Comparative Evaluation of Treatment Conditions on Physical and Mechanical Properties of Acetylated Beech (*Fagus orientalis* Lipsky) Wood

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Esterified wood was produced from beech (*Fagus orientalis* Lipsky) using acetic anhydride *via* a soaking-impregnation process with varying impregnation (Im) and reaction (Re) durations. Oven-dried beech wood samples were immersed in acetic anhydride for either 60 or 180 minutes.The samples were then wrapped in foil and placed in an oven at 103 ± 2 °C for 60 or 120 minutes to facilitate the acetylation reaction. The weight percent gain (WPG) was determined to assess the extent of the chemical modification. Flexural strength (FS), flexural modulus (FM), impact strength (IS), and compression strength (CS), along with water absorption (WA), thickness swelling (TS), and anti-swelling and anti-shrinkage efficiencies were evaluated. The WPG increased with increasing reaction, reaching 9.1% for Im60-Re60 and 13.6% for Im180-Re120 treatments. Acetylation significantly reduced water absorption and dimensional changes compared with untreated wood. Higher WPG levels resulted in reductions in FS and IS, whereas FM and CS were not significantly affected. Among the tested conditions, the Im60-Re60 treatment provided the most balanced performance, achieving improved dimensional stability with minimal reduction in mechanical properties. These results demonstrate that controlled acetylation can enhance the moisture resistance and dimensional stability of beech wood while maintaining acceptable mechanical performance.

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INTRODUCTION

Wood is a vital renewable resource that is extensively used in diverse industries due to its favorable mechanical properties, aesthetic appeal, and environmental advantages (He *et al*. 2023). Despite this benefit, wood is inherently vulnerable to biological degradation, moisture, ultraviolet (UV) radiation, and weathering. These vulnerabilities limit its service life and applications, particularly in outdoor environments (Petrillo *et al*. 2019). In light of these challenges, enhancing wood durability, dimensional stability, and resistance to environmental factors is essential.

Historically, conventional wood preservation techniques involving chromium-, copper- and arsenic-based chemicals have extended the longevity of wood, sometimes by decades(Lebow *et al*. 2015; Momohara *et al*. 2021). However, rising environmental and health concerns have shifted the focus towards more sustainable and non-toxic alternatives (Emenike *et al*. 2024). Among these, chemical modification, particularly through altering wood's reactive hydroxyl groups, has emerged as a promising method for enhancing moisture and decay resistance without introducing harmful substances (Huang *et al*. 2025).

Acetylation is a widely researched chemical modification method that involves the reaction of wood polymers with acetic anhydride. This process reduces wood hygroscopicity by substituting hydroxyl groups with acetyl groups, thereby enhancing dimensional stability (Hill 2006; Yang *et al*. 2023). Impregnation with acetic anhydride is a well-established method for wood acetylation, as the reagent penetrates cell walls and reacts with the hydroxyl groups of the lignocellulosic polymers. This chemical modification reduces hygroscopicity and enhances dimensional stability. Digaitis *et al.* (2021) analyzed the diffusion mechanisms of acetic anhydride and demonstrated its impact on physical and mechanical properties. Sandak *et al.* (2024) further confirmed that acetylation improves weathering resistance and extends service life under outdoor exposure. Overall, impregnation efficiency is a key factor in the success of acetylation treatments, justifying the present focus on beech wood. Previous studies indicate that acetylation also improves biological resistance against decay fungi by making cell wall polymers less accessible to enzymatic attack (Slabohm *et al*. 2023; Belt and Awais 2025). Furthermore, acetylation protects lignin from photodegradation, increasing resistance to weathering (Nagarajappa *et al*. 2020).Comparative analyses of wood preservatives and chemical modification techniques provide valuable insights into their relative effectiveness. For instance, Sandak *et al*. (2024) evaluated the effectiveness of different treatments on hardwood species in outdoor conditions, confirming that acetylation offers superior durability and moisture resistance.

The surface characteristics and mechanical properties of wood after chemical modification remain critical factors influencing its performance. Wang *et al.* (2024) reported that the degree of modification is proportional to the increase in surface roughness following acetic anhydride treatment. By contrast, acetylation enhances hardness and bending strength while only causing minor changes to the modulus of elasticity. Improvements in dimensional stability have been consistently observed. Significant reductions in swelling and shrinkage in acetylated narrow-leaved ash woodwere reported by Popović and Điporović-Momčilović (2012). Xing *et al.* (2025) and Sandak *et al*. (2021) found that higher levels of acetylation enhance weathering resistance. While the mechanical strength properties of acetylated wood are not significantly different from those of untreated wood, its durability is substantially improved (Rowell 2006). Hosseini and Masteri Farahani (2012) reported that the acetylation of beech wood using acetic anhydride significantly improved the dimensional stability while only moderately affecting the mechanical properties, depending on the treatment severity.

Despite these advancements, challenges persist in optimizing acetylation protocols and understanding species-specific reactions. Fully characterizing long-term performance under varying environmental conditions also remains difficult. Iranian beech wood, which is widely used in the region, faces challenges related to limited natural durability and dimensional instability. Chemical modification, such as acetylation, offers promising approaches to enhance its suitability for outdoor applications. Hosseinihashemi *et al*. (2023) showed that pre-impregnation of beech wood flour with acetic anhydride and

controlled heating or reaction times reduces hygroscopicity and alters mechanical performance. After 24 h immersion in distilled water, the water absorption ranged from 0.94% (PIT60-H/RT120 min) to 3.45% (PIT60-H/RT60 min) versus 1.26% for the control, thickness swelling ranged from -2.58% (PIT180-H/RT60 min) to 2.65% (control), and the best mechanical results occurred at PIT60-H/RT60 min with flexural strength 57.90 MPa, tensile strength 22% higher, and tensile modulus 26% higher than control, and impact strength 0.46 J/m, indicating that tuning impregnation and heating times allows trade-offs between reduced water uptake and changes in strength and stiffness.

Impregnation plays a key role in the chemical modification of wood, as it determines the penetration depth and distribution of reactive chemicals within the cell wall and lumen structure. In hardwood species such as beech (*Fagus orientalis*), impregnation efficiency is strongly affected by anatomical characteristics, specimen dimensions, and treatment conditions, particularly in the absence of vacuum-pressure cycles. Non-pressure impregnation with acetic anhydride is therefore often associated with surface-dominated modification, which can lead to substantial variations in weight percent gain (WPG) and property development among different specimen types.

Accordingly, the main objective of this study was to evaluate the combined effects of impregnation time and reaction time on the physical and mechanical properties of beech wood during acetylation with acetic anhydride. Additionally, the aim was to determine a process condition that would minimize the decrease in the mechanical performance and improve the dimensional stability.

EXPERIMENTAL

Materials

Beech wood (*Fagus orientalis* Lipsky) was purchased from the AfaraGostar Wood Industries Company in Iran. The wood was harvested from the forests of Royan County in Mazandaran province. It was prepared in plank form with dimensions of 70 × 460 × 1300 mm^3.

Samples Preparation and Treatment Procedure

Wood planks were cut to standardized dimensions for various tests in accordance with ISO 3131 (1975), and 3133 (1975), and ISO 3129 (1975) international standards. For the mechanical tests, the specimens were prepared to the dimensions required for each test. For flexural strength (FS) and flexural modulus (FM), impact strength (IS) and compression strength (CS) tests parallel to the grain, the specimens were cut to standard dimensions. Similarly, for physical tests including anti-swelling efficiency, water absorption (WA), volumetric swelling (VS) and weight percent gain (WPG), specimens were cut to standard dimensions (Table 1). The wood specimens were treated with acetic anhydride as a preservative.

First, the samples were dried in an oven at 103 ± 2 °C for 24 hours to determine their dry weight. Subsequently, the samples were placed in a desiccator containing silica gel for a period of 15 minutes with the objective of preventing moisture absorption, after which they were weighed. The dimensions of the samples (20 × 20 × 20 mm^3) were then measured in three directions (radial, tangential, and longitudinal) using a caliper gauge, in preparation for physical testing.

Table 1. Treatment Conditions and Standardized Dimensions of Wood Samples

Test (Dimension)	Impregnation Time (min)	Reaction Time (min)	Replicates	Sum of Samples
FS/FM (20×20×360 mm³)	60	60	3	15
	60	120	3	
	180	60	3	
	180	120	3	
	Control	Control	3	
IS (20×20×280 mm³)	60	60	3	15
	60	120	3	
	180	60	3	
	180	120	3	
	Control	Control	3	
CS (20×20×60 mm³)	60	60	3	15
	60	120	3	
	180	60	3	
	180	120	3	
	Control	Control	3	
WA (20×20×20 mm³)	60	60	3	15
	60	120	3	
	180	60	3	
	180	120	3	
	Control	Control	3	

The oven-dried wood samples were immersed in acetic anhydride for either 60 or 180 minutes, to allow sufficient time for the wood to absorb the preservative (Fig. 1). Since wood moisture limits the penetration of the chemical substance, the samples were immersed in acetic anhydride while completely dry.

Fig. 1. Beech wood samples impregnation into the acetic anhydride

Following immersion, the samples were wrapped in foil and placed in an oven at 103 ± 2 °C for 60 or 120 minutes, as detailed in Table 1, to facilitate the acetylation reaction.

Following oven treatment, the samples were washed several times in warm water to eliminate the strong odour of acetic anhydride. They were then stored at room temperature for three days to prevent cracking caused by high humidity, before undergoing final oven drying. After completion of the acetylation reaction, all specimens were oven-dried at 103 ± 2 °C to remove any unreacted acetic anhydride and residual acetic acid, and to ensure consistent oven-dried mass values. These values were then used to determine weight percent gain (WPG) and compare the physical and mechanical properties. This uniform post-treatment drying step was not intended to promote further chemical reaction. After drying, the samples were placed in a desiccator for 15 minutes and then weighed. The dimensions of the 20 × 20 × 20 mm³ samples were measured again in three directions, radial, tangential and longitudinal, using a caliper gauge.

Measurement of WPG

The samples were weighed before and after treatment in the laboratory using a digital balance with an accuracy of 0.001 g. The weight percentage gain was calculated using Eq. 1,

$$\text{WPG (\%)} = [(W_1 - W_o)/W_o] \times 100 \quad (1)$$

where W_1 is the oven-dry weight of the sample after treatment (g) and W_o is the oven-dry weight of the sample before treatment (g).

Measurement of Physical Properties

Physical properties, such as water absorption and thickness swelling, were measured in accordance with ASTM D703-15 (2015). Flexural strength and modulus of elasticity were determined according to ASTM D143-14 (2014), while water absorption and thickness swelling were measured in accordance with ASTM D4442-16 (2016). The weight of the samples was measured to an accuracy of 0.001 g using a digital balance, and their thickness was measured to an accuracy of 0.01 mm using a micrometer. The samples were oven-dried, and their initial weight and dimensions were recorded before immersion in distilled water at room temperature. After 2 and 24 hours of immersion, weight and thickness measurements were taken to calculate the percentages of water absorption and thickness swelling.

Measurement of Mechanical Properties

The bending test was conducted in accordance with ASTM D790-17 (2017) (three-point bending) using an Instron testing machine. Impact resistance was measured in accordance with ASTM D256-10 (2010) on unnotched samples. Compression parallel to the grain was performed on samples measuring 20 × 20 × 60 mm³ using an Instron 4486 testing machine. The samples were placed between the fixed and moving jaws of the machine, and the results were recorded in megapascals (MPa).

Data Analysis

The values of FS, FM, WPG, CS, IS, WA, thickness swelling (TS), and anti-swelling and shrinkage efficiencies (ASwE, AShE) were statistically analyzed using SPSS software (IBM Corp., version 24.0, Redmond, WA, USA). The data were analyzed using a one-way ANOVA, followed by a Duncan's Multiple Range Test (DMRT) at a 95% confidence level.

RESULTS AND DISCUSSION

Weight Percent Gain

Figure 2 illustrates the variation in weight percent gain (WPG) for different specimen types and treatment conditions, showing a wide range of values from approximately 1.4% to 13.6%. The results of univariate analysis (Table A1, Appendix) indicate that specimen type had a highly significant effect on WPG (F=85.65; p-value <0.001), whereas impregnation time and reaction time did not exhibit any statistically significant main effects. The lack of significant interaction effects confirmed that differences in WPG were primarily governed by specimen-related factors rather than treatment duration.

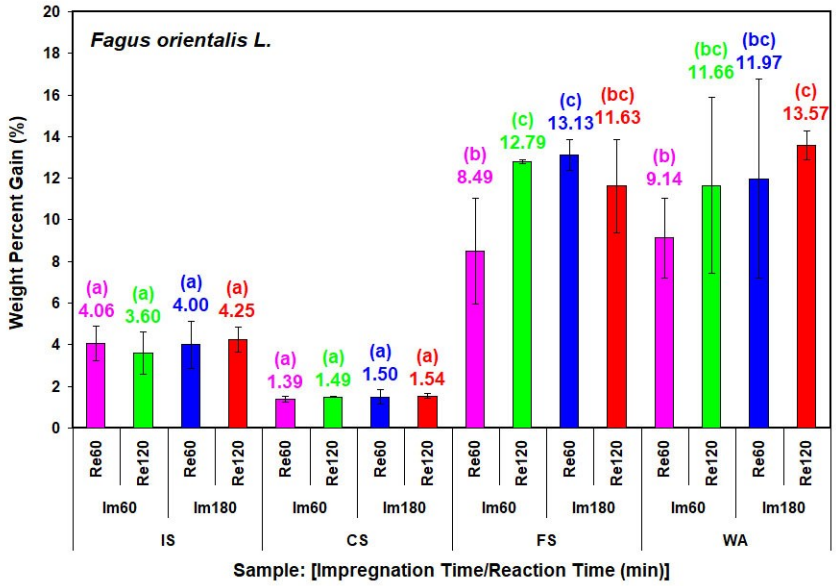

Fig. 2. Interaction effect of impregnation and reaction times on the WPG values of acetylated beech wood

The observed increase or decrease in WPG among the specimens can largely be explained by limitations to diffusion under the conditions of soaking impregnation. Although the cross-sectional dimensions of all samples were identical (20 × 20 mm²), their lengths differed, influencing diffusion path length and the contribution of end-grain penetration. Shorter specimens allowed more uniform chemical access to the entire volume, while longer specimens were more likely to contain untreated core regions, resulting in lower apparent WPG values. Similar trends have been reported for acetylated hardwoods, where it was found that specimen geometry and diffusion constraints were the main factors influencing chemical uptake (Siau 1984; Hill 2006; Rowell 2014).

In addition to geometric effects, the inherent morphology of the wood may have contributed to the observed variability in WPG. It is known that differences in annual ring width, cutting orientation (radial, tangential or intermediate) and radial position within the stem affect permeability in beech wood. Moreover, it is possible that the presence of red heartwood in beech, which is associated with increased extractive content and reduced permeability, contributed to local reductions in chemical uptake in some specimens. Although such anatomical variability could not be completely eliminated, its influence is

considered secondary to the dominant effects of specimen geometry and diffusion path length under the applied treatment conditions.

The Effect of Acetylation on the Mechanical Properties of Beech Wood

Flexural strength

The FS was sensitive to the severity of acetylation, with statistically significant differences observed among most of the treatment conditions (Fig. 3 and Table A2 (Appendix)). Minor variations in the FS at higher WPG levels may be associated with changes in cell wall chemistry and the bulking effects induced by acetylation. However, the absence of direct microstructural or spectroscopic evidence means that definitive conclusions regarding over-acetylation cannot be made.Similar observations have been reported in previous studies on acetylated hardwoods. These studies found that moderate acetylation improved dimensional stability without substantially reducing stiffness (Hill 2006; Rowell 2014). For example, Papadopoulos (2008) highlighted that optimal acetylation occurs at a moderate WPG, consistent with the intermediate FS observed for Im60-Re60 and Im180-Re60. Similar interactions between impregnation and reaction duration have been reported in studies of acetylated veneer composites (Adebawo *et al*. 2016, 2020, 2021, 2022).Huang *et al*. (2018) cautioned that overly aggressive reaction conditions may damage structural polymers and negate strength gains. This highlights the importance of the statistically significant groupings indicated by the lettering in Fig. 3. Im60-Re120 and Im180-Re120 belong to letter groups that differ significantly from the control group ($p < 0.05$), whereas Im60-Re60 and Im180-Re60 fell into intermediate groups.

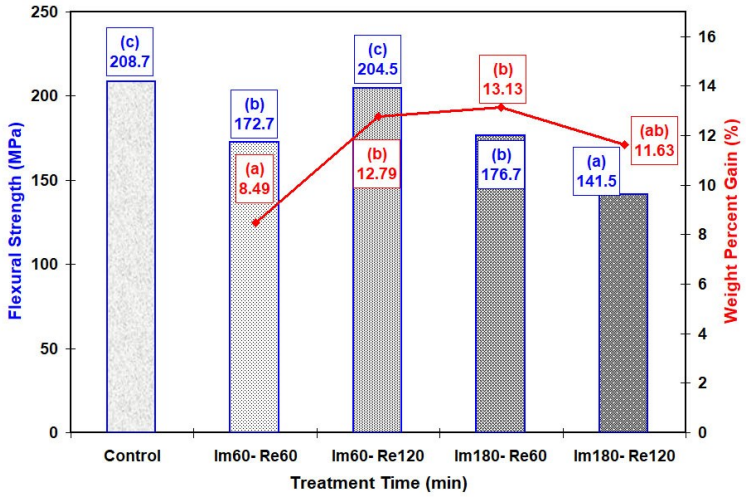

Fig. 3. Interaction effect of impregnation and reaction times on the WPG and FS values of acetylated beech wood samples compared with the control samples; (Duncan's multiple range tests are given in the parentheses)

Flexural modulus

As shown in Fig. 4 and Table A3 (Appendix), acetylation did not result in any statistically significant changes to the FM across the examined treatment conditions. Although WPG increased with longer reaction times, FM values remained within the narrow range of 14.7to19.8 GPa and all treated samples were comparable to the control

sample. The absence of a systematic decrease in FM indicates that acetylation primarily modified hygroscopic behavior without adversely affecting the elastic stiffness of beech wood under the applied conditions. The minor fluctuations observed at higher WPG levels may be due to natural variability in the material rather than chemical degradation, as no direct evidence of structural damage was found. The FM of acetylated beech wood increased relative to the untreated control. These results are consistent with those of Wang *et al.* (2024), who found that acetylation increases stiffness by raising wood cell wall density and reducing bound water content. Similarly, Čermák *et al*. (2022) noted that the stiffening effect strongly depends on impregnation efficiency and the extent of acetyl substitution. In this study, Im60-Re120 and Im180-Re120 treatments produced moderately high FM values, whereas Im60-Re60 exhibited the highest modulus. This indicates that excessive reaction times do not necessarily improve stiffness, which is likely due to thermally induced hemicellulose degradation, as also described by Esteves and Pereira (2009). Moreover, Guo *et al*. (2022) demonstrated that optimized acetylation can enhance the elastic modulus without severe polymer degradation. This supports the statistical trend observed in this work, where optimized conditions outperformed both the control and under reacted samples.

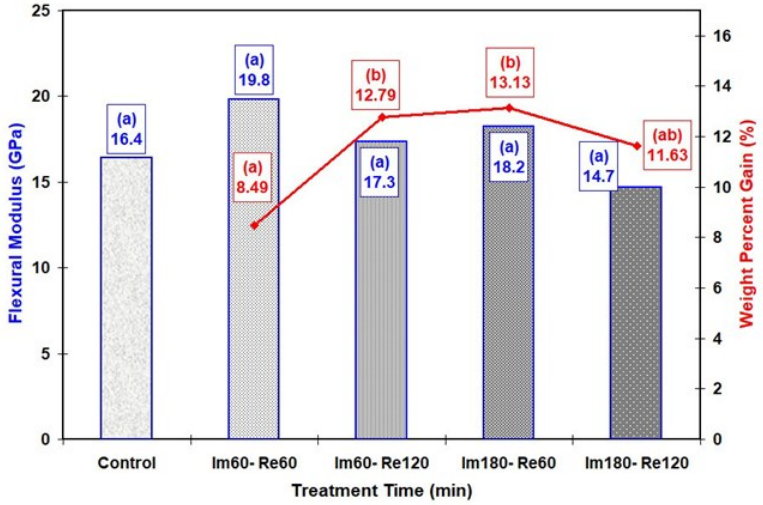

Fig. 4. Interaction effect of impregnation and reaction times on the WPG and FM values of acetylated beech wood samples compared with the control samples; (Duncan's multiple range tests are given in the parentheses)

Impact strength

Figure 5and Table A4 (Appendix) show the effect of acetylation on impact strength of beech wood. Although the IS values of the acetylated specimens were generally lower than that of the control, the differences among treatment conditions were limited and partially overlapping from a statistical standpoint. No clear monotonic relationship between the WPG and the IS was observed. Minor reductions in the IS at higher WPG levels may be associated with increased brittleness resulting from reduced moisture plasticization. However, these variations remained within the range of natural material variability and did not provide evidence of severe chemical degradation under the applied treatment conditions.

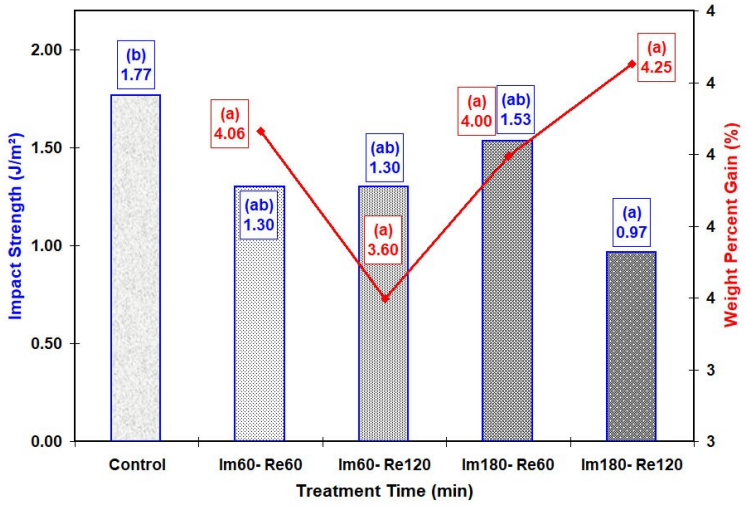

Fig. 5. The interaction effect of impregnation and reaction times on the WPG and IS values of acetylated beech wood samples compared with the control samples; (Duncan's multiple range tests are given in the parentheses)

According to Rowell *et al*. (2013), acetylation may either improve or reduce toughness depending on the balance between reduced hygroscopicity and microstructural embrittlement. Similarly, Mantanis (2017) reported that excessive acetylation often leads to lower impact resistance due to diminished plastic energy absorption. This interpretation is consistent with the findings of Forsman *et al*. (2020), who observed improved fracture resistance under controlled acetylation conditions. Moreover, Gindl *et al*. (2003) emphasized that microstructural analyses, such as scanning electron microscopy, are essential to elucidate the morphological origins of toughness variations, which could further explain the divergent responses observed among treatments in this study.

Compression strength

As illustrated in Fig. 6 and Table A5 (Appendix), compression strength of beech wood was not significantly affected by acetylation under the examined treatment.

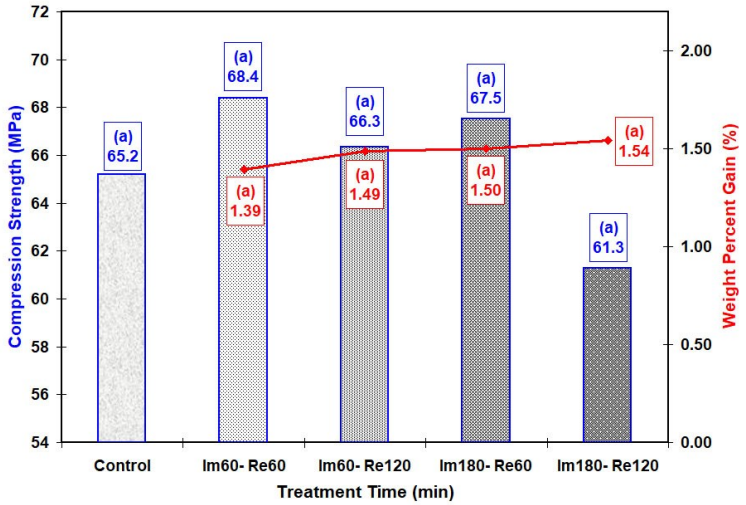

Fig. 6. Interaction effect of impregnation and reaction time on compressive strength of acetylated beech wood and control wood samples; (Duncan's multiple range tests are in parentheses)

All the treated specimens exhibited CS values that were statistically comparable to the control, despite minor numerical variations. The absence of a systematic trend with increasing WPG indicates that acetylation primarily altered hygroscopic behavior without compromising load-bearing capacity under compressive loading. The observed fluctuations are attributed to inherent material variability rather than chemical degradation.

The results of the compression strength testing were consistent with the findings of Hill *et al*. (2021), who stated that acetylation primarily enhances compressive properties by reducing bound water content and increasing wood cell wall bulking. Similar trends were noted by Bongers and Beckers (2003), linking improvements in compressive behavior to increased density and reduced equilibrium moisture content. The highest CS in Im180-Re60 indicates that extended impregnation promotes deeper reagent penetration and more uniform acetyl distribution. This is consistent with Bi *et al*. (2021), who demonstrated a strong correlation between compressive strength and weight percent gain in acetylated wood. Finally, Che *et al*. (2019) emphasized that statistical significance testing is essential for validating small yet meaningful improvements in mechanical properties, reinforcing the current study's conclusion that the modest increases in compressive strength observed here are nevertheless reliable. In contrast, at higher modification levels, a reduction in compression strength compared with untreated wood was also noted, consistent with the findings of Papadopoulos and Pougioula (2010). These authors further demonstrated that the enhancement in compressive performance resulting from chemical modification is not directly related to the degree of wood cell wall bulking, but rather to the extent of hydroxyl group substitution within the cell wall matrix. This interpretation lends support to the view that moderate acetylation can enhance the strength of wood by optimizing chemical substitution without causing excessive structural embrittlement.

The Effect of Acetylation on the Physical Properties

This dataset presents a detailed evaluation of the physical and hygroscopic properties of *Fagus orientalis*]wood samples, all measuring 20 ×20 ×20 mm^3, treated with acetic anhydride under varying impregnation (Im) and reaction (Re) times. Despite identical dimensions, the samples showed significant variation in WPG, WA, VSh, VSw and TS, and AShE and ASwE. These differences are primarily attributed to the duration of chemical exposure and saturation, which directly influence the depth and completeness of acetylation.

Samples treated with longer impregnation and reaction times (Im180-Re120) exhibited the highest WPG (13.57%), indicating more extensive chemical uptake. This correlates with reduced WA (14.44% after 24 h) and minimal swelling and shrinkage, confirming improved dimensional stability. In contrast, untreated control samples show significantly higher WA (22.49%) and pronounced swelling and shrinkage, reflecting their vulnerability to moisture. Although the AShE and ASwE were higher in the treated samples, variability suggested that microstructural factors and reagent distribution could influence these outcomes. These findings are consistent with Rowell's foundational work (Rowell *et al*. 2009), which emphasized that acetylation reduces the availability of hydroxyl groups, thereby limiting water bonding and improving stability. Similarly, Hill (2006) demonstrated that acetylated wood resists swelling and shrinkage due to reduced polarity in the cell wall. Building on this, Rowell *et al*. (1994) demonstrated that longer reaction times with acetic anhydride lead to a significant decrease in water uptake and dimensional changes in various wood species. Guo *et al.* (2022) confirmed that combining mechanical densification with acetylation improves the physical and mechanical properties

of softwoods such as spruce. Li *et al*. (2009) and Lv*et al*. (2017) investigated the effect of temperature and reaction time on acetylation efficiency. They revealed that greater WPG and stability are achieved at higher temperatures and longer durations. Papadopoulos and Hill (2003) also established a strong correlation between WPG and reduced water absorption, suggesting a predictable relationship between chemical uptake and hygroscopic behavior.

Overall, differences in the measured properties of the treatments are driven by the depth of chemical penetration and the completeness of the reaction, which are both governed by the time spent on impregnation and reaction. The results confirm that acetic anhydride treatment effectively improves the performance of wood in moisture-sensitive applications, aligning with a substantial body of literature in wood science and reinforcing the importance of optimizing treatment parameters for maximum efficacy.

Density and weight percent gain

The results showed no significant differences in the wet density (D_h) and oven-dry density (D_o) before and after acetylation among all treatment groups and the control ($p > 0.05$). This indicates that the acetylation process, despite increasing the wood's weight through the introduction of acetyl groups (WPG between 9.14% and 13.57%), did not substantially alter the bulk density of beech wood (Table 2).

Table 2. Mean ± (SD) Values of Density and WPG of Control- and Acetylated-Beech Wood Samples

Physical Properties	Im60-Re60 (min)	Im60-Re120 (min)	Im180-Re60 (min)	Im180-Re120 (min)	Control
D_h (BIm) (gr/cm^3)	0.77 a ± (0.01)	0.75 a ± (0.02)	0.77 a ± (0.03)	0.71 a ± (0.02)	0.75 a ± (0.02)
D_o (BIm) (gr/cm^3)	0.72 a ± (0.01)	0.71 a ± (0.02)	0.70 a ± (0.04)	0.69 a ± (0.02)	0.70 a ± (0.01)
D_o (AIm) (gr/cm^3)	0.72 a ± (0.01)	0.71 a ± (0.02)	0.72 a ± (0.02)	0.70 a ± (0.02)	
WPG (%)	9.14 a ± (1.91)	11.66 a ± (4.24)	11.97 a ± (4.77)	13.57 a ± (0.69)	

D_h (BIm): Wet density before impregnation; D_o (BIm): Oven-dry density before impregnation; D_o (AIm): Oven-dry density after impregnation; WPG: Weight percent gain; Groups with the same letters in each row indicated no statistical difference ($p<0.05$) between the samples according to Duncan's multiple range test.

The observed mass increase without a proportional density change suggests volumetric expansion due to cell wall modification, rather than simple pore filling. These findings are consistent with those of previous studies (Obataya and Gril 2005), which found that acetylation increased the mass of wood without significantly affecting its density. This suggests that the acetyl groups primarily occupy cell wall polymers rather than filling voids or pores.

Dimensional stability: Volumetric shrinkage and volumetric swelling

Table 3 displays the volumetric shrinkage (VSh, %) and volumetric swelling (VSw, %) in the acetylated and control beech wood samples after 2 and 24 h, respectively. A similar trend was found as in the VSh and VSw. The lowest VSh and VSw were found in the treatment time of Im60-Re120 min, with values of -6.5% and -5.9% after 2 h, respectively. The highest VSh and VSw with respect to the control (6.9% and 7.5%) after

24 h were found by wood treatment at Im60-Re60 min, with values of -0.89% and -0.85%, respectively. Acetylated samples exhibited significant reductions in VSh and VSw compared to the control samples, both at 2 and 24 h immersion.These reductions demonstrate the enhanced dimensional stability imparted by acetylation. The mechanism underlying this improvement lies in the substitution of hydrophilic hydroxyl groups with hydrophobic acetyl groups in the wood cell wall polymers, which reduces water uptake and associated dimensional changes (Obataya and Shibutani 2005). The negative values in shrinkage and swelling indicate dimensional stability or slight expansion, further confirming the efficacy of acetylation.

Table 3. Mean ± (SD) Values of Physical Properties of Control- and Acetylated-Beech Wood Samples

Physical Properties		Im60-Re60 (min)	Im60-Re120 (min)	Im180-Re60 (min)	Im180-Re120 (min)	Control
VSh (%)	2 h	-1.75 ab ± (1.18)	-6.50 a ± (5.88)	-2.53 ab ± (5.75)	-3.24 ab ± (2.89)	3.30 b ± (0.46)
VSh (%)	24 h	-0.89 a ± (1.80)	-4.75 a ± (4.98)	-1.43 a ± (4.70)	-2.19 a ± (2.76)	6.94 b ± (0.27)
VSw (%)	2 h	-1.71 ab ± (1.16)	-5.92 a ± (5.03)	-2.27 ab ± (5.44)	-3.09 ab ± (2.70)	3.41 b ± (0.49)
VSw (%)	24 h	-0.85 a ± (1.76)	-4.39 a ± (4.43)	-1.27 a ± (4.55)	-2.10 a ± (2.69)	7.45 b ± (0.31)

VSh 2 h: Volumetric shrinkage 2 h; VSh 24 h: Volumetric shrinkage 24 h; VSw 2 h: Volumetric swelling 2 h; VSw 24 h: Volumetric swelling 24 h. Groups with the same letters in each row indicated no statistical difference ($p<0.05$) between the samples according to Duncan's multiple range test

Water absorption and thickness swelling

The WA was notably decreased in acetylated-beech wood samples, with values ranging from 9.65% to 14.44% after 24 h immersion duration, which wassignificantly lower than the 22.49% observed in the control samples (Table 4).

Table 4. Mean ± (SD) Values of Water Absorption and Thickness Swelling of Control- and Acetylated-Beech Wood Samples

Physical Properties	Im60-Re60 (min)	Im60-Re120 (min)	Im180-Re60 (min)	Im180-Re120 (min)	Control
WA 2 h (%)	1.11 a ± (2.98)	-0.12 a ± (5.07)	1.17 a ± (7.02)	3.55 a ± (2.43)	6.96 a ± (5.16)
WA 24 h (%)	12.51 a ± (5.76)	9.65 a ± (3.71)	12.13 a ± (5.75)	14.44 ab ± (1.31)	22.49 b ± (6.00)
TS 2 h (%)	-0.98 a ± (0.81)	-1.77 a ± (2.59)	-0.65 a ± (3.34)	-2.13 a ± (0.71)	3.63 b ± (1.58)
TS 24 h (%)	-0.31 a ± (1.41)	-1.06 a ± (2.04)	0.23 a ± (2.96)	-1.29 a ± (1.21)	6.92 b ± (1.79)

WA 2 h: Water absorption 2 h; WA 24 h: Water absorption 24 h; TS 2 h: Thickness swelling 2 h; Thickness swelling 24 h; Groups with the same letters in each row indicated no statistical difference ($p<0.05$) between the samples according to Duncan's multiple range test

This supports the hypothesis that acetylation reduces wood's affinity for water due to the reduced availability of hydroxyl groups, thereby improving its resistance to moisture. Thickness swelling (TS) measurements reinforced these results, as acetylated-beech

samples exhibited minimal swelling or even slight dimensional contraction compared to the control samples, which showed swelling of up to 6.92% after 24 h immersion duration. This enhanced dimensional stability is critical for wood applications in environments subject to humidity fluctuations.

Anti-shrinkage efficiency and anti-swelling efficiency

According to Table 5, AShE and ASwE were markedly higher in acetylated samples, with Im180-Re120 treatment showing the highest values (AShE up to 297.44% and ASwE up to 273.45% at 2 h immersion duration).

Table 5. Mean ± (SD) Values of Anti-shrinkage and Anti-swelling of Acetylated-Beech Wood Samples

Physical Properties	Im60-Re60 (min)	Im60-Re120 (min)	Im180-Re60 (min)	Im180-Re120 (min)
AShE 2 h (%)	153.20 a ± (36.05)	297.44 a ± (178.62)	176.98 a ± (174.91)	198.37 a ± (87.80)
AShE 24 h (%)	112.74 a ± (25.87)	168.42 a ± (71.76)	120.56 a ± (67.72)	131.57 a ± (39.81)
ASwE 2 h (%)	150.19 a ± (33.81)	273.45 a ± (147.59)	166.47 a ± (159.46)	190.46 a ± (79.04)
ASwE 24 h (%)	111.48 a ± (23.66)	158.97 a ± (59.40)	117.00 a ± (61.04)	128.13 a ± (36.09)

AShE 2 h: Anti-shrinkage efficiency 2 h; AShE 24 h: Anti-shrinkage efficiency 24 h; ASwE 2 h: Anti-swelling efficiency 2 h; ASwE 24 h: Anti-swelling efficiency 24 h; Groups with the same letters in each row indicated no statistical difference ($p<0.05$) between the samples according to Duncan's multiple range test

These values reflect the improved resistance of acetylated wood to dimensional changes caused by moisture. These findings corroborate earlier work by Obataya and Gril (2005), confirming that acetylation process significantly enhances the dimensional stability of wood by altering its chemical structure to reduce hygroscopicity. Chai (2015) demonstrated that acetylated plantation poplar with a WPG above 15% exhibited excellent dimensional stability and an ASF above 50%. Furthermore, the mechanical properties of the acetylated wood remained largely unchanged when the acetylation temperature was below 120 °C.

After acetylation, hornbeam dimensional stability (anti-swelling efficiency) increased to 81 to 88% (Fodor *et al*. 2017), which had a direct influence on reducing stresses on bondlines in the delamination tests associated with water immersion and drying cycles. Additionally, compared to untreated wood, the mechanical properties of acetylated wood decreased less under wet conditions. This indicates that acetylated wood has higher bond strength under wet conditions. Furthermore, compared to untreated wood, the mechanical properties decreased less in wet conditions, indicating a higher bonding strength in wet conditions as well (Hofferber *et al*. 2006; Bongers *et al*. 2014).

Consequently, the acetylation process effectively improved the physical and dimensional stability properties of beech wood. The treatment was found to reduce shrinkage, swelling, and water absorption by chemically modifying cell wall polymers and increasing hydrophobicity. The results are consistent with previous studies and confirm that acetylation is a reliable method for improving wood performance in humid environments. This modification enhances the durability and stability of beech wood, potentially broadening its industrial applications.

CONCLUSIONS

1. Acetylation of beech wood using acetic anhydride improved dimensional stability while largely maintaining mechanical performance under the applied process conditions.
2. According to the mechanical property results, the immersion for 60 and reaction for 60(Im60-Re60) min treatment showed better pressure resistance and elastic modulus than the other groups, while the Im60-Re120 treatment showed a better elastic modulus. In contrast, the Im180-Re60 treatment showed better IS resistance. Therefore, it is recommended to select the appropriate process type based on the mechanical properties that are important in the final application.
3. Longer reaction times tended to increase the weight percentage gain (WPG), while slight reductions in the flexural and impact strengths were observed, possibly associated with the changes in cell-wall chemistry.
4. Water absorption decreased by up to 36% compared with the control, while anti-swelling efficiency exceeded 150% under the studied conditions.
5. These findings indicate that controlled acetylation has the potential to enhance the dimensional stability of beech wood with the limited adverse effects on the mechanical properties within the scope of this study.

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Conflict of Interest

The authors declare no conflicts of interest.

Use of Generative AI

The authors would like to declare that generative AI (ChatGPT-4.0) was used solely for assistance in checking and refining the English language in this manuscript.

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APPENDIX

Table A1. Univariate Analysis Test Results for Weight Percent Gain (WPG) of Acetylated Beech Wood

Source	Type III Sum of Squares	df	Mean Square	F	p-Value
Corrected Model	1041.713	15	69.448	18.385	0.000
Intercept	2445.707	1	2445.707	647.474	0.000
Sample	970.557	3	323.519	85.648	0.000
Impregnation Time	15.093	1	15.093	3.996	0.054
Reaction Time	8.795	1	8.795	2.328	0.137
Sample × Impregnation Time	11.130	3	3.710	0.982	0.413
Sample × Reaction Time	9.873	3	3.291	0.871	0.466
Impregnation Time × Reaction Time	6.872	1	6.872	1.819	0.187
Sample × Impregnation Time × Reaction Time	19.392	3	6.464	1.711	0.184
Error	120.874	32	3.777		
Total	3608.294	48			
Corrected Total	1162.587	47			

Table A2. One-way ANOVA Results for Flexural Strength (FS) of Acetylated Beech Wood

Source	Sum of Squares	df	Mean Square	F	p- Value
Between Groups	8916.471	4	2229.118	111.998	0.000
Within Groups	199.032	10	19.903		
Total	9115.503	14			

Table A3. One-way ANOVA Results for Flexural Modulus (FM) of Acetylated Beech Wood

Source	Sum of Squares	df	Mean Square	F	p- Value
Between Groups	43811226.670	4	10952806.670	1.615	0.245
Within Groups	67816333.330	10	6781633.333		
Total	111627560.000	14			

Table A4. One-way ANOVA Results for Impact Strength (IS) of Acetylated Beech Wood

Source	Sum of Squares	Df	Mean Square	F	p- Value
Between Groups	1.069	4	0.267	1.831	0.200
Within Groups	1.460	10	0.146		
Total	2.529	14			

Table A5. One-way ANOVA Results for Compression Strength (CS) of Acetylated Beech Wood

Source	Sum of Squares	df	Mean Square	F	p- Value
Between Groups	92.676	4	23.169	0.339	0.846
Within Groups	683.659	10	68.366		
Total	776.334	14			