include thermal modification, chemical modification, and the production of wood-based composites (Mantanis 2017). The production of laminated wood is an effective composite manufacturing technique that enables the creation of more homogeneous and predictable materials with enhanced properties by assembling selected thin wood layers (veneers or lamellas) with suitable adhesives (Ayrilmis and Winandy 2009; Keskin and Togay 2019). The lamination process can provide improvements in dimensional stability and resistance to water compared to solid wood by distributing the effects of natural defects (knots, grain deviation, *etc.*) and through the adhesive line acting as a barrier (Liang *et al.* 2022; Zhu *et al.* 2022). Nevertheless, to further advance the performance of traditional laminated wood and to reduce the environmental footprint of its production processes, there is a growing interest in the use of natural, sustainable, and innovative reinforcement materials.

In this context, biopolymers, particularly nanocellulosic materials, have shown great potential in recent years for improving the physical properties of wood-based composites. Bacterial cellulose (BC) is a natural polymer with a unique three-dimensional nanofibrillar network structure. It is produced extracellularly as pure cellulose by various bacterial species, such as *Gluconacetobacter* (Ladero *et al.* 2017; Tabarsa *et al.* 2017; Hervy *et al.* 2018). Characterized by properties, such as a high degree of crystallinity, large surface area, remarkable water-holding capacity (in its native state), and biocompatibility, BC can be readily obtained, particularly through the fermentation of kombucha culture (Hervy *et al.* 2018). When dried and densified or integrated into a composite structure, this unique structure of BC holds the potential to limit the water absorption and enhance the dimensional stability of wood laminates by creating a tortuous path for water molecules or by providing a platform for hydrophobic modifications (Fillat *et al.* 2018; Cazón *et al.* 2020).

Environmental and health-related concerns, such as formaldehyde emissions and the petroleum-based nature of synthetic adhesives such as phenol-formaldehyde and urea-formaldehyde used in traditional laminated wood production, render the use of natural and biodegradable materials like BC even more appealing (Mbituyimana *et al.* 2021). However, the interaction mechanisms of BC on the physical properties of wood laminates have not yet been fully elucidated, particularly concerning topics, such as how the BC layer affects water vapor diffusion and liquid water penetration, the structure of the wood-BC interface, and the contribution of this integration to overall dimensional stability.

In light of this background, this study investigated the potential use of BC sheets obtained from kombucha culture in the production of laminated wood material. In the research, to evaluate the physical properties of the manufactured laminated samples, density, thickness swelling, and water absorption tests were performed. Furthermore, advanced characterization methods, such as Scanning Electron Microscopy (SEM) and Thermogravimetric Analysis (TGA), were utilized to analyze the structural and thermal properties of the BC sheets. This manuscript represents the first part of a comprehensive study. Accordingly, the scope of this paper is limited to the investigation of some physical properties of the developed composites. The mechanical properties of these materials, which constitute the second part of the research, will be presented and discussed in a subsequent article.

EXPERIMENTAL

Materials

Preparation of wooden materials

In this study, the woods of Scots pine (*Pinus sylvestris* L.), Oriental beech (*Fagus orientalis* L.), and Anatolian chestnut (*Castanea sativa* Mill.), which are commonly used in the Turkish furniture industry, were utilized. In accordance with TS ISO 3129 (2021), first-grade, defect-free blanks with dimensions of 400 mm x 100 mm x 10 mm were prepared from the sapwood sections in the radial direction. These blanks were conditioned at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 3% until they reached a constant weight in accordance with TS ISO 13061-1 (2021). After conditioning, the specimens were brought to the net dimensions of 400 x 100 x 6 mm for the control group and 400 x 100 x 6.6 mm for the BC sheet-reinforced group and were then re-conditioned under the same conditions before lamination.

Adhesive

In the production of laminated wood, polyvinyl acetate (PVAc), polyurethane (PU), and urea-formaldehyde (UF) adhesives were used. The adhesives were applied to the surfaces at a spread mass per unit area of 170 g/m^2 (controlled with a precision of 0.01g), in accordance with the ASTM D3023-98 (2017) standard and the manufacturer's recommendations. The basic properties of the adhesives used, and the pressing parameters are summarized in Table 1.

Table 1. Basic Properties of the Adhesives Used in Laminated Wood Production and the Corresponding Pressing Parameters

Adhesive Type	Solid Content (%)	Density (g/cm³)	pH (at 20 °C)	Viscosity (cP)	Press Type	Time (min)	Temperature (°C)
UF	65	1.28	7.3	3500	Hot Press	10	90
PVAc	54	1.10	6.7	13500	Cold Press	120	20
PU	96.8	1.10	7.0	4500	Cold Press	120	20

Kombucha Pellicle Production

Bacterial cellulose (BC) intended for use as a reinforcement layer in lamination was produced *via* static fermentation of kombucha tea. The fermentation medium was prepared using 90 g sucrose and 5 g tea bags per liter of water, followed by the addition of 0.2 L of previously fermented kombucha tea (from the prior batch) and 24 g of kombucha starter culture (SCOBY) as inoculum (Hermann 1928; Reiss 1994). Prior to the process, all equipment was washed with water at 90 °C to ensure hygienic conditions. The mixture was fermented for approximately 25 days at 22 ± 4 °C and 80 ± 5% relative humidity. The pH of the medium was monitored throughout the process and maintained within a range of 3.0 to 4.0. This process yielded wet BC pellicles with an average thickness of ~10 mm.

Following fermentation, the harvested pellicles were thoroughly washed with water to remove soluble surface contaminants. The aim was to utilize the pellicle in a state with minimal processing. The drying was conducted in still room air by laying the pellicles on baking paper on a flat laboratory bench. This process took an average of 30 days, during which the sheets were inverted every two days to promote uniform drying. The thickness of the final dried sheets, measured at eight points on each sheet (the four corners and the midpoint of the four edges) using a digital caliper, was found to have an average value of 1.0 mm with a standard deviation of 0.15 mm. Finally, the sheets were conditioned at 20 ± 2 °C and 65% ± 3 relative humidity before use in the lamination process.

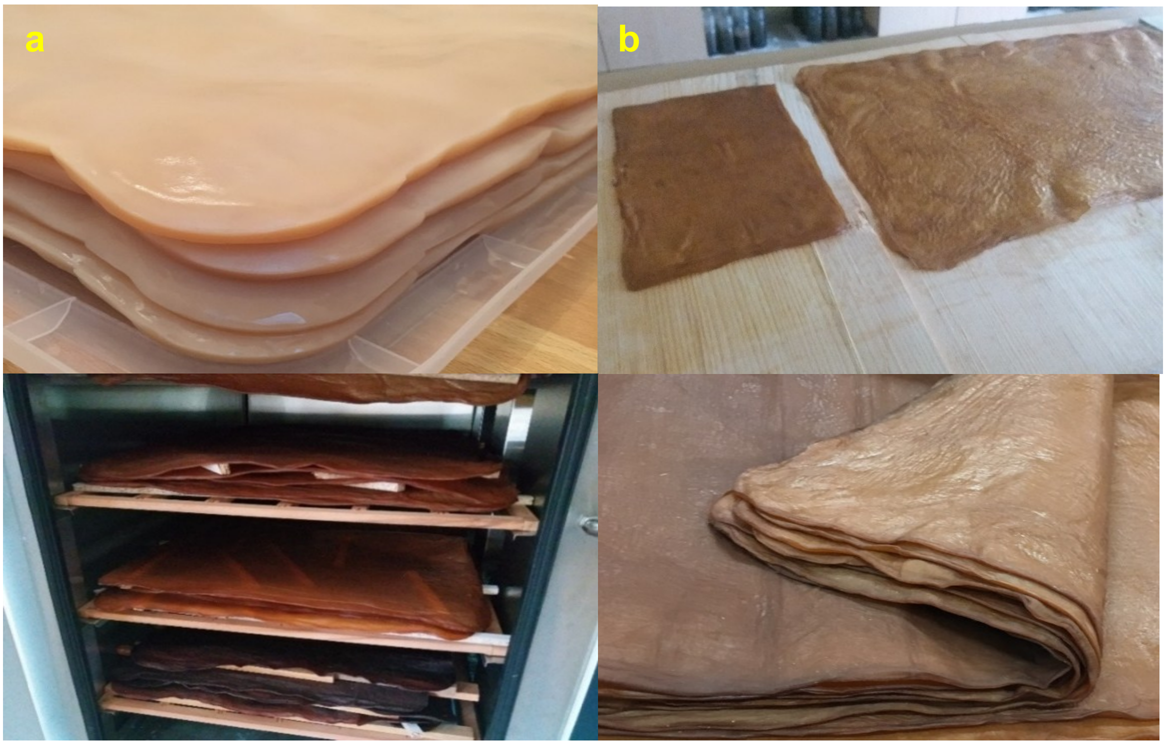

Fig. 1. Kombucha-derived BC pellicles: (a) conditioning/drying process; (b) stacked dried pellicles

Preparation of Test Specimens

The conditioned test specimens were manufactured into 3-layer laminated wood materials with dimensions of 400 × 100 × 20 mm in a hydraulic press. The layers are arranged as shown in Fig. 2.

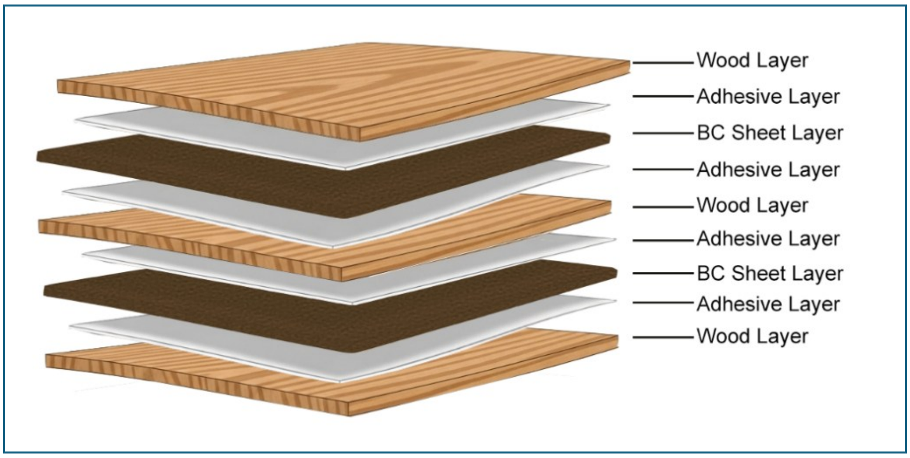

Fig. 2. Exploded view of a multi-layered laminated wood structure

The PVAc and UF adhesives were applied to the surface with a glue roller, whereas the PU adhesive was applied with a notched trowel. In the BC sheet-reinforced laminated materials (Fig. 3), the BC sheets were placed between the wood layers.

Fig. 3. Production process of laminated wood materials reinforced with BC sheets: (a) gluing, (b) layering, (c) pressing, and (d) conditioning

The laminated specimens, initially prepared with dimensions of 400 × 100 × 20 mm, were re-sized for the physical tests according to relevant standards. For both water absorption and thickness swelling (TS) tests, and density measurements, the samples were re-sized to 30 mm in length, 20 mm in width, and 20 mm in thickness. To eliminate moisture content differences originating from the gluing and sizing processes, all specimens were conditioned at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 3% until they reached a constant weight according to TS 13061-1 (2021).

Methods

Density test

Oven-dry density (δ_0) was determined according to the TS ISO 13061-2 (2021) standard. The specimens were dried at 103 ± 2 °C until they reached a constant weight (M_0). Their masses were measured on an analytical balance with a precision of ± 0.01 g, and their volumes (V_0) were determined by measuring their dimensions with a digital caliper with a precision of ± 0.01 mm. The oven-dry density was calculated using the following Eq. 1,

$$\delta_0 = \frac{M_0}{V_0} \tag{1}$$

where δ_0 represents the oven-dry density in grams per cubic centimeter (g/cm^3), M_0 is the oven-dry mass in grams (g), and V_0 is the oven-dry volume in cubic centimeters (cm^3). In the BC sheet-reinforced laminated specimens, the oven-dry densities could not be determined because the BC sheets deformed at 103 ± 2 °C. Therefore, the air-dry densities (δ_{12}) of these specimens were calculated using the following Eq. 2,

$$\delta_{12} = \frac{M_{12}}{V_{12}} \tag{2}$$

where δ_{12} denotes the air-dry density in grams per cubic centimeter (g/cm^3), M_{12} is the air-dry mass in grams (g), and V_{12} is the air-dry volume in cubic centimeters (cm^3).

Determination of Swelling and Water Absorption

The swelling ratio (%) in the pressing direction (α_{max}) was determined based on the TS 13061-15 (2021) standard. However, in the reinforced laminated specimens, the oven-drying step specified in the standard could not be applied because the BC sheets deformed at 103 ± 2 °C; instead, the initial measurements were performed on specimens conditioned at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 3%.

The initial dimensions of the conditioned specimens in the pressing direction (L_{min}) were measured with a digital caliper with a precision of ± 0.01 mm. Subsequently, the samples were fully immersed in distilled water (with a wire mesh placed on them, Fig. 4) and kept until their dimensional changes ceased. After being removed from the water, their final dimensions in the pressing direction (L_{max}) were measured. The swelling ratio in the pressing direction was calculated using the following Eq. 3,

$$\alpha_{max} = \frac{L_{max} - L_{min}}{L_{min}} x100 \qquad (3)$$

where α_{max} is the total swelling ratio in the pressing direction expressed as a percentage (%), L_{max} is the dimension in the pressing direction after water immersion (mm), and L_{min} is the dimension in the pressing direction after conditioning (mm).

The water absorption ratio (%) was determined using the same test specimens. The initial mass of each specimen (a_1) before water immersion and its final mass (a_2) weighed after its dimensional changes ceased. It was removed from the water, and its surface was wiped dry and it was measured on a balance with a precision of ± 0.01 g. The water absorption was calculated using the following Eq. 4,

$$WA = \frac{a_2 - a_1}{a_1} x100 \qquad (4)$$

where WA is the water absorption expressed as a percentage (%), a_1 is the initial mass of the test piece before water immersion in grams (g), and a_2 is the final mass of the test piece after water immersion in grams (g).

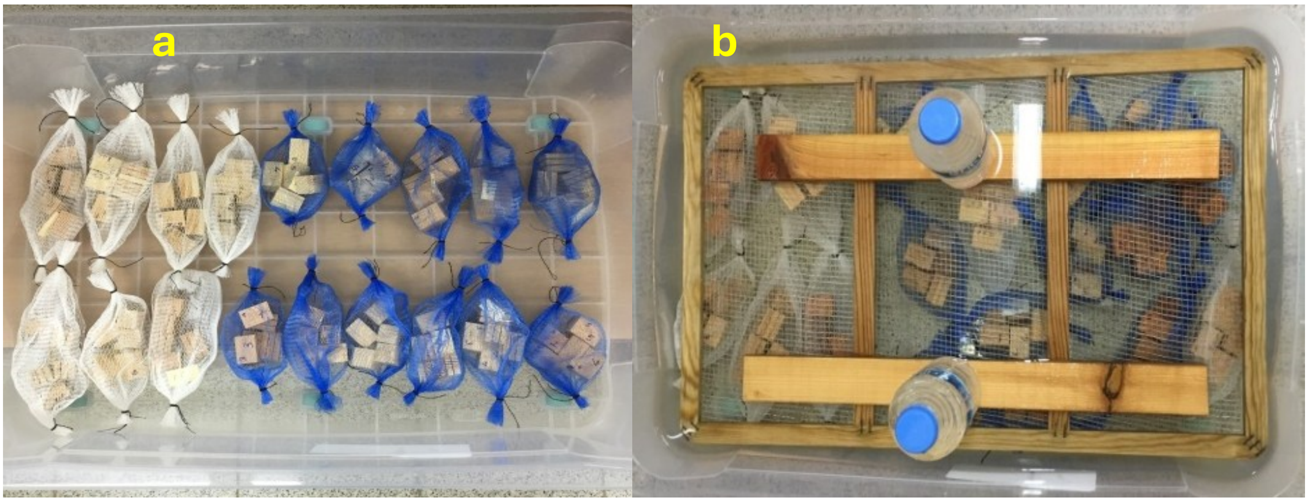

Fig. 4. Swelling test setup: (a) samples in mesh bags, (b) immersion under weights

Thermogravimetric Analysis

The TGA tests of the BC sheets obtained from kombucha pellicles were performed at the Düzce University Scientific and Technological Research Application and Research Center (DUBIT), using a Shimadzu DTG 60H - DSC 60 instrument. In the analysis, the mass changes of the sample under a controlled temperature increase were examined.

Scanning Electron Microscopy Analysis

The morphological examination of the BC sheets obtained from kombucha pellicles by SEM was carried out at DUBIT, using an FEI Quanta FEG 250 instrument. For this purpose, a cross-section of the BC sheet was taken and coated with gold in a Denton Vacuum Desk V device for clearer imaging. The coated specimens, with dimensions of 3 × 3 × 1 mm, were imaged on their cross-sectional surfaces under high vacuum.

Statistical Analysis

For the statistical evaluations, the MSTAT-C software package (University of Michigan, MI, USA) was used. The effects of the factors were determined through analysis of variance (ANOVA) tests. Duncan's multiple range test (DMRT), using the least significant difference (LSD) critical value, was used to determine the significant differences between the variables.

RESULTS AND DISCUSSION

Density

The mean oven-dry and air-dry densities of the BC sheet-reinforced laminated wood are given in Tables 2 and 3.

Table 2. Arithmetic Means of Oven-dry Density for the Control Group (g/cm³)

Factors	Polyvinyl Acetate	Polyurethane	Urea Formaldehyde
Beech	0.58	0.60	0.65
Chestnut	0.50	0.54	0.50
Pine	0.57	0.56	0.62

According to Table 2, the highest oven-dry density was determined in the control group beech specimens laminated with UF adhesive, while the lowest density was found in the control group chestnut specimens laminated with PVAc and UF adhesives. For the BC sheet-reinforced laminated specimens, the oven-dry density values could not be determined because the BC sheets deformed because of the 103 ± 2 °C temperature.

Table 3. Arithmetic Means of Air-dry Density (g/cm³)

Factors	Polyvinyl Acetate		Polyurethane		Urea Formaldehyde	
	Control	BC Sheet Reinforced	Control	BC Sheet Reinforced	Control	BC Sheet Reinforced
Beech	0.62	0.69	0.63	0.67	0.68	0.68
Chestnut	0.54	0.61	0.58	0.60	0.55	0.63
Pine	0.61	0.65	0.59	0.66	0.66	0.68

According to Table 3, the highest air-dry density was observed in the BC sheet-reinforced beech specimens laminated with PVAc adhesive, whereas the lowest density was found in the control group chestnut specimens also laminated with PVAc adhesive.

Swelling in the Pressing Direction

The arithmetic mean values for the swelling ratio in the pressing direction (%), which were obtained to determine the effect of BC sheets in laminated wood production, differed according to wood species, adhesive type, and lamination factors. To determine the factors causing this variation, an ANOVA was performed, and the results are presented in Table 4.

Table 4. ANOVA Results for Swelling Values in the Pressing Direction (%)

Factors	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Level of Significance ($p \leq 0.05$)
Wood type (A)	2	318.543	159.271	1317.6771	0.0000*
Adhesive Type (B)	2	34.748	17.374	143.7360	0.0000
Lamination (C)	1	63.824	63.824	528.0229	0.0000
Interaction (AB)	4	35.438	8.860	73.2964	0.0000
Interaction (AC)	2	48.925	24.463	202.3830	0.0000
Interaction (BC)	2	1.255	0.627	5.1910	0.0078
Interaction (ABC)	4	29.469	7.367	60.9513	0.0000
Error	72	8.703	0.121		
Total	89	540.904			

*Significant at 95% confidence level

According to the ANOVA results, the swelling values in the pressing direction showed a significant difference ($p \leq 0.05$) depending on the wood species, adhesive type, lamination factor, and the interactions between these factors. To determine the source of this variation, DMRT was applied using the LSD critical value. The results of this comparison at the levels of wood species, adhesive type, and lamination factors are presented in Table 5.

Table 5. Duncan Test Comparison Results for Swelling in the Pressing Direction According to Wood Species, Adhesive Type, and Lamination Factor

Wood Type	$\bar{x}$	HG
Pine	6.295	B
Beech	9.225	A*
Chestnut	4.680	C
LSD ± 0.1790		
Adhesive Type	$\bar{x}$	HG
Polyvinyl Acetate	7.599	A*
Polyurethane	6.432	B
Urea Formaldehyde	6.169	C
LSD ± 0.1790		
Lamination	$\bar{x}$	HG
Control	5.891	B
BC Sheet Reinforced	7.575	A*
LSD ± 0.1462		

Note: $\bar{x}$ = Arithmetic mean; HG = homogeneity group; and * = The highest swelling in the pressing direction

According to Table 5, at the wood species level, the highest swelling value in the pressing direction was obtained in the laminated specimens produced from beech wood (9.22%), while the lowest was obtained in those produced from chestnut wood (4.68%). At the adhesive type of level, the highest value was determined in the laminated specimens adhered with PVAc adhesive (7.59%), whereas the lowest value was found in those adhered with UF adhesive (6.16%). At the lamination factor level, the highest swelling was determined in the BC sheet-reinforced laminated specimens (7.57%), and the lowest in the control group laminated specimens (5.89%).

In the evaluation based on wood species, the swelling in the pressing direction of the laminated specimens made from beech wood was found to be approximately 46.5% higher than that of the pine wood specimens. In contrast, the swelling ratio of the specimens made from chestnut wood was 25.7% lower than that of pine wood. These differences are thought to originate from the anatomical and chemical properties of the wood species, such as their fiber structure, porosity level, and responses to water. The literature indicates that wood species with higher density have thicker cell walls, and therefore exhibit greater dimensional changes; however, they have less void volume, which leads to lower water absorption (Bal and Bektaş 2012). The fact that beech wood is denser than the other wood species used in this study, and therefore exhibits a higher swelling, is consistent with the literature.

When evaluated by adhesive type, the swelling of specimens using PVAc adhesive was found to be 18.1% higher than that of the polyurethane-adhered specimens. In contrast, specimens adhered with urea-formaldehyde exhibited a swelling 18.8% lower than those with PVAc and 4.1% lower than those with PU. These differences are considered to be related to the adhesive's capacity to form a barrier against water and its interaction with the wood. Furthermore, this is thought to be because adhesion with PVAc occurs only physically, through the evaporation of water from the solution, and lacks the chemical reaction present in the other adhesives used in the study. As stated in the literature, PVAc adhesive is a product of polymerization, and its curing is a physical process (Gadhave 2023; Lee *et al.* 2025). Additionally, it is reported that chemically based adhesives are more water-resistant than physically-based adhesives (Kurt 2008). This, in turn, may have caused the PVAc adhesive to absorb more water.

In terms of the lamination factor, the swelling in the pressing direction in the BC sheet-reinforced specimens was 28.6% higher than that of the control group. This result suggests that the BC sheet reinforcement application may have increased water permeability and therefore negatively affected the swelling ratios. In the literature, it is stated that there are two types of thickness increase in plywood. The first is the apparent thickness increase due to the springback of the wood material that was compressed by the press pressure; the second is the true thickness increase that occurs as the wood absorbs water up to the fiber saturation point (Bal and Bektaş 2012). In this study, the BC sheet-reinforced laminated specimens exhibited a higher swelling while having a lower water absorption. This seemingly paradoxical behavior can be interpreted through a multi-faceted mechanism. Firstly, the BC sheet itself, being highly hydrophilic, likely swells significantly upon water uptake, contributing directly to the total thickness increase even if its contribution to the overall mass of absorbed water is low. Secondly, the interface between the BC sheet, the adhesive, and the wood surface plays a critical role. Any imperfect adhesion could create micro-voids that, while not retaining significant water mass, contribute to dimensional expansion. Furthermore, this distinct interlayer may have exacerbated the 'springback' phenomenon; the compressed wood lamellas could recover more of their pre-compression thickness upon wetting, using the less-integrated BC layer as a point of release, leading to a higher overall swelling measurement.

The DMRT comparison results for the interaction level of wood species, adhesive type, and lamination factors, along with the results of the collective comparisons, are presented in Fig. 5.

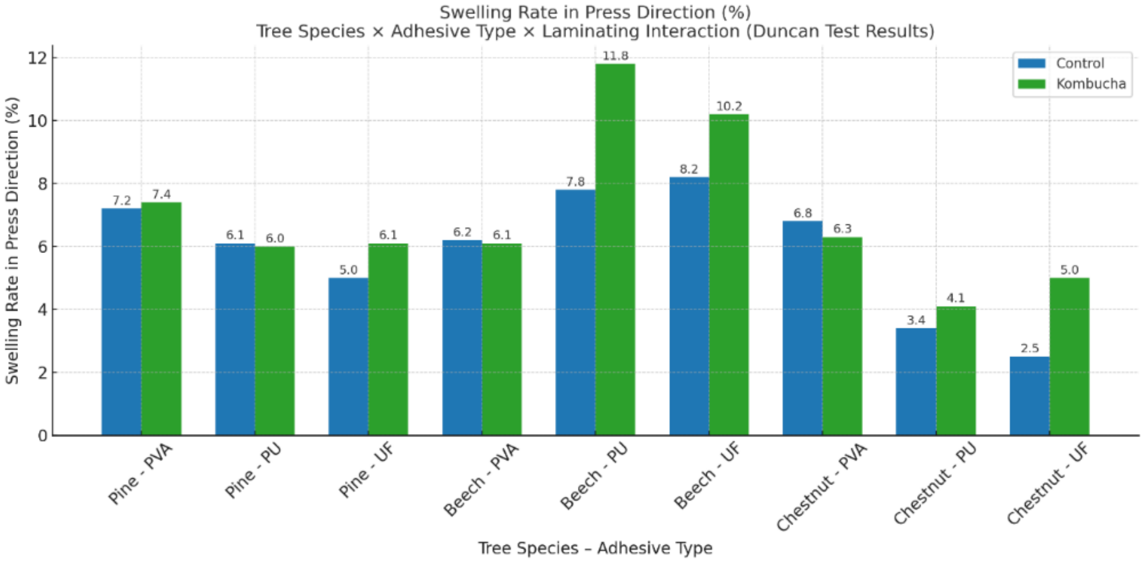

Fig. 5. DMRT comparison results for swelling values in the pressing direction based on the interaction of wood species, adhesive type, and lamination factor

According to the data in Fig. 5, the highest value for the swelling in the pressing direction (11.8%) was observed in the beech wood specimens treated with BC sheet and bonded with polyurethane adhesive. In contrast, the lowest swelling (2.5%) was determined in the chestnut specimens that were not treated with BC sheet and were bonded with urea-formaldehyde adhesive.

Water Absorption in the Pressing Direction

The arithmetic mean values for the water absorption (%), obtained to determine the effect of BC sheets in laminated wood production, differed according to wood species, adhesive type, and lamination factors. To determine the factors causing this variation, an Analysis of Variance (ANOVA) was performed, and the results are presented in Table 6.

Table 6. ANOVA Results for Water Absorption Values in the Pressing Direction (%)

Factors	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Level of Significance ($p \leq 0.05$)
Wood type (A)	2	4188.864	2094.432	831.5631	0.0000*
Adhesive Type (B)	2	17.770	8.885	3.5276	0.0346
Lamination (C)	1	372.873	372.873	148.0438	0.0000
Interaction (AB)	4	433.560	108.390	43.0347	0.0000
Interaction (AC)	2	762.666	381.333	151.4025	0.0000
Interaction (BC)	2	577.699	288.850	114.6835	0.0000
Interaction (ABC)	4	1148.438	287.110	113.9926	0.0000
Error	72	181.344	2.519		
Total	89	7683.215			

*Significant at 95% confidence level

According to the ANOVA results, the effects of wood species, adhesive type, lamination factor, and the interactions between these factors on the water absorption were found to be significant ($p \leq 0.05$). To determine the source of this variance, the DMRT test was applied at the levels of wood species, adhesive type, and lamination factors using the LSD critical value, and the comparison results are presented in Table 7.

Table 7. Duncan Test Comparison Results for Water Absorption in the Pressing Direction According to Wood Species, Adhesive Type, and Lamination Factor

Wood Type	$\bar{x}$	HG
Pine	29.52	C
Beech	42.65	B
Chestnut	45.04	A*
LSD ± 0.8169		
Adhesive Type	$\bar{x}$	HG
Polyvinyl Acetate	39.64	A*
Polyurethane	38.56	B
Urea Formaldehyde	39.00	AB
LSD ± 0.8169		
Lamination	$\bar{x}$	HG
Control	41.11	A*
BC Sheet Reinforced	37.03	B
LSD ± 0.6670		

Note: $\bar{x}$ = Arithmetic mean; HG = homogeneity group; and * = The highest water absorption in the pressing direction

According to Table 7, at the wood species level, the highest water absorption was obtained in the laminated specimens produced from chestnut wood (45.04%), while the lowest water absorption was obtained in the specimens produced from pine wood (29.52%). When evaluated at the adhesive type level, the highest water absorption was determined in the PVAc-adhered specimens (39.64%), while the lowest water absorption was observed in the PU-adhered specimens (38.56%). The UF-adhered specimens were found to have an intermediate value (39%). At the lamination factor level, the water absorption was measured to be higher in the control group (41.11%), while this ratio was found to be lower in the reinforced-laminated specimens (37.03%).

In the evaluation based on wood species, the water absorption of laminated specimens produced from chestnut wood was approximately 52.5% higher than that of the pine wood specimens. In contrast, it was determined that the specimens produced from beech wood had a 44.5% higher water absorption compared to pine. These differences are thought to originate from the natural properties of the woods, such as their porosity structure, fiber density, and sap content. In literature studies, it is stated that the water absorption of pine wood is higher than that of beech wood (Pelit *et al.* 2017). The discrepancy between the findings of this study and the data in the literature may be attributed to the variation in the physical and mechanical properties of trees depending on factors such as their growing region and environmental conditions. Additionally, the resinous structure of pine wood may have reduced its water permeability, thereby lowering the water absorption. The literature states that woods containing natural resins or extractive substances provide a certain degree of water repellency in panels (Gündüz *et al.* 2005).

When examined by adhesive type, the PVAc-adhered specimens absorbed approximately 2.8% more water than the PU-adhered specimens. The water absorption of the UF-adhered specimens was 1.6% lower than that of the PVAc-adhered specimens and 1.1% higher than that of the PU-adhered ones. These small differences indicate that the barrier effect of the adhesive against water and the quality of the bond it forms with the wood played a role.

At the lamination factor level, the water absorption of the specimens in the control group was approximately 11% higher than that of the reinforced specimens. Although BC sheets are hydrophilic, it is hypothesized that the penetration of the adhesive into the porous BC network, followed by consolidation during the pressing stage, created a densified and less permeable physical barrier. This barrier would physically restrict water ingress into the composite's core, thus leading to a decrease in the overall water absorption. This phenomenon is likely influenced by the specific BC-adhesive interactions under pressure. During hot pressing with UF adhesive, the thermosetting resin could have penetrated and cured within the BC's nanofibrillar network, creating a rigid, cross-linked, and less permeable interphase. In contrast, thermoplastic adhesives such as PVAc may have formed a less integrated film. Furthermore, the high pressure applied during lamination likely densified the porous BC network. This densified, adhesive-infiltrated BC layer would create a highly tortuous path for water molecules, significantly slowing their diffusion rate and reducing the total mass of absorbed water, even as other mechanisms contributed to thickness swelling. Furthermore, in the study, different layer thicknesses were used for the control group and the BC sheet-reinforced laminations to achieve the same final lamination thickness. Because the use of thicker layers in the control group laminations compared to the reinforced ones would increase the amount of wood material, this may have caused the control group to absorb more water. This result may suggest that the BC sheet reinforcement created a more compact structure by somewhat limiting the wood's water absorption capacity.

The DMRT comparison results for the interaction level of wood species, adhesive type, and lamination factors, along with the results of the collective comparisons, are presented in Fig. 6.

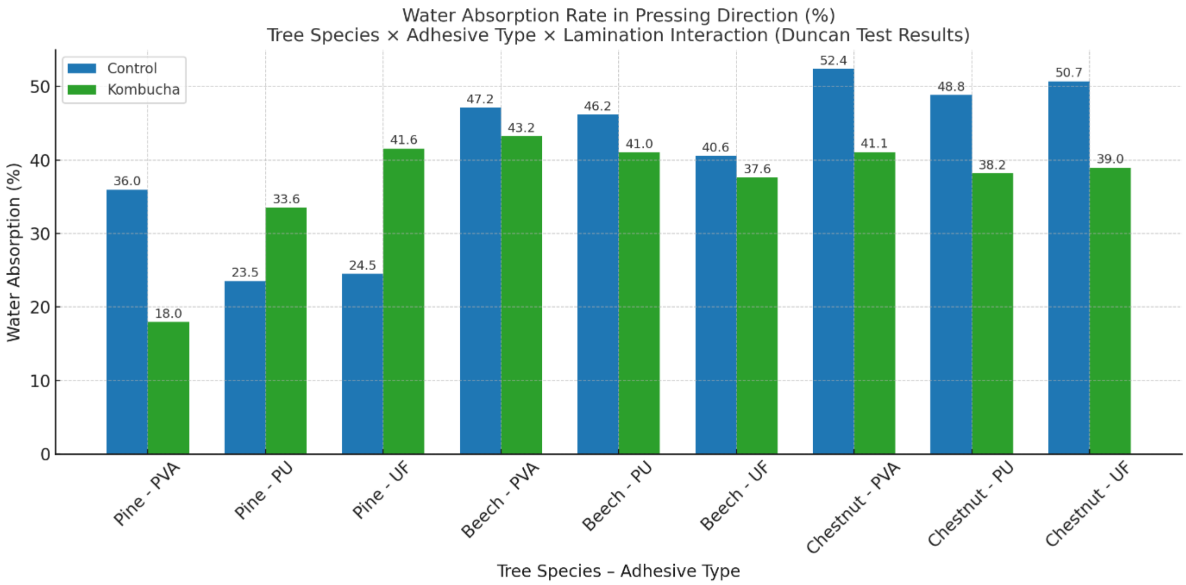

Fig. 6. DMRT comparison results for water absorption in the pressing direction based on the interaction of wood species, adhesive type, and lamination factor

According to the data in Fig. 6, the lowest water absorption (18.0%) was obtained in the pine wood specimens treated with BC sheet and laminated with polyvinyl acetate (PVAc) adhesive. In contrast, the highest water absorption was recorded for the chestnut specimens not reinforced with BC sheets and bonded with PVAc (52.4%).

TGA

In this study, TGA was performed to determine the thermal behavior of the BC sheet used in the production of reinforced laminated wood material (Fig. 7).

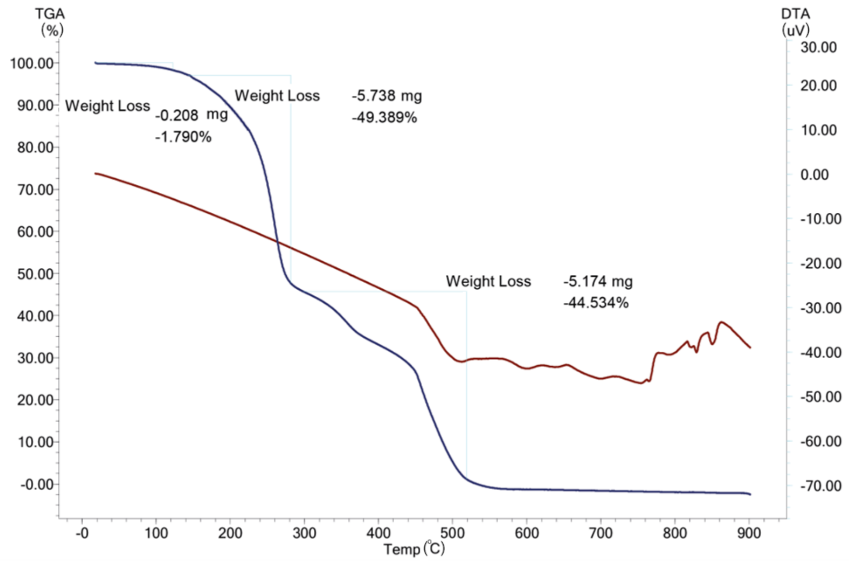

Fig. 7. TGA analysis

As a result of the TGA analysis, the BC sheet was observed to exhibit a multi-stage degradation profile. The initial weight loss of 1.8% occurred during the temperature increase up to approximately 110 °C, and this loss is attributed to the removal of moisture. The main degradation phase started at approximately 150 °C and continued up to 285 °C, during which the sample lost 49.39% of its mass. At this stage, it is understood that the organic structure was largely and thermally decomposed. When the temperature reached 500 °C, the total weight loss exceeded 95%, indicating that the sample had almost completely degraded.

SEM Analysis

To investigate the microstructure and the nature of the interface in the reinforced composite, SEM analysis was performed on the cross-section of the reinforced laminated wood material. For this analysis, small sections were cut from the final laminated composites using a microtome.

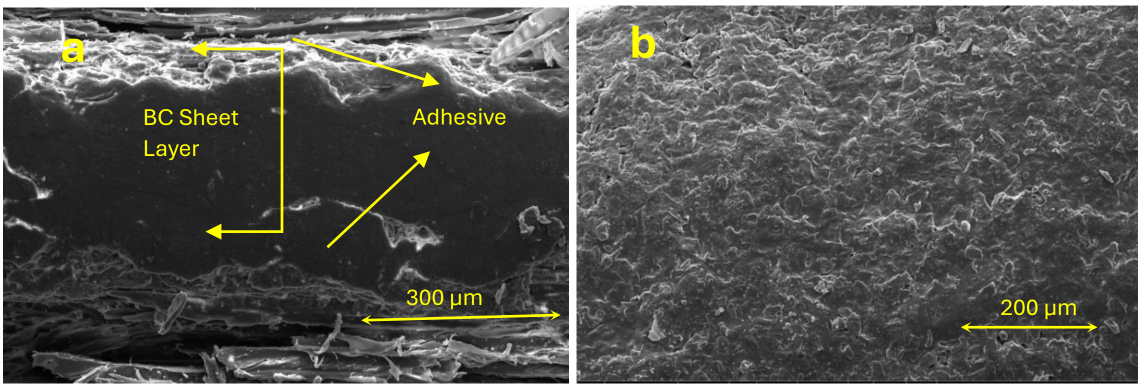

Fig. 8. SEM images: (a) cross-sectional SEM image showing the BC sheet–wood interface; (b) overall surface morphology of BC sheet

Figure 8 clearly reveals that the BC sheet formed a distinct, dense, and continuous layer integrated between the wood layers. The initially porous and fibrillar network of the raw BC sheet appears to have been significantly consolidated during the hot-press lamination process, forming a solid matrix fully embedded within the adhesive. This observation of a densified, adhesive-saturated BC layer supports the hypothesis that a less permeable barrier was created. Such a structure, featuring a highly tortuous path for water molecules, would explain the lower water absorption observed in the BC-reinforced samples. Additionally, a very sharp and well-defined interface between the BC layer and the wood fibers was observed. The formation of such a distinct and consolidated interlayer could be a contributing factor to the increased thickness swelling. It is also possible that this rigid layer amplifies the springback of the pressed wood, causing it to swell more in thickness when it gets wet. It should also be noted that although the BC sheet acts as a dense barrier limiting water diffusion through the composite, its intrinsic hydrophilic nature remains. Upon immersion, water can still be absorbed *within* the nanofiber network of the BC layer itself, causing localized swelling. Upon immersion, water molecules can penetrate the consolidated nanofiber network, causing the BC layer itself to swell significantly. While the mass of water absorbed by the thin BC layer is minor compared to the total mass of the composite, its percentage increase in thickness could be substantial. This disproportionate swelling of the interlayer, combined with the swelling of the wood lamellas, would result in a greater total thickness swelling for the composite, helping to explain the observed phenomenon of high swelling coupled with low water absorption. Thus, the SEM analysis provides crucial microstructural evidence that helps explain the seemingly paradoxical physical properties observed in this study.

CONCLUSIONS

This study investigated the effect of bacterial cellulose (BC) sheets derived from kombucha pellicles on the physical properties of laminated wood made from Scots pine, beech, and chestnut, using polyvinyl acetate (PVAc), polyurethane (PU), and urea formaldehyde (UF) adhesives. As a result of the experimental analyses and statistical evaluations performed, the following conclusions were reached:

1. The main contribution of this study is the initial demonstration that kombucha-derived bacterial cellulose sheets can be used to reinforce laminated wood, revealing a paradoxical physical effect where the reinforcement layer significantly decreases water absorption while simultaneously increasing thickness swelling.
2. The air-dry density values in the reinforced specimens were generally higher than in the control group. This suggests that the structural density of the BC has an effect on the laminated system.
3. The swelling ratio in the pressing direction was found to be significantly higher in the reinforced specimens compared to the control group. This increase is thought to be due to the BC layers not integrating sufficiently with the wood and adhesive systems and failing to form an effective barrier against water passage.
4. In terms of water absorption, lower values were obtained in the reinforced specimens compared to the control group. This can be interpreted as the penetration of the adhesive into the structure of the cellulose layer creating a hydrophobic effect, thus limiting water absorption.

5. As a result of the thermogravimetric analysis (TGA) and scanning electron microscope (SEM) analyses, it was observed that the BC exhibited a multi-stage thermal degradation profile and had structural irregularities on its surface. These observations indicate that the purity degree of the BC and the post-production processing can directly affect the material's performance.
6. This study examined the potential of reinforcing wood laminates with BC panels, without addressing scalability concerns. Notably, the direct production of ready-to-use mats presents a major advantage over conventional fiber sources. Future research may focus on scalability, enhancing panel homogeneity through controlled drying and reducing production time via optimized fermentation.

ACKNOWLEDGMENTS

The authors are grateful to the staff of the Düzce University Scientific and Technological Research Application and Research Center (DUBIT) for their support in performing the Scanning Electron Microscopy (SEM) and Thermogravimetric Analysis (TGA) measurements. Sincere thanks are also extended to the local manufacturing companies for their support in material procurement.

REFERENCES CITED

Asdrubali, F., Ferracuti, B., Lombardi, L., Guattari, C., Evangelisti, L., and Grazieschi, G. (2017). "A review of structural, thermo-physical, acoustical, and environmental properties of wooden materials for building applications," *Building and Environment* 114, 307-332. DOI: 10.1016/j.buildenv.2016.12.033

ASTM D3023-98 (2017). "Standard practice for determination of resistance of factory-applied coatings on wood products to stains and reagents," ASTM International, West Conshohocken, PA, USA.

Ayrilmis, N., and Winandy, J. E. (2009). "Effects of post heat-treatment on surface characteristics and adhesive bonding performance of medium density fiberboard," *Materials and Manufacturing Processes* 24(5), 594-599. DOI: 10.1080/10426910902748032

Báder, M., and Németh, R. (2019). "Moisture-dependent mechanical properties of longitudinally compressed wood," *European Journal of Wood and Wood Products* 77(6), 1009-1019. DOI: 10.1007/s00107-019-01448-1

Bal, B. C., and Bektaş, İ. (2012). "The effects of wood species, load direction, and adhesives on bending properties of laminated veneer lumber," *BioResources* 7(3), 3104-3112. DOI: 10.15376/biores.7.3.3104-3112

Brischke, C., and Alfredsen, G. (2020). "Wood-water relationships and their role for wood susceptibility to fungal decay," *Applied Microbiology and Biotechnology* 104(9), 3781-3795. DOI: 10.1007/s00253-020-10479-1

Budakçı, M., Pelit, H., Sönmez, A., and Korkmaz, M. (2016). "The effects of densification and heat post-treatment on hardness and morphological properties of wood," *BioResources* 11(3), 7822-7838. DOI: 10.15376/biores.11.3.7822-7838

Cazón, P., Velázquez, G., and Vázquez, M. (2020). "Bacterial cellulose films: Evaluation of the water interaction," *Food Packaging and Shelf Life* 25, article 100526. DOI: 10.1016/j.fpsl.2020.100526

Fillat, A., Martínez, J., Valls, C., Cusola, O., Roncero, M. B., Vidal, T., Valenzuela, S. V., Diaz, P., and Pastor, F. I. J. (2018). "Bacterial cellulose for increasing barrier properties of paper products," *Cellulose* 25(10), 6093-6105. DOI: 10.1007/s10570-018-1967-0

Gadhave, R. V. (2023). "Comparative study of polyvinyl acetate-acrylic acid and polyvinyl acetate-methacrylic acid copolymer-based wood adhesives," *Journal of the Indian Academy of Wood Science* 20(2), 173-182. DOI: 10.1007/s13196-023-00319-w

Grottesi, G., and Coelho, G. B. A. (2023). "Heat and moisture induced stress and strain in wooden artefacts and elements in heritage buildings: A review," *Journal of Cultural Heritage* 60, 218-231. DOI: 10.1016/j.culher.2023.01.006

Guenther, R., Tajmar, M., and Bach, C. (2024). "Wood and wood-based materials in space applications—A literature review of use cases, challenges and potential," *Aerospace* 11(11), article 910. DOI: 10.3390/aerospace11110910

Gündüz, G., and Masraf, Y. (2005). "The effect of changing production conditions on the mechanical and physical properties of three-layer oriented strand board," *Journal of the Bartin Faculty of Forestry* 7(1), 58-71.

Hermann, S. (1928). "Über die sogenannte ‘Kombucha’ [About the so-called 'Kombucha']," *Biochemische Zeitschrift* 202, 176-199.

Hervy, M., Blaker, J. J., Letícia, A., and Lee, K. (2018). "Mechanical response of multi-layer bacterial cellulose nanopaper reinforced polylactide laminated composites," *Composites Part A: Applied Science and Manufacturing* 107, 155-163. DOI: 10.1016/j.compositesa.2017.12.025

Keskin, H., and Togay, A. (2019). "Physical and mechanical properties of laminated wood materials made up with the combination of oriental beech wood and poplar wood," *Turkish Journal of Forestry* 20(4), 366-373. DOI: 10.17568/og.602519

Kılınç, İ., Budakçı, M., and Korkmaz, M. (2023). "The use of environmentally friendly abrasive blasting media for paint removal from wood surfaces," *BioResources* 18(1), 1185-1205. DOI: 10.15376/biores.18.1.1185-1205

Kurt, Ş. (2008). *Changes in Some Technological Properties of Impregnated Laminated Veneer Lumber (LVL) in the Marine Environment*, Ph.D. Thesis, Zonguldak Karaelmas University, Zonguldak, Turkey.

Ladero, M., Villar, J. C., and Santos, S. M. (2017). "Paper reinforcing by *in situ* growth of bacterial cellulose," *Journal of Materials Science* 52(10), 5882-5893. DOI: 10.1007/s10853-017-0824-0

Lee, S. H., Yoon, S. G., and Lee, D. W. (2025). "Precise polymerization control and applications of polyvinyl acetate," *Polymer (Korea)* 49(1), 1-16. DOI: 10.7317/pk.2025.49.1.1

Liang, Z., Chen, G., Wang, Y., Wang, Z., and Gong, M. (2022). "The dimensional stability and bonding performance of hybrid CLT fabricated with lumber and COSB," *Buildings* 12(10), article 1669. DOI: 10.3390/buildings12101669

Mantanis, G. I. (2017). "Chemical modification of wood by acetylation or furfurylation: A review of the present scaled-up technologies," *BioResources* 12(2), 4476-4489. DOI: 10.15376/biores.12.2.Mantanis

Mbituyimana, B., Liu, L., Ye, W., Ode Boni, B. O., Zhang, K., Chen, J., Thomas, S., Vasilievich, R. V., Shi, Z., and Yang, G. (2021). "Bacterial cellulose-based composites for biomedical and cosmetic applications: Research progress and existing products," *Carbohydrate Polymers* 273, article 118565. DOI: 10.1016/j.carbpol.2021.118565

Pelit, H., Korkmaz, M., and Budakçı, M. (2017). "Effects of water repellents on some physical properties of different wood materials," *Journal of Advanced Technology Sciences* 6(3), 1027-1036.

Reiss, J. (1994). "Influence of different sugars on the metabolism of the tea fungus," *Zeitschrift für Lebensmittel-Untersuchung und -Forschung* 198(3), 258-261. DOI: 10.1007/BF01192606

Tabarsa, T., Sheykhnazari, S., Ashori, A., and Mashkour, M. (2017). "Preparation and characterization of reinforced papers using nano bacterial cellulose," *International Journal of Biological Macromolecules* 101, 334-340. DOI: 10.1016/j.ijbiomac.2017.03.108

TS ISO 13061-1 (2021). "Physical and mechanical properties of wood - Test methods for small clear wood specimens - Part 1: Determination of moisture content for physical and mechanical tests," Turkish Standards Institution, Ankara, Turkey.

TS ISO 13061-2 (2021). "Physical and mechanical properties of wood - Test methods for small clear wood specimens - Part 2: Determination of density for physical and mechanical tests," Turkish Standards Institution, Ankara, Turkey.

TS ISO 13061-15 (2021). "Physical and mechanical properties of wood - Test methods for small clear wood specimens - Part 15: Determination of radial and tangential swelling," Turkish Standards Institution, Ankara, Turkey.

TS ISO 3129 (2021). "Wood – Sampling methods and general requirements for physical and mechanical testing of small clear wood specimens," Turkish Standards Institution, Ankara, Turkey.

Zhan, T., Lyu, J., and Eder, M. (2021). "*In situ* observation of shrinking and swelling of normal and compression Chinese fir wood at the tissue, cell and cell wall level," *Wood Science and Technology* 55(5), 1359-1377. DOI: 10.1007/s00226-021-01321-6

Zhu, X., Li, X., Zhang, Z., Cheng, L., Wu, J., Li, L., and Zhang, Z. (2022). "Effect of structural design on the pore structure, water resistance, and mechanical properties of engineered wood/bamboo laminated composites," *Polymers* 14(24), article 5386. DOI: 10.3390/polym14245386

Article submitted: June 18, 2025; Peer review completed: July 26, 2025; Revisions accepted: August 12, 2025; Published: August 20, 2025.
DOI: 10.15376/biores.20.4.8976-8992