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Mechanical Wood Properties and Color of Combined PLA- and Thermal-Treated Beech Wood (*Fagus sylvatica* L.)

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Abstract

European beech (*Fagus sylvatica* L.) was modified by thermal treatment at 180 °C, oligomeric lactic acid (OLA) impregnation followed by catalyst-free polymerization (120 or 160 °C), and their combined application to evaluate changes in mechanical performance and color. The results for untreated beech wood showed low variability; in a four-point bending test, it exhibited an average modulus of rupture of 120.4 MPa and a bending modulus of elasticity of 8.7 GPa. Its compression strength and compression modulus of elasticity were 45.4 MPa and 2.48 GPa, respectively, while the corresponding Brinell–Mörath hardness values were 29.0 MPa on the side and 64.0 MPa on the end grain. Thermal treatment alone maintained bending strength of untreated beech, while highly increasing strength properties. OLA-based treatments generally produced significant reductions in modulus of rupture, bending modulus of elasticity, and deflection at maximum load. OLA-treated specimens exhibited increased brittleness and variability. Color measurements revealed substantial treatment-dependent darkening, with overall color differences ranging from 19.5 to 69.0. The results demonstrate that moderate thermal modification can enhance selected mechanical properties of beech wood, whereas OLA impregnation, especially under severe curing conditions, causes pronounced mechanical deterioration with the curing performed.

Keywords: Brinell–Mörath hardness; color measurement; heat treatment; compression strength; in situ polymerization; lactic acid; *MoE*; *MoR*; beech wood properties

1. Introduction

Beech wood (*Fagus sylvatica* L.) is regarded as one of the most promising hardwood species for environmentally friendly wood modification because of its relatively homogeneous anatomical structure, excellent impregnability resulting from the open vessel network within the heartwood, and its wide availability at comparatively low cost, both currently and in the next decades. Furthermore, its low extractive content is advantageous for most chemical and thermal modification (TM) processes.

TM of beech (*Fagus sylvatica* and *Fagus orientalis*) is an established commercial technology primarily used to enhance dimensional stability and resistance to biotic degradation. Atmospheric treatments, categorized as dry processes, typically occur between 160 °C and 240 °C under air, vacuum, or inert gas media [1]. Schmidtová et al. [2] investigated industrial treatments in an oxidizing air atmosphere at 190 °C, while Percin et al. [3] explored atmospheric pressure conditions between 150 °C and 200 °C. The mechanical effects of these treatments are significant, often involving a trade-off between stability

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and strength. While the modulus of elasticity (*MoE*) remains statistically unchanged or slightly increased in some publications, strength properties like the modulus of rupture (*MoR*) and Brinell hardness significantly decline as temperature and duration increase. On average, structural-size beech timber can exhibit a 17%–20% reduction in bending strength. Authors attribute these changes to complex chemical transformations. The primary cause of strength loss is the thermal degradation of hemicelluloses, the most labile cell wall polymers. Improved dimensional stability is linked to the reduction of accessible hydroxyl groups and lignin cross-linking through the formation of methylene bridges, which creates a more rigid network [2–5].

The modification of wood with lactic acid (LA) is a promising, environmentally friendly approach to enhance the properties of solid wood, particularly for species like beech. The process typically begins with the preparation of lactic acid oligomers (OLA) through direct polycondensation of LA monomers, involving the removal of water at elevated temperatures between 75 and 140 °C under reduced pressure without the use of catalysts [6–8]. Impregnation of beech wood with OLA is generally performed under vacuum or vacuum–pressure cycles to ensure deep penetration into the wood structure. Subsequent in situ polymerization is induced through thermal curing, typically at temperatures ranging from 110 °C to 160 °C. Research focusing on catalyst-free treatments highlights that curing temperature and curing time are the most critical factors for stabilizing the polymer within the wood [7,9]. The mechanical effects of these treatments on beech are significant. Bak et al. [10] reported a 15%–25% increase in oven-dry density and a 15%–40% improvement in end-grain hardness. Noël et al. [11] observed that the mechanical state of the modified wood is highly dependent on the curing cycle: short heating cycles result in a softened, easily bendable material, whereas extended heating leads to a hardened, higher-density composite. These changes are primarily attributed to the physical bulking of the cell lumens and cell walls, which enhances the lateral stability of the wood tissue and significantly reduces the equilibrium moisture content. However, catalyst-free polymerization often leaves non-polymerized residues within the wood structure. A significant portion of OLA remains as low-molecular-weight oligomers that do not fully polymerize even after 48 h at 160 °C. These residues are prone to leaching; for instance, curing at 120 °C can lead to up to 80% of the product being leached when exposed to water, as the polymerization is insufficient to fix the OLA within the wood matrix. Fixation at higher temperatures likely occurs through physical entanglement rather than chemical grafting to wood hydroxyl groups [7,11].

Both TM and lactic acid (LA)-based impregnation have been shown to improve dimensional stability, biological durability, and water resistance. However, these treatments are also associated with certain disadvantages, including reductions in mechanical performance and, in some cases, non-uniform modifier distribution throughout the wood structure. A previous investigation on beech wood modified with chestnut tannins demonstrated that oligomeric LA systems substantially enhanced dimensional stability—by as much as 70%—while also providing excellent fungal resistance, with the wood–LA composite polymerized at 160 °C exhibiting the most favorable overall performance. Similar improvements have been reported for LA formulations combined with different polyols, although these systems may introduce compromises between stiffness, strength, and the variability of mechanical properties [7,11–14].

The sequence in which TM and impregnation are applied plays a decisive role because TM alters both the chemical composition of wood and its permeability. TM may generate additional transport pathways and enlarge pore structure, thereby facilitating subsequent impregnation. Conversely, TM reduces wood wettability and modifies the chemical environment of the cell wall at the same time, which may either promote or restrict

modifier penetration depending on the treatment parameters and the modifier employed. Investigations involving other impregnation systems have likewise demonstrated that the penetration behavior of beech is strongly governed by its anatomical characteristics, particularly vessel architecture and internal wood structure [15–20].

Consequently, both TM and impregnation with LA represent interesting opportunities for reducing hygroscopicity, improving dimensional stability, and enhancing fungal durability. Nevertheless, these benefits must always be evaluated alongside their potential adverse effects on the mechanical performance of the modified wood [3,9,20]. TM often improves moisture resistance and decay resistance while lowering bending-related performance at higher severities, making bending and compression tests essential for judging whether the modified wood still meets engineering needs [3,21,22]. Hardness is equally important because it reflects surface resistance and is a practical indicator of wear performance, indentation resistance, and service quality after modification [9]. Modification can change surface integrity in either direction: some treatments increase hardness, while others reduce it substantially, so hardness helps distinguish a beneficial surface strengthening from a more brittle, failure-prone material [9,23,24]. In TM, chemical changes in beech wood can improve hydrophobicity and surface performance, but severe treatment also degrades hemicelluloses and is linked to mechanical weakening and brittle behavior. That means a harder surface is not automatically a better one: if the cell wall becomes too damaged, the wood may resist indentation but fail more easily under service loads [5,12,17,25]. For LA treatment, the processing conditions strongly influence the final physical and mechanical response. LA impregnation and polymerization may produce a more reinforced surface or simply a stiffened but potentially brittle material [7,8,26].

Color change is another hallmark of TM, with wood acquiring darker, tropical-like tints. But color is not merely an aesthetic issue. Heat-induced discoloration often tracks chemical changes. The darkening is caused by the formation of colored degradation products from hemicelluloses and oxidation products such as quinones, as well as lignin transformation. In this way, color measurement helps to document treatment severity and also product acceptance for visible applications. The latter question also applies to LA-treated wood due to its significant darkening [4,5,12,17,27–29].

The studies summarized above ensured comprehensive background information relevant to the objectives of the present investigation. Although thermally modified wood exhibits numerous desirable properties, it is also associated with several well-recognized limitations. Accordingly, this study aimed to evaluate the individual and combined effects of TM and LA impregnation employing different polymerization regimes in highly permeable European beech. Particular emphasis was placed on identifying potential synergistic interactions between these modification techniques, while preserving the natural character of the wood.

The present paper specifically focuses on the changes in mechanical performance and color induced by TM, LA impregnation, and their combined application. Accordingly, bending properties, compression properties, hardness, and color characteristics constitute the primary subject of this investigation. The study therefore complements the previously published work by Bak et al. [30], which addressed the physical properties, wood–water relationships, and fungal durability of the same modification systems. Together, the two studies provide a comprehensive understanding of the effects of these combined modification techniques on the performance of beech wood.

2. Materials and Methods

2.1. Samples and Treatments

European beech (*Fagus sylvatica* L.) was selected as the raw material for the experiments. To minimize the inherent variability of wood, all specimens were prepared from a single kiln-dried board. Six samples were established according to the treatments listed in Table 1. Selected samples were subjected to TM at 180 °C under atmospheric conditions to simulate the industrial thermal treatment processes most commonly applied in practice. A detailed description of the TM procedure is provided by Bak et al. [30].

Table 1. Identifiers of the samples used in this study and the short description of their treatments.

Short Description of the Treatment	Treatment Abbreviations Used in the Study
Untreated	Untreated
OLA impregnated and polymerized at 120 °C	Impregnated 120 °C
OLA impregnated and polymerized at 160 °C	Impregnated 160 °C
Thermally treated at 180 °C	Thermally treated
Thermally treated at 180 °C followed by OLA impregnation and polymerization at 120 °C	Thermally treated and Impregnated 120 °C
OLA impregnated and polymerized at 120 °C, followed by thermal treatment at 180 °C	Impregnated 120 °C and Thermally treated

Lactic acid modification was performed by impregnating the highly permeable beech wood with oligomeric lactic acid without the use of additional catalysts, to preserve the environmentally friendly nature of the wood. The raw material consisted of a 90% (*w*/*w*) aqueous solution of L(+)-lactic acid monomer supplied by Acros Organics b.v.b.a. (Geel, Belgium). Prior to impregnation, the lactic acid solution was dehydrated and partially oligomerized. This pretreatment generated oligomeric molecules that remained sufficiently small to penetrate the wood structure while substantially shortening and simultaneously moderating the subsequent in situ polymerization process within the wood. Following impregnation, the specimens underwent a curing stage carried out at different temperatures. The curing temperatures are summarized in Table 1, whereas the oligomerization process and other remaining treatment parameters were identical to those reported by Bak et al. [30]. Curing at 120 °C temperature is a proven and effective method based on numerous previous studies [8,10,26], therefore it became the basis for the combined treatments never tied before. Curing at 160 °C temperature, under the same conditions as the lower-temperature curing, was an initial attempt based on the description by Grosse et al. [7].

TM was subsequently combined with the LA treatment procedure, resulting in the additional samples presented in the last two rows of Table 1. The treatments were carried out in the specified sequence. Consequently, in the Impregnated 120 °C and Thermally treated sample, polymerization of the lactic acid occurred twice: initially during the conventional curing stage at 120 °C, followed by a second polymerization stage during TM at 180 °C for 10 h, excluding the gradual increase and decrease in temperature.

2.2. Tests

A total of 20 specimens per sample was used for bending tests, which measured 12 × 18 × 200 mm (width × height × length along the grain). The reduced specimen dimensions were necessary due to the limited capacity of the vacuum chamber. Four-point bending tests were carried out using an Instron 4208 universal testing machine (Illinois Tool Works Inc., Norwood, MA, USA), which provides more reliable measurements for highly modified wood than a conventional three-point loading configuration. The shorter side of the specimen was positioned parallel to the loading force. The modulus of rupture (*MoR*) and the bending modulus of elasticity (MoE_b) were determined from these

tests. Because the specimen geometry differed from standard dimensions, the calculations were performed according to the procedure proposed by Báder and Németh [31], using Equations (1) and (2).

$$MoR = \frac{3 \cdot F \cdot a}{2 \cdot b \cdot h^2}, \quad (1)$$

where F represents the maximum applied load, b denotes the height of the specimen, h denotes the width of the specimen parallel to the load, and a denotes the distance between the loading roller and the nearest support, which was 50 mm in the present study. Accordingly, the upper loading span was 50 mm.

$$MoE_b = \frac{\Delta F \cdot a^2 \cdot (3 \cdot L - 4 \cdot a)}{b \cdot h^3 \cdot \Delta w}, \quad (2)$$

where L represents the lower support span (150 mm), and Δw is the crosshead displacement corresponding to the load interval between 10% and 25% of the maximum load (ΔF).

Compression tests were also performed using the Instron 4208 universal testing machine in accordance with ISO 13061-17:2014 [32] standard. A constant rate of 0.4 mm/min was applied throughout the measurements. Each test was terminated when the applied load reached a stable load during continuous compression. In addition to compression strength, the compression modulus of elasticity (MoE_c) was also determined from the linear portion of the load–displacement curve between 30% and 55% of the maximum applied load, on ten specimens in each sample.

Brinell–Mörath hardness ($H_{B\text{-}M}$) was determined following the procedure specified in EN 1534:2020 [33] standard while also considering the original methodology proposed by Mörath [34] on ten specimens per sample. The only deviation from the standard testing procedure concerned the specimen dimensions. Owing to limitations in the available raw material, hardness measurements were performed on specimens measuring 18 × 28 × 30 mm (width × height × length along the grain) Unlike the Janka test and other methods based on deep indentation, the Brinell–Mörath method is considerably less sensitive to reduced specimen dimensions, making it suitable for testing smaller specimens. After removal of the load of 500 N, the specimens were allowed to recover for a minimum of 3 min before the residual indentation diameter was measured using a scaled magnifier with an accuracy of 0.1 mm. Ten specimens from each sample were tested both on the end-grain and the side. $H_{B\text{-}M}$ was subsequently calculated according to the standard equation [33].

The mechanical properties were not adjusted to the standard MC of 12%, as the objective was to evaluate the actual effects of the modification treatments while accounting for the substantial changes in equilibrium moisture content. Nevertheless, whenever required, all specimens were conditioned to constant mass at 20 °C and 65% relative humidity prior to testing.

Following planing, the specimens exhibited smooth and uniform-quality surfaces suitable for color measurements. Five specimens were in each sample, and each specimen was measured at five predefined points before and after treatment in the oven-dry state. Therefore, in the absence of any changes, the Untreated sample was not included in the color evaluation. Color measurements were carried out using a Konica Minolta CM-2600d spectrophotometer (Konica Minolta Inc., Tokyo, Japan). Within the CIE Lab* color system, L^* represents lightness (0–100), a^* corresponds to the green (−) to red (+) axis, and b^* represents the blue (−) to yellow (+) axis. Measurements were performed using the D65 standard illuminant, a 10° standard observer, and an 8 mm aperture. Considering the characteristic growth-ring width of beech, each measurement incorporated a minimum of three and a maximum of six annual rings on the radial surface. The overall color difference (ΔE^*) was calculated from the L^*, a^*, and b^* coordinates as a quantitative measure of

perceptible color change according to Tolvaj [35]. The same book was also used to interpret the visual perception thresholds corresponding to the calculated ΔE^* values.

The influence of the applied modification treatments on the investigated material properties was statistically evaluated using one-way analysis of variance (ANOVA), followed by Fisher's least significant difference (LSD) post hoc test at a significance level of $p < 0.05$. Statistical analyses were performed using TIBCO Statistica version 14.0.1.25 (TIBCO Software Inc., Palo Alto, CA, USA).

3. Results and Discussion

The Results and Discussion section is organized according to the tests performed. It begins with an analysis of bending properties, followed by other mechanical properties (compression test and hardness test) and finally the color characteristics. All of these are compared with the changes in mass and density, as well as other physical and biological durability data, which can be found in the study based on the results of experiments conducted on the same samples [30]. As expected, thermal modification (TM) resulted in mass loss, whereas LA impregnation produced a considerable increase in specimen mass, even after accounting for the mass reduction associated with polymerization, relative to the oven-dry mass measured before impregnation (Table 2). In every case, the mass changes were calculated from comparisons of oven-dry specimen masses, as reported by Bak et al. [30].

Table 2. Changes in mass of the samples resulting from the different treatments, in terms of weight percentage gain (positive mass changes) and weight percentage loss (negative mass changes). "Treatment 1" refers to the first treatment performed in chronological order, while "Treatment 2" refers to the second treatment performed as part of the combined modifications. Oven-dry results are reported based on the study of Bak et al. [30]. Oven-dry densities were measured after treatments and before soaking; *EMC* is equilibrium moisture content after conditioning at 20 °C and 65% relative humidity following soaking and re-drying processes.

	Mass Change Resulted in Treatment 1	Mass Change Resulted in Treatment 2	Total Change in Mass	Oven-Dry Density [g/cm^3]	*EMC*
Untreated	-	-	-	0.64 ± 0.02	10.8 ± 0.3%
Impregnated 120 °C	−3.2%	-	−3.2%	0.65 ± 0.03	8.7 ± 0.3%
Impregnated 160 °C	39.3%	-	39.3%	0.77 ± 0.05	7.8 ± 0.6%
Thermally treated	43.7%	-	43.7%	0.80 ± 0.04	5.8 ± 1.3%
Thermally treated and Impregnated 120 °C	−3.7%	53.6%	48.0%	0.82 ± 0.08	7.8 ± 0.9%
Impregnated 120 °C and Thermally treated	56.5%	−16.1%	31.4%	0.78 ± 0.05	5.6 ± 1.1%

3.1. Bending Test

The four-point bending tests yielded average values of 120.4 MPa for the modulus of rupture (*MoR*), 8.7 GPa for the bending modulus of elasticity (MoE_b), and 9.60 mm for the maximum deflection of the untreated sample. According to the literature, the corresponding values for beech are 115.9 ± 9.6 MPa for *MoR* and 14.0 ± 1.3 GPa for *MoE* [3,36–38]. Thus, the measured *MoR* agreed well with published data, whereas the MoE_b was 37.9% lower. This discrepancy is most likely attributable to the four-point bending configuration used in the present study, as most published mechanical property data are obtained from three-point bending tests. In addition, the specific characteristics of the growing sites may also have had a great influence. Nevertheless, this difference does not affect the comparability of the treatment effects because all specimens were tested under identical

experimental conditions. Regarding the modifications carried out, the results typically show a material-weakening effect. The lowest mechanical performance was consistently observed in the three samples in which OLA was polymerized at the higher temperature or where TM and impregnation were combined (Figure 1). These yielded statistically identical results. Compared with the controls, these specimens exhibited average reductions of 53.1% in *MoR*, 26.2% in MoE_b, and 58.5% in deflection at maximum force. None of the treatments improved the pliability of the wood. Instead, the modified specimens reached their maximum load at 44.0%–60.5% lower deflection values and failed shortly thereafter. All this occurred despite the fact that there is a strong inverse relationship between MoE_b and pliability [39]. In the present study, however, despite the statistically significantly higher MoE_b of the Thermally treated sample (11.5 GPa), the statistically unchanged MoE_b of the Impregnated 120 °C sample (8.38 GPa), and the significantly lower MoE_b values of the combined treatments, all modified samples exhibited a statistically significant reduction in pliability. This behavior can be attributed to the increased brittleness of the wood resulting from chemically induced alterations of the cell wall structure.

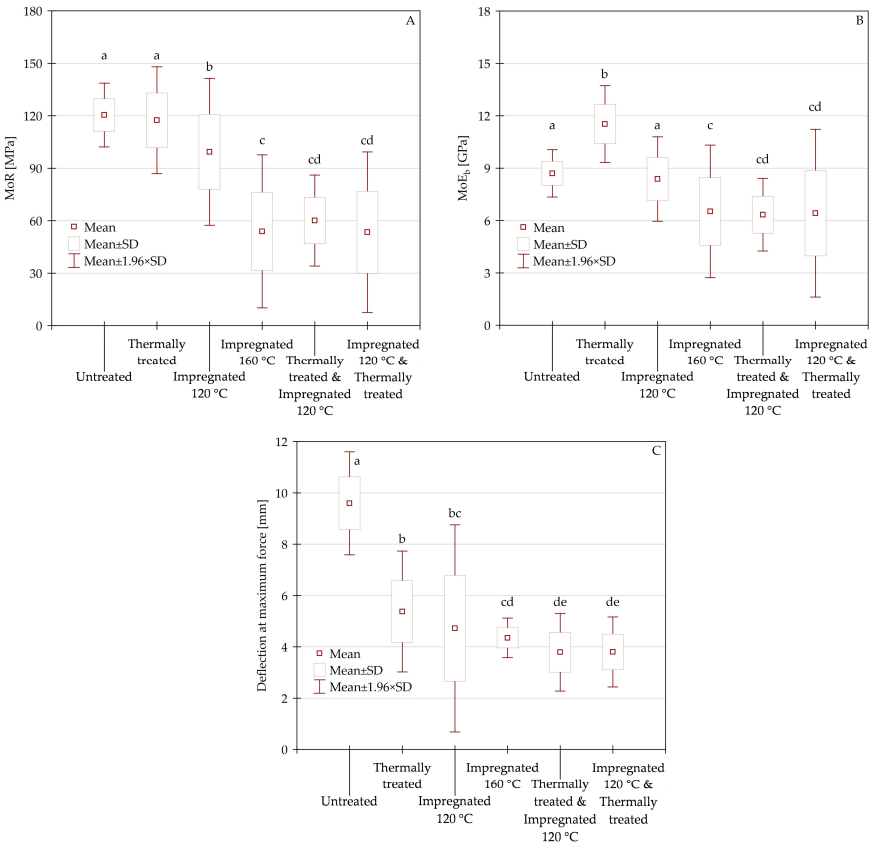

Figure 1. Box plot diagrams on the bending test results: (**A**) modulus of rupture (*MoR*), (**B**) bending modulus of elasticity (MoE_b), and (**C**) deflection at maximum force. The horizontal axis distinguishes the treatments: thermal modification was performed at 180 °C and impregnation was carried out using oligomeric lactic acid, followed by polymerization at the temperatures indicated for each sample. SD denotes standard deviation. The lowercase letters above the whiskers denote the similarities according to the statistical analysis.

Regarding *MoR*, the TM did not produce a statistically significant difference, although the CV increased from 7.7% to 13.3%. A similar increase in CV was observed for the other treatments, which is a commonly reported phenomenon in modified wood [2,40,41]. The visual observations further supported the mechanical test results. The Thermally treated and Impregnated 120 °C sample and the Impregnated 120 °C and Thermally treated sample

exhibited predominantly brittle fracture characteristics, whereas the fracture surfaces of the Untreated and Thermally treated samples showed the typical morphology associated with normal bending failure. The embrittlement of LA-treated wood is primarily caused by the acid-catalyzed degradation of cell wall polymers, particularly hemicelluloses [8]. Beech wood is highly susceptible to this process due to its high xylan content, which decomposes under the acidic environment facilitated by LA/OLA impregnation [7]. Furthermore, intense curing temperatures of at least 160 °C promote the thermal decomposition of the wood matrix and the formation of micro-cracks within the cell walls [8,26]. While the resulting rigid, highly polymerized OLA matrix enhances density, these chemical and physical alterations collectively reduce the elasticity of the wood and its overall structural toughness [7,26].

3.2. Compression and Hardness Tests

The material-weakening effect of the modifications carried out on the samples, previously observed in the bending tests, was also evident in the compression and hardness tests. Consistent with the findings of Percin et al. [3], the TM increased the compression strength by 49.8% and the compression modulus of elasticity (MoE_c) by 35.1% compared to the untreated sample, which exhibited values of 45.4 MPa and 2.48 GPa, respectively. The corresponding literature value for compression strength is 61.7 ± 7.2 MPa [3,36–38]. Percin et al. [3] reported that compression strength parallel to the grain initially increases during moderate treatments (150–175 °C), though severe conditions (200 °C for 5 h) eventually trigger a decline. MoE_c (measured in bending) follows a comparable trajectory, showing minor initial gains followed by substantial reductions as treatment intensity increases. Authors attribute the initial mechanical enhancement to increased cellulose crystallinity and condensation reactions in lignin, which create a more rigid molecular framework. Conversely, subsequent degradation is primarily driven by the thermal decomposition of hemicelluloses—the most heat-sensitive polymers—resulting in reduced density and mechanical properties [3,42]. Microscopic evaluations reveal physical deterioration, including cell wall distortion and cracking, which further compromises structural integrity [43,44]. Apart from the thermally treated sample, all other treatments resulted in statistically significant reductions in mechanical performance compared to the Untreated sample (Figure 2A,B). Moreover, the standard deviations of the results increased considerably, particularly for the LA-treated samples. For example, the CV reached 62.6% for the compression strength of the Thermally treated and Impregnated 120 °C specimens, while the MoE_c of the Impregnated 120 °C and Thermally treated specimens exhibited a CV of 66.1%. On average, the LA treatments reduced MoE_c by 53.1%, which closely corresponded to the 50.7% decrease in compression strength. These reductions were particularly pronounced for the Impregnated 120 °C and Thermally treated sample, supporting the presumed conclusions drawn from the bending tests that acidic treatment, especially when combined with elevated-temperature processing, substantially intensifies degradation of the wood structure, thereby impairing its mechanical properties.

According to the literature, the average Brinell–Mörath side hardness ($H_{B\text{-}M;S}$) and end-grain hardness ($H_{B\text{-}M;E}$) of beech are 36.6 ± 2.7 MPa and 69.4 ± 2.7 MPa, respectively [3,36,38]. In the present study, the corresponding values for untreated wood were 29.0 ± 3.4 MPa and 64.0 ± 7.5 MPa. The results are consistent with the data in the literature. Unfortunately, hardness measurements could not be performed on the Impregnated 160 °C specimens, either on the side surface or on the end grain, because their hardness was too low to reach the instrument's required load of 500 N before the complete indentation of the steel ball. This finding indicates that the treatment permanently softened not only the surface but also the bulk material. The most plausible explanation is that

OLA polymerization at the elevated temperature intensified acid-catalyzed degradation of the wood polymers. This interpretation is supported by the study of Bak et al. [10], in which beech impregnated with OLA and polymerized at 110, 120, and 140 °C for six hours and conditioning exhibited end-grain hardness reductions of 41.08%, 43.94%, and 80.93%, respectively, compared to untreated wood. At this stage, polymerization only occurred partially. After another polymerization cycle (at 103 °C for 48 h), a huge improvement was observed in the three samples, resulting in a 15%–40% increase in hardness compared to untreated wood [10], as described in the Introduction. Polymerization at 140 °C before further drying already resulted in a dramatic loss of hardness; increasing the polymerization temperature by a further 20 °C in the case of the present study would therefore be expected to cause even more severe softening, to the extent that hardness can no longer be determined even using the relatively careful Brinell–Mörath method with a maximum load of 500 N. In untreated beech, the average indentation depth of the steel ball on the end-grain surface was only 0.255 mm, demonstrating the low invasiveness of the test.

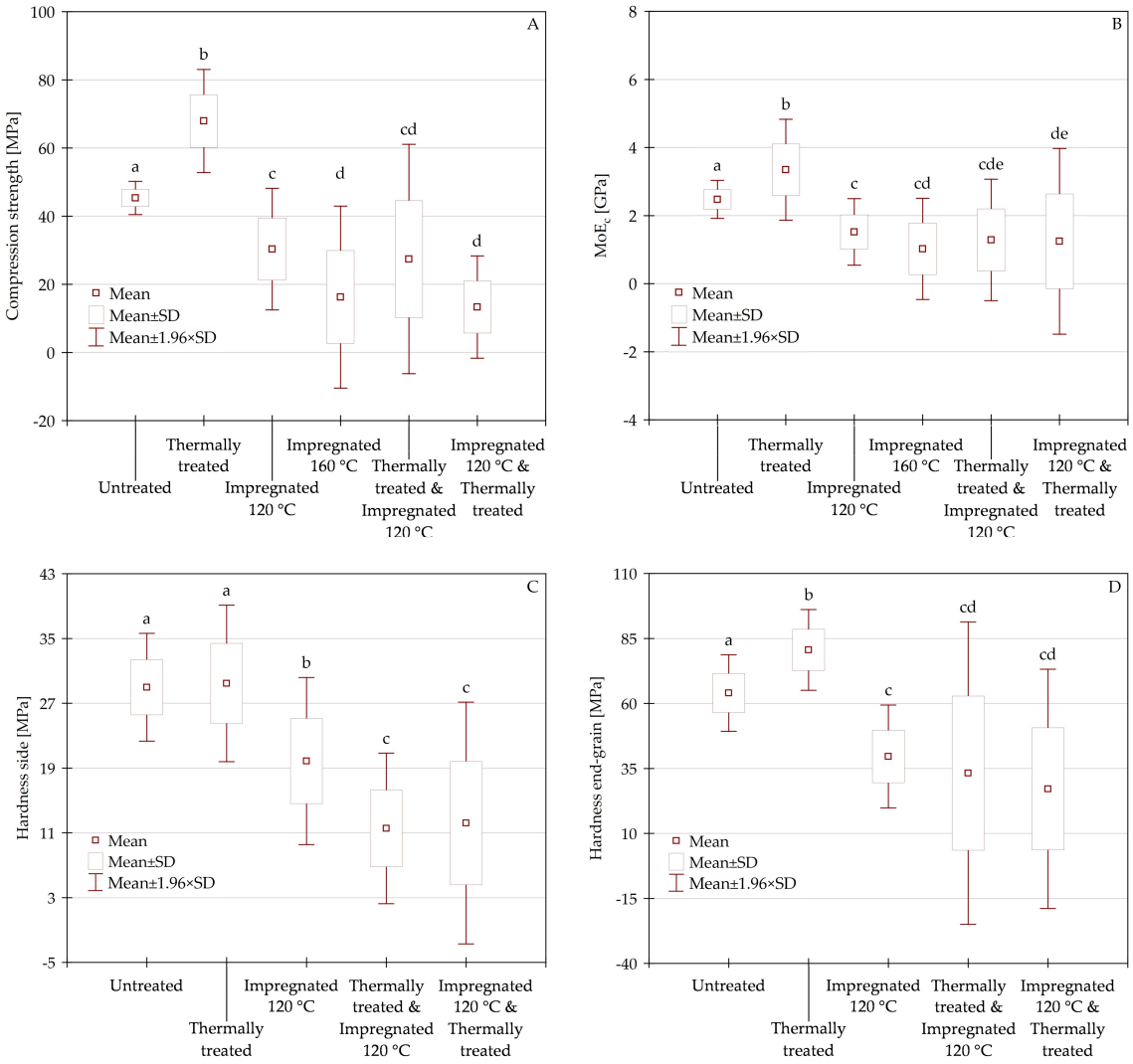

Figure 2. Box plot diagrams showing the results of (**A**) compression strength, (**B**) compression modulus of elasticity (MoE_c), (**C**) end-grain hardness, and (**D**) side hardness. The horizontal axis distinguishes the treatments: thermal modification was performed at 180 °C and impregnation was carried out using oligomeric lactic acid, followed by polymerization at the temperatures indicated for each sample. SD denotes standard deviation. The lowercase letters above the whiskers denote the similarities according to the statistical analysis.

For $H_{B\text{-}M;S}$, only two statistically homogeneous samples were identified: Untreated and Thermally treated samples, and the two combined-treatment samples. In contrast, $H_{B\text{-}M;E}$ increased significantly by 25.92% following TM, consistent with observations reported in previous studies. The magnitude and direction of changes in wood hardness depend on treatment temperature, duration, and species. Mild treatments can lead to a slight initial increase in hardness, while more severe conditions (typically above 180–200 °C) generally result in a substantial decline [3,42]. The increase in hardness is attributed to condensation reactions and increased cross-linking within the lignin matrix, which hardens the material. Conversely, the subsequent decrease is primarily driven by the thermal degradation of cell wall polymers, particularly hemicelluloses [3,42]. This chemical breakdown leads to significant mass loss and reduced density, which closely correlates with hardness values. Because TM caused only negligible mass loss in the present study, the resulting $H_{B\text{-}M;S}$ changes closely matched those reported in the literature. Conversely, the impregnated specimens—particularly those subjected to the combined treatments—exhibited statistically similar $H_{B\text{-}M;E}$ values, averaging 48.0% lower compared to the Untreated sample (Figure 2C,D), a phenomenon that has likewise been reported previously. In addition, the combined treatments showed exceptionally high variability compared with the Untreated and Thermally treated samples, with an average CV of 87.9%. Noël et al. [26] found that wood modification using OLA significantly impacts material hardness through a temperature-dependent thermal curing process. Initially, short-term curing (for example 120 °C for 1 h) induces a temporary softened state, characterized by high flexibility and reduced elasticity. The softening is an effect of OLA entering the wood structure during impregnation. Conversely, extended curing (up to 160 °C) allows the wood to regain its original hardness and evolve into a denser composite with even higher mechanical performance. This increase is primarily driven by a greater degree of in situ polycondensation, polymerization and physical retention of the polymer matrix through filling cell lumens and entanglement within the wood cell wall, leading to a permanent increase in density and enhanced mechanical stability, allowing the wood to regain its hardness [7,26]. Overall, the LA modification resulted in a pronounced reduction in both $H_{B\text{-}M;S}$ and $H_{B\text{-}M;E}$, consistent with the trends observed in the other mechanical tests. This deterioration can be attributed to acid-induced degradation of the wood cell wall, which became even more pronounced when combined with TM. Based on the experimental observations and previous studies, it is likely that polymerization was incomplete, leaving considerable amounts of residual OLA and LA monomers within the wood structure. For this reason, it was not possible to achieve the improvements in hardness described in other studies [10,26]. At the same time, this adverse effect represents the trade-off associated with achieving a substantially lower equilibrium moisture content, which improved fungal durability [30].

3.3. Color Properties

The color of each specimen was measured at five predefined points, first on the planed surface of the untreated specimens and subsequently at the same points after the single and combined modification treatments followed by re-planing. This procedure ensured freshly prepared and uniform surfaces for every color measurement. The lowest overall color difference (ΔE^*) was observed for the Impregnated 120 specimens, with a mean value of 19.473 and a CV of 18.8%. The greatest ΔE^* of 69.044 was recorded for the Impregnated 160 specimens, with a CV of 6.1% (Figure 3). Similarly pronounced color changes were also observed following the Impregnated 120 and Thermally treated combined treatment. The correlation between visual perception by naked eye and ΔE^* was very large in all cases according to the description of Mokrzycki and Tatol [45].

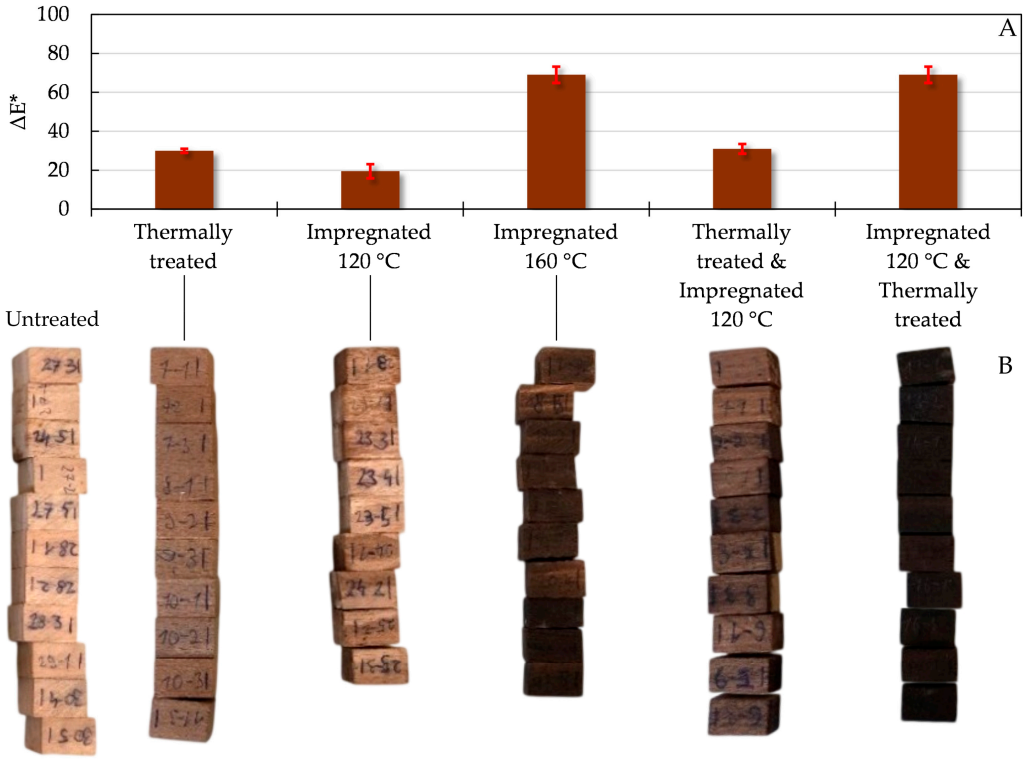

Figure 3. (**A**) Average color differences (Δ*E**) resulted by the different modifications, compared to untreated wood, and (**B**) differences visible to the naked eye in the photos of the samples. The horizontal axis distinguishes the treatments: thermal modification was performed at 180 °C and impregnation was carried out using oligomeric lactic acid, followed by polymerization at the temperatures indicated for each sample. Standard deviation is indicated by the red line.

The effect of TM on wood color is well known [46–48], indicating that the specimens in the present study underwent a moderate TM. In contrast, the LA treatment alone exerted a considerably smaller influence on color. However, the pronounced absolute color changes, primarily darkening, observed in the specimens polymerized at 160 °C and in those subjected to TM after impregnation indicate substantial alterations in the chemical composition of the wood. The strongly acidic environment combined with elevated temperature had a particularly pronounced effect on lightness, reducing the *L** value by 76.0%–89.8% (Figure 4). The other two color coordinates also changed. For example, the *a** value approximately doubled in the Impregnated 160 °C specimens, whereas the impregnation and polymerization at 120 °C followed by TM caused a marked reduction in the *b** coordinate (Figure 4). These changes are primarily associated with the degradation of hemicelluloses and amorphous cellulose. It should be noted that the chemical conclusions and explanations are based on data from the literature, or conclusions drawn from WPG, EMC, and other changes, not on chemical measurement results directly on the samples of the study, therefore, they must be treated with reserve.

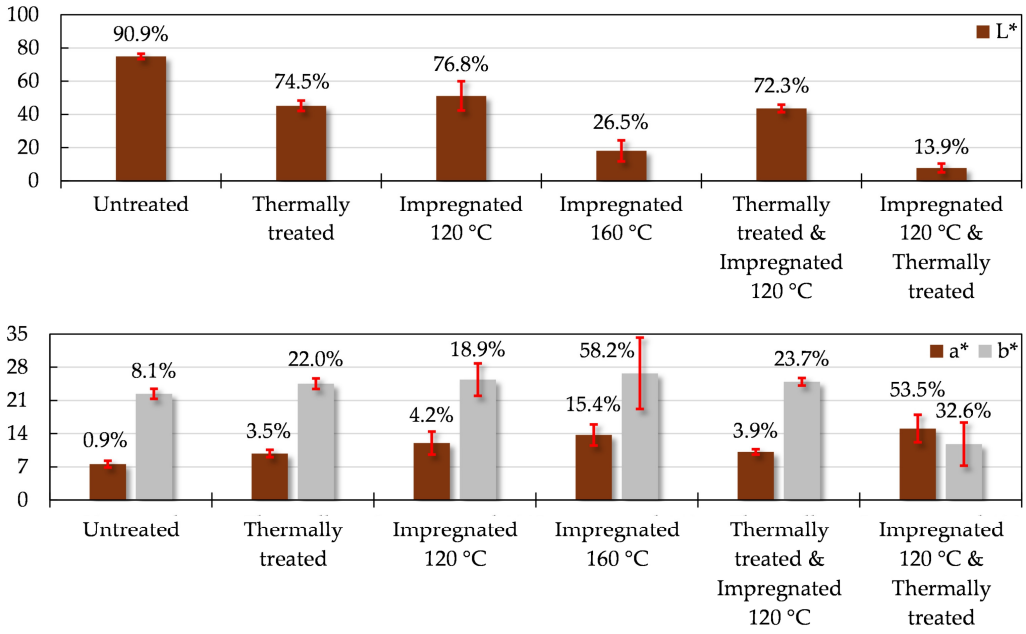

Figure 4. The diagrams show the average CIELab color coordinates of untreated and differently modified beech (*Fagus sylvatica* L.) wood samples plotted along the vertical axis (dimensionless): L* represents lightness, while a* and b* represent redness and yellowness, respectively. Standard deviation is indicated by the red line, while the percentages above the columns show the average contribution ratio of the given color coordinate to ΔE^*, meaning the ratio responsible for causing the color difference. Thermal modification was performed at 180 °C. Impregnation was carried out using oligomeric lactic acid, followed by polymerization at the temperatures indicated for each sample.

4. Conclusions

This study investigated the effects of thermal modification at 180 °C, oligomeric lactic acid (OLA) impregnation with catalyst-free polymerization (120 and 160 °C), and their sequential combinations on the mechanical properties and color of European beech (*Fagus sylvatica* L.). Mechanical performance was evaluated by four-point bending, compression, and Brinell–Mörath hardness tests, while color changes were assessed using the CIELab system. The untreated beech sample showed good mechanical performance, with an average (±standard deviation) bending strength of 120.4 ± 9.3 MPa and a bending modulus of elasticity of 8.7 ± 0.7 GPa. Its compression strength was 45.4 ± 2.5 MPa, while the Brinell–Mörath hardness reached 29.0 ± 3.4 MPa on the side and 64.0 ± 7.5 MPa on the end grain, providing the baseline for evaluating the effects of the modification treatments. Thermal modification produced the most favorable mechanical response. Although no statistically significant improvement in bending strength was observed, compression strength increased from 45.4 MPa to 67.9 MPa and the compression modulus of elasticity increased by 35.1%. End-grain hardness also increased by 25.9%, confirming that moderate thermal treatment can improve selected load-bearing and surface properties. In contrast, OLA-based modifications caused substantial deterioration of mechanical performance. It can be concluded from the results that polymerization occurred only partially, particularly in the samples polymerized at lower temperatures. On average, lactic acid treatments reduced compression strength by 50.7% and compression modulus by 53.1%, while the combined treatments exhibited exceptionally high variability, with coefficients of variation reaching 62.6% for compression strength, 66.1% for compression modulus of elasticity, and 87.9% for hardness. Polymerization at 160 °C resulted in such severe softening that hardness could not be determined. Color was strongly affected by treatment severity, with total color changes increasing from 19.5 after polymerization at 120 °C to 69.0 after polymerization at 160 °C. Overall, the results indicate that while OLA impregnation may provide benefits

related to moisture performance and durability, the associated acid-catalyzed degradation and high-temperature curing substantially impair the mechanical integrity of beech wood. Thermal modification at 180 °C therefore represents the most balanced modification strategy among the treatments investigated, but only in terms of mechanical properties.

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