

Article

Impregnation of Beech Wood (*Fagus sylvatica* L.) with Corn Oil: A Comprehensive Evaluation of Hygroscopic Behavior, Surface Properties, and Artificial Weathering

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Abstract

Beech (*Fagus sylvatica* L.) is a widely used hardwood species whose limited natural durability and dimensional instability under moisture restrict its outdoor applications. This study investigated the effect of vacuum impregnation with corn oil (*Zea mays* L.), a low-cost and underexplored vegetable oil, on the surface and hygroscopic properties of beech wood. Specimens were impregnated for 30 or 60 min and characterized, together with non-impregnated controls, for weight percentage gain (WPG), dimensional change, FTIR spectra, color, hardness, surface roughness, and contact angle, before and after accelerated artificial weathering in a Xenon chamber; hygroscopic behavior was further assessed through water absorption and dimensional swelling during 24 h of water immersion. FTIR analysis confirmed effective oil penetration into the wood structure through characteristic triglyceride absorption bands. Impregnation resulted in high oil uptake (WPG > 45%) at both durations without inducing substantial dimensional change and significantly increased the contact angle and reduced water absorption (by 65%–66%) and radial and tangential swelling relative to the controls ($p < 0.05$), while surface hardness remained unaffected ($p = 0.263$). Color difference (ΔE^*) after artificial weathering was significantly higher in impregnated specimens than in the controls ($p < 0.001$), reflecting the natural yellowish hue of the oil rather than material degradation. Overall, corn oil impregnation, applied for as little as 30 min, improved the hydrophobicity and dimensional stability of beech wood without compromising its hardness, supporting its potential as a sustainable, bio-based wood modification medium.

Keywords: *Fagus sylvatica* L.; corn oil; vacuum impregnation; wood modification; hygroscopic properties; artificial weathering; contact angle



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1. Introduction

Beech (*Fagus sylvatica* L.) is among the most important broadleaved forest species in Europe and constitutes a raw material of high industrial value, with extensive use in furniture manufacturing, interior construction, flooring production, and a wide range of wood products. Its widespread use is attributed mainly to its relatively uniform anatomical features, good workability, and favorable machining performance [1]. In Greece, beech occurs mainly in the forests of the central and northern parts of the country, where it

exhibits considerable productive potential [2]. Furthermore, beech wood has been reported to exhibit satisfactory bonding performance in standardized applications [3]. Despite these advantages, the natural durability of the species is relatively limited, and its dimensional stability decreases under fluctuating moisture conditions, which restricts its outdoor use without prior protective treatment [4].

To address these limitations, numerous wood modification techniques have been developed to improve dimensional stability, moisture resistance, and biological durability [5–7]. Among these, impregnation with natural or synthetic substances is one of the most widely applied approaches, as it allows the filling of cell cavities, and in some cases, cell walls with the impregnating medium, thereby reducing the space available for water penetration [8]. Comparable effects have also been reported for epoxidized vegetable oils such as linseed and soybean oil [9]. The interaction of wood with moisture and impregnating agents is strongly influenced by its chemical composition, particularly by the hydroxyl-rich cellulose, which is the principal component responsible for moisture sorption due to the abundance of accessible hydroxyl (–OH) groups. Although hemicelluloses and lignin also interact with moisture, their contribution is considerably lower because of their lower accessibility and reduced hydrophilic character [10]. In addition to its chemical composition, the effectiveness of wood impregnation is strongly influenced by the permeability of the wood species. Beech exhibits relatively good permeability compared with many temperate hardwood species, facilitating the penetration of impregnating agents into their anatomical structure and making it a suitable species for impregnation treatments [10]. These characteristics, together with its wide availability and industrial importance, were among the main reasons for selecting beech wood for the present study.

In recent years, vegetable oils have attracted growing research interest as environmentally friendly wood modification media, offering an alternative to many conventional preservatives whose use has been restricted for toxicological and environmental reasons [11]. Oils such as linseed, tung, castor, and soybean oil have been extensively evaluated as impregnation media, with reported reductions in moisture uptake, improved dimensional stability, and increased surface hydrophobicity [12,13]. Tung oil, for instance, has been shown to reduce wood hygroscopicity while improving thermal behavior and dimensional stability [14]. Castor oil impregnation has similarly been reported to enhance physical properties without substantially affecting Janka hardness or bending strength [15], while emulsions of epoxidized linseed oil combined with carnauba wax have produced comparably favorable results [16].

For beech specifically, impregnation with rapeseed oil has been shown to reduce water absorption and dimensional swelling, albeit with a modest reduction in the tensile strength of glued joints [17]. Combined thermal modification and hemp oil impregnation has likewise improved the color, dimensional stability, and hygroscopic behavior of European beech, with the oil contributing more than the thermal treatment itself [18]. Natural essential oils such as lavender oil have also been proposed as ecological wood protection agents without adverse effects on physical properties [19]. Despite this body of work on vegetable oils, corn oil (*Zea mays* L.) remains comparatively unexplored as an impregnation medium, even though it is an inexpensive and widely available by-product of the food industry.

Beyond dimensional stability and hygroscopicity, resistance to environmental stress is a decisive factor in evaluating modified wood materials. Prolonged exposure to solar radiation causes photo-oxidative degradation, mainly of lignin, resulting in color change, increased surface roughness, and altered surface wetting behavior. Xenon-arc weathering chambers, which reproduce ultraviolet solar radiation, are widely used to simulate these processes under controlled laboratory conditions [20]. Although Xenon weathering chambers reproduce the full solar spectrum more realistically than UV-only devices, they cannot

fully replicate the complexity of natural outdoor exposure, where biological, seasonal, and environmental factors also contribute to wood degradation. It is worth mentioning that contact angle is one of the most widely used indicators of wood surface hydrophobicity, and its use in estimating the surface free energy of wood has been extensively documented in the literature [20,21], building on classical theories of wetting on rough and heterogeneous surfaces [22,23].

Although the effects of various vegetable oils on wood properties have been studied fairly extensively, few studies have jointly examined surface properties (color, hardness, roughness, and contact angle), hygroscopic behavior (water absorption and dimensional swelling), and resistance to artificial weathering within a single experimental framework, particularly for corn oil.

Therefore, the aim of this study was to investigate the effect of corn oil impregnation, at two treatment durations (30 and 60 min) on the surface properties (color, hardness, roughness, and contact angle) and hygroscopic behavior (water absorption and dimensional change) of beech wood, before and after accelerated artificial weathering in a Xenon chamber. The findings are expected to contribute to the evaluation of corn oil as a natural wood modification medium capable of improving the resistance of beech wood to moisture and to the conditions of artificial weathering.

2. Materials and Methods

2.1. Material and Specimen Preparation

A total of 60 specimens of European beech, originating from the Pindus Mountains in Thessaly Greece, were prepared with nominal dimensions of approximately $30 \times 20 \times 10$ mm (longitudinal $\times$ tangential $\times$ radial). Prior to treatment, all specimens were conditioned at 20 ± 2 °C and $65 \pm 5\%$ relative humidity until equilibrium moisture content (approximately 12%) was achieved. The initial dimensions (length, width and thickness) and mass of each specimen were recorded before impregnation.

Ten specimens remained untreated and served as the control group. The remaining 50 specimens were randomly divided into two equal groups of 25 specimens each. The first group was impregnated with commercial corn oil (*Zea mays* L.), produced by the Greek enterprise KOPE A.E., headquartered in Koropi (Attica), Greece, labeled as Corola Corn Oil, for 30 min, whereas the second group was impregnated for 60 min. Oil impregnation was carried out using a Vevor Vacuum Pump (branded and distributed by Shanghai Vevor Machinery Equipment Co., Ltd., Shanghai, China) connected to a sealed vacuum chamber. A vacuum pressure of approximately -1 atm (gauge pressure) was applied to remove air from the wood pores and facilitate the corn oil penetration into the wood structure. Two impregnation durations were investigated (30 and 60 min). After impregnation, all specimens were gently wiped with absorbent paper to remove excess oil from the surface before being reweighed and remeasured. The increase in mass was used to calculate the weight percentage gain (WPG), while dimensional measurements were used to determine the dimensional changes caused by the impregnation process. The findings suggest that most accessible wood voids were already filled during the first 30 min of impregnation. Therefore, extending the impregnation time beyond 30 min appears to provide limited additional oil uptake under the conditions of the present study. Subsequently, each impregnation group was divided into two subsets. Fifteen specimens from each treatment group, together with five untreated controls, were used for the artificial weathering experiment. The remaining ten specimens from each treatment group, together with five controls, were used for the evaluation of hygroscopic properties. Surface hardness was determined using a digital Shore D durometer mounted on a vertical test stand to ensure constant loading and perpendicular contact between the indenter and the specimen surface. The same

35 specimens (15 impregnated for 30 min, 15 impregnated for 60 min, and 5 untreated controls) were measured before and after artificial weathering, and hardness values were expressed on the Shore D scale (0–100).

2.2. Determination of Weight Percentage Gain and Dimensional Changes

Following impregnation, the specimens were reweighed and measured, and calculated according to:

Equation (1): Weight percentage gain (WPG)

$$WPG(\%) = \frac{W_i - W_0}{W_0} \times 100, \quad (1)$$

where W_0 is the initial mass of the conditioned specimen before impregnation and W_i is the mass of the specimen after impregnation.

Equation (2): Dimensional change after impregnation

$$DCx(\%) = \frac{X_i - X_0}{X_0} \times 100, \quad (2)$$

where X_0 is the initial dimension of the conditioned specimen before impregnation, X_i is the corresponding dimension after impregnation, and $X = L, T, R$.

Equation (3): Water absorption (WA) during immersion

$$WA(\%) = \frac{W_t - W_0}{W_0} \times 100, \quad (3)$$

where W_0 is the initial mass of the conditioned specimen before water immersion and W_t is the mass after immersion time t .

Equation (4): Dimensional swelling (S)

$$S(\%) = \frac{X_t - X_0}{X_0} \times 100, \quad (4)$$

where X_0 is the initial dimension of the conditioned specimen before water immersion, X_t is the corresponding dimension after immersion t , and $X = L, T, R$.

Equation (5): Overall color difference (ΔE^*)

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}, \quad (5)$$

where ΔL^* , Δa^* and Δb^* correspond to the changes in lightness, red–green coordinate, and yellow–blue coordinate, respectively, after artificial weathering.

Weight percentage gain (WPG), dimensional change after impregnation, water absorption (WA), and dimensional swelling (S) were calculated using Equations (1)–(4), respectively. For all dimensional calculations, the conditioned dimensions measured prior to impregnation or water immersion were used as the reference values. The overall color difference (ΔE^*) was calculated from the measured CIE L^* , a^* and b^* coordinates, before and after artificial weathering.

2.3. Fourier Transform Infrared (FTIR) Spectroscopy

Fourier transform infrared (FTIR) spectroscopy was employed to verify the successful impregnation of beech wood with corn oil and to identify the characteristic functional groups associated with both the wood constituents and the impregnating oil. One untreated control specimen and one representative specimen from each impregnation treatment

(30 min and 60 min) were analyzed. FTIR spectra were recorded using a Lambda Scientific FTIR-7600S Fourier transform infrared spectrometer (Lambda Scientific Pty Ltd., Adelaide, Australia) with a single-beam FTIR system equipped with an attenuated total reflectance (ATR) sampling accessory, allowing for direct analysis of the solid wood specimens without additional sample preparation.

Spectral measurements were performed over the wavenumber range of 4000–400 cm^{-1} at room temperature. The obtained spectra were evaluated by comparing the characteristic absorption bands of untreated and impregnated specimens. Attention was given to the absorption bands associated with hydroxyl (O–H) groups, aliphatic C–H stretching vibrations, ester carbonyl (C=O) groups, aromatic lignin structures, and cellulose-related C–O–C vibrations. Peak assignments were interpreted according to the published literature on lignocellulosic materials and vegetable oils.

2.4. Hygroscopic Properties

Hygroscopic behavior was assessed on 25 specimens (10 impregnated for 30 min, 10 for 60 min, and 5 untreated controls). Before the immersion, the initial dimensions (length, width and thickness) and mass of each specimen were recorded after conditioning. The specimens were then fully immersed in distilled water at room temperature, and their mass and dimensions were measured after 2, 4, 8, 12, and 24 h of immersion. Water absorption (%) and dimensional swelling (%) were calculated for each immersion period in the three principal anatomical directions (longitudinal, radial and tangential). Each specimen was measured once at every immersion interval throughout the experiment.

2.5. Artificial Weathering

Artificial weathering was carried out to assess changes in color, surface roughness, wettability (contact angle), and surface hardness of the untreated and impregnated beech wood specimens following exposure. For this test, 35 specimens were used (15 impregnated for 30 min, 15 for 60 min, and 5 untreated controls). Artificial weathering was performed in a Xenon radiation chamber according to EN 927 [24] and ISO 4892-2 [25] using a radiation intensity of 200 W m^{-2} in the wavelength range of 290–400 nm, a black-panel temperature of 65 °C, and a relative humidity of 50%. The total exposure time was 72 h. All of the following measurements were performed once before the artificial weathering treatment and immediately after the completion of the weathering cycle.

2.6. Surface Characterization

2.6.1. Color Measurements

Surface color was measured using a Konica Minolta (manufactured by Konica Minolta, Inc. (specifically its Sensing Business Unit), headquartered in Tokyo (Chiyoda city), Japan) according to ASTM D1536 [26] in the CIE $L^*a^*b^*$ color space, where L^* represents lightness and a^* and b^* describe chromatic change along the red–green and yellow–blue axes, respectively.

2.6.2. Surface Roughness Measurements

Surface roughness was measured with a Mitutoyo SurfTest SJ-301 contact stylus profilometer (Mitutoyo Corporation, Kawasaki, Japan) according to ISO 21920-2 [27], with a stylus angle of 90°, a traverse speed of 10 mm/min, a stylus tip radius of 4 μm , and a sampling length of 4.5 mm; the parameters R_a (arithmetic mean roughness), R_q (root-mean-square roughness), and R_z (mean peak-to-valley height) were recorded. The specimens were measured for both longitudinal and radial/tangential dimensions.

2.6.3. Surface Wettability Measurements

Surface wettability was assessed using a KRÜSS FM40 EasyDrop goniometer equipped with a CCD camera (KRÜSS GmbH, Hamburg, Germany). Measurements were performed using the sessile drop method, which is widely accepted for evaluating the wettability of wood surfaces [28–30]. A constant-volume deionized water droplet (approximately $4 \pm 1 \mu\text{L}$) was deposited onto the wood surface using a microsyringe. The droplet profile was recorded immediately after deposition and analyzed using the KRÜSS Drop Shape Analysis (DSA) advance software. Static contact angle values were determined using the height–width fitting method, based on the droplet height and base width. Measurements were carried out immediately after droplet deposition at room temperature ($23 \pm 2^\circ\text{C}$) and performed once on each specimen before and after artificial weathering, with the droplet placed at approximately the same surface location whenever possible. Contact angle measurements were conducted on the radial anatomical surfaces, reflecting the actual surfaces available after specimen preparation. The measurement protocol followed the same general sessile drop approach commonly adopted in studies investigating the wettability of beech wood surfaces using KRÜSS Drop Shape Analysis systems [28–31].

2.6.4. Surface Hardness Measurements

Unless otherwise stated, all surface characterization tests (color, surface roughness and wettability) were performed on the same specimens before and after artificial weathering. Each specimen was measured once before Xenon exposure and once after completion of the weathering procedure. Whenever possible, measurements were carried out at approximately the same location on the specimen surface to ensure comparability of the results.

2.7. Statistical Analysis

Data was processed with IBM SPSS Statistics 29 software. One-way analysis of variance (ANOVA) was performed to compare the three experimental groups (control, 30-min, and 60-min impregnation) for each property examined, including color, hardness, roughness, contact angle, water absorption, and dimensional swelling. Where ANOVA indicated statistically significant differences, pairwise comparisons among group means were performed using Tukey's honestly significant difference (HSD) test [32]. A p -value below 0.05 was adopted as the threshold for statistical significance.

Artificial intelligence (AI) disclosure: Artificial intelligence (AI)-assisted tools, specifically “ClaudeAi”, were used exclusively for the graphical formatting and visual presentation of figures derived from experimentally obtained data. All experimental procedures, measurements, data collection, calculations, statistical analyses, interpretation of results, and scientific conclusions were performed by the authors. The AI tool was not used to generate, modify, or interpret the experimental data, but solely to improve the visual layout and presentation of the figures.

3. Results

3.1. FTIR Spectroscopy—Confirmation of Beech Wood Impregnation with Corn Oil

Fourier transform infrared (FTIR) spectroscopy was applied to three beech wood specimens: one non-impregnated control and two specimens impregnated with corn oil for 30 and 60 min. Corn oil consists mainly of linoleic, oleic, and palmitic acid triglycerides [33], which produce characteristic absorption bands that allowed for confirmation of their presence in the wood. Spectra were recorded over the range $400\text{--}4000 \text{ cm}^{-1}$ (Figure 1), and the main peaks, assigned following established band assignments for lignocellulosic materials [34], are summarized in Table 1.

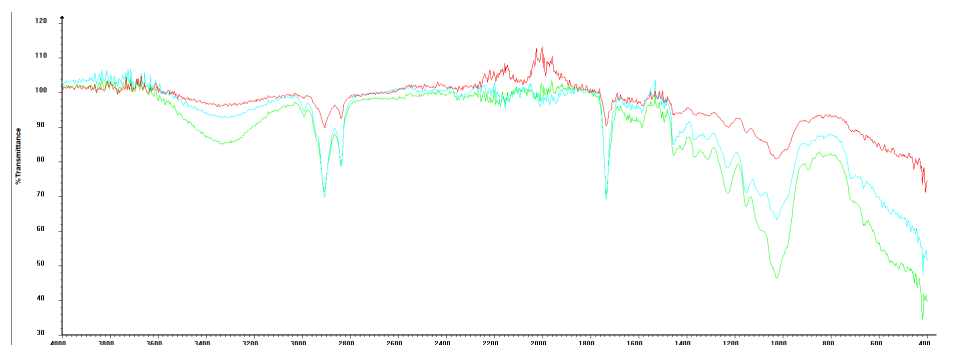


Figure 1. FTIR spectra of beech wood: control (red), 30-min impregnation (green), and 60-min impregnation (cyan).

Table 1. Main FTIR peaks and their assignment in the beech wood specimens.

Peak (cm^{-1})	Assignment	Observation
3600–3200	O–H stretching (cellulose, hemicellulose)	Slight decrease in impregnated specimens
2922/2853	$\nu_{\text{as}}/\nu_{\text{s}}$ C–H (CH_2 , CH_3)—fatty acids	Appeared strongly only in impregnated specimens
1745	C=O stretching of esters (oil triglycerides)	Absent in control, present in impregnated specimens
1600/1510	Aromatic lignin skeleton (C=C)	Present in all three specimens
1460/1375	C–H deformation (CH_2/CH_3)	Enhanced in impregnated specimens—traces of oil
1160/1030	C–O–C stretching (cellulose)	Intensity varied with impregnation time
722	C–H out-of-plane (long chains)	Characteristic peak of corn oil

3.1.1. Oil Penetration into Wood

The impregnated specimens exhibited intense peaks at 2922 and 2853 cm^{-1} , corresponding to C–H stretching vibrations of the aliphatic triglyceride chains [35–37]. These peaks were essentially absent from the control, confirming the presence of corn oil after impregnation. The characteristic C=O ester peak ($\sim 1745 \text{ cm}^{-1}$) likewise appeared only in the impregnated specimens [38], while the peak at $\sim 722 \text{ cm}^{-1}$, attributed to long aliphatic triglyceride chains, further supported the presence of the oil.

Comparison of the spectra showed that increasing the impregnation time from 30 to 60 min was accompanied by more intense C–H (~ 2922 and 2853 cm^{-1}) and C=O ($\sim 1745 \text{ cm}^{-1}$) bands, together with lower transmittance (%T) in the 400–1500 cm^{-1} region. These findings indicate greater corn oil retention in the 60-min specimens, consistent with the WPG results.

3.1.2. Oil Interaction with Wood Structural Components

In the impregnated specimens, small changes were observed in the O–H band (3200–3600 cm^{-1}), likely related to interactions between the polar groups of the oil and the hydroxyls of cellulose [39]. Differences in the C–O–C peaks (~ 1160 and $\sim 1030 \text{ cm}^{-1}$) suggest penetration of the oil into the wood microstructure, without substantial change in the characteristic lignin peaks (~ 1600 and $\sim 1510 \text{ cm}^{-1}$), indicating that the impregnation involves mainly physical deposition rather than the chemical modification of lignin.

Overall, FTIR analysis confirmed the successful penetration of corn oil into beech wood through the appearance of characteristic triglyceride peaks. The stronger absorption observed in the 60-min specimens indicates greater corn oil retention within the wood structure, while the limited changes in the O–H and C–O–C regions point to potential

interactions with wood structural components without evidence of a substantial chemical alteration of lignin.

3.2. Corn Oil Uptake and Dimensional Change During Impregnation

3.2.1. Weight Percentage Gain (WPG)

Vacuum impregnation with corn oil resulted in high oil uptake in beech wood at both treatment durations. Specimens impregnated for 30 min exhibited an average weight percentage gain (WPG) exceeding 45%, with similarly high values observed for the 60-min treatment. Comparison of the two treatments indicated that extending the impregnation time from 30 to 60 min did not result in a substantial increase in oil uptake.

The initial mass and dimensions used for the calculation of the weight percentage gain (WPG) and dimensional changes corresponded to the conditioned specimens before impregnation and not to the oven-dry state.

The observed WPG values are consistent with previous studies reporting enhanced oil uptake following the vacuum impregnation of wood with vegetable oils, in which the effective removal of air from vessels and cell cavities facilitates deeper penetration of the impregnating agent into the wood.

3.2.2. Linear Dimensional Change After Impregnation with Corn Oil

The effectiveness of the impregnation treatment was assessed through the evaluation of the dimensional stability of the treated specimens. For this purpose, the weight percentage gain (WPG), as presented in Figure 2, and the dimensional changes in the three principal anatomical directions (axial, radial, and tangential) were determined after impregnation, as presented in Figure 3. The results obtained are presented in Figure 4.

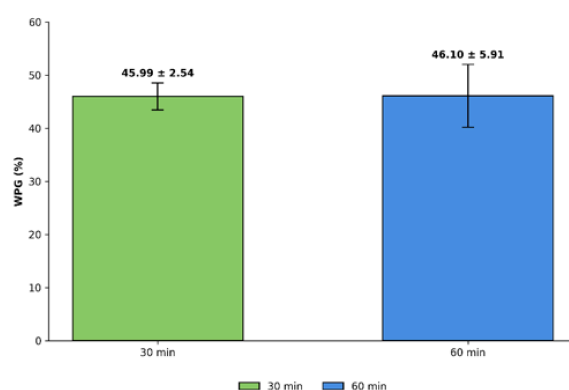


Figure 2. Weight percentage gain (WPG) after the impregnation of beech wood specimens with corn oil for 30 and 60 min. Values are presented as mean $\pm$ standard deviation.

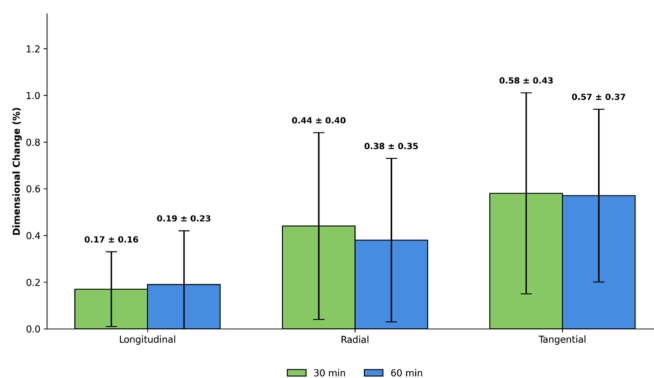


Figure 3. Overall dimensional stability of beech wood specimens after impregnation with corn oil. Values are presented as mean $\pm$ standard deviation.

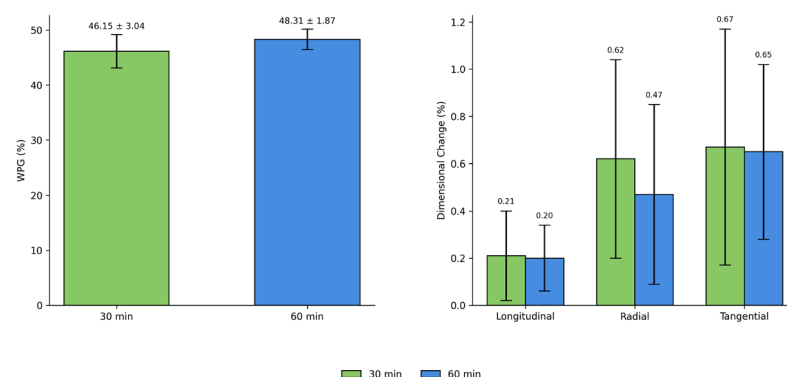


Figure 4. Weight percentage gain (WPG) and overall dimensional stability of beech wood specimens after impregnation with corn oil for 30 and 60 min. Values are expressed as the mean $\pm$ standard deviation.

As expected, the longitudinal direction (Figure 5) exhibited the smallest dimensional changes among the three anatomical directions, with values of $0.17 \pm 0.16\%$ and $0.19 \pm 0.23\%$ for the 30- and 60-min treatments, respectively. This behavior reflects the inherent dimensional stability of wood along the grain.

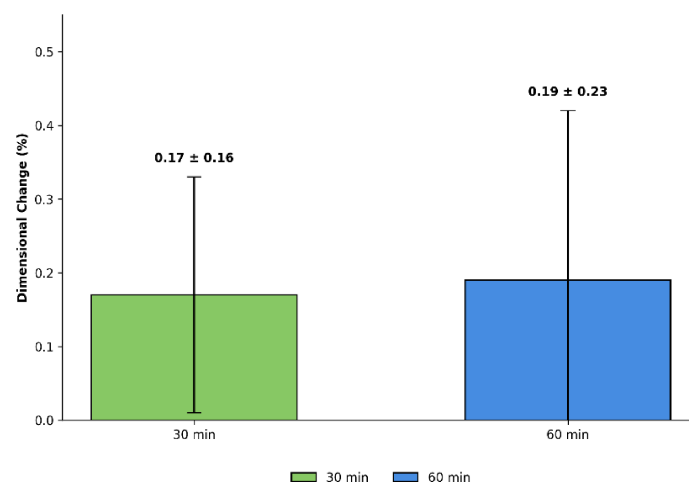


Figure 5. Longitudinal dimensional change of beech wood specimens before and after impregnation with corn oil. Values are presented as mean $\pm$ standard deviation.

Radial dimensional changes (Figure 6) remained limited in both treatment groups, indicating that corn oil impregnation did not adversely affect wood stability in this anatomical direction: $0.44 \pm 0.40\%$ for the 30-min group and $0.38 \pm 0.35\%$ for the 60-min group, a difference within the range of standard deviation.

The greatest dimensional changes were observed in the tangential direction (Figure 7), which is consistent with the anisotropic structure of wood, with nearly identical values for the two treatments ($0.58 \pm 0.43\%$ and $0.57 \pm 0.37\%$ for 30 and 60 min, respectively). Despite this direction's typically greater sensitivity to dimensional change, the values remained low, indicating that corn oil impregnation effectively limited dimensional change, even in the most sensitive anatomical direction of the wood.

Overall, corn oil impregnation resulted in high oil uptake without causing substantial dimensional changes in the wood. The smallest changes occurred in the axial direction, and the largest in the tangential direction, consistent with the anatomical structure of wood; even so, tangential values remained low. Extending the impregnation time from 30 to 60 min did not provide a substantial additional benefit in either oil uptake or dimensional stability, indicating that a 30-min impregnation is sufficient to achieve high corn oil uptake and

effective wood stabilization, making the shorter impregnation time a practical alternative under the experimental conditions of this study.

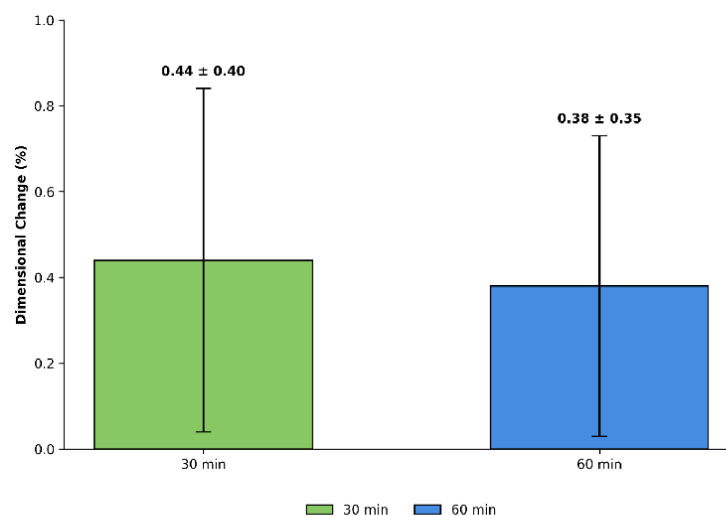


Figure 6. Radial dimensional change of beech wood specimens before and after impregnation with corn oil. Values are presented as the mean $\pm$ standard deviation.

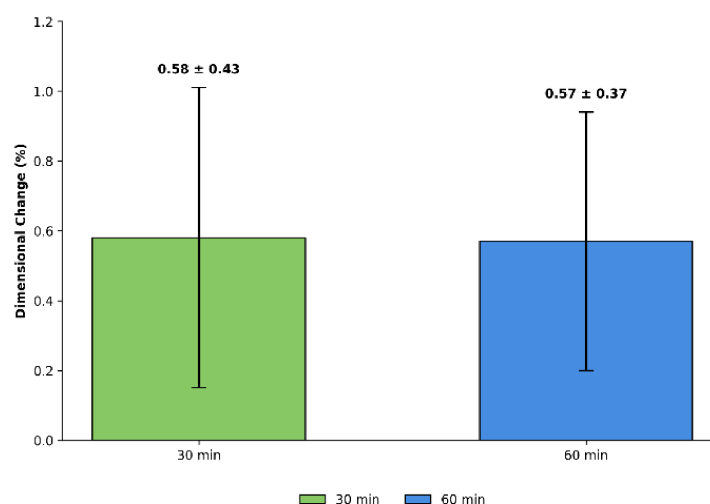


Figure 7. Tangential dimensional change of beech wood specimens before and after impregnation with corn oil. Values are presented as the mean $\pm$ standard deviation.

The high oil uptake observed in the impregnated specimens, exceeding 45% at both treatment durations, demonstrates the effectiveness of the vacuum method applied. The applied vacuum facilitates the removal of air from the vessels and cell cavities of the wood, allowing a deeper penetration of corn oil into the wood structure without causing substantial dimensional change. The oil occupies part of the available space within the wood cell walls and lumina, limiting the accessibility of hydroxyl (–OH) groups and reducing the capacity of the wood to absorb water from the environment. This interpretation is consistent with the FTIR observations reported for similarly treated beech wood, which indicate a reduction in the availability of hydrophilic sites following oil impregnation. Consequently, the reduced water uptake contributes to the lower moisture-induced swelling observed in the present study. These findings are in agreement with the FTIR results, which suggest that corn oil penetrated the wood structure and partially reduced the accessibility of hydroxyl groups, thereby contributing to the lower moisture uptake observed in the impregnated specimens.

3.3. Color Change of Corn Oil-Impregnated Beech During Artificial Weathering

Accelerated artificial weathering produced marked color changes in all specimens; however, these changes were considerably more pronounced in specimens previously impregnated with corn oil. The control group showed a total color difference (ΔE^*) of 5.31 ± 1.79 , while specimens impregnated for 30 and 60 min recorded 19.87 ± 2.14 and 18.48 ± 1.86 , respectively—approximately four times higher than the controls, confirming that impregnation decisively affects the color appearance of beech after Xenon exposure. ANOVA revealed a highly significant difference between the three groups ($F = 106.92$, $p < 0.001$), indicating that corn oil application was the dominant factor affecting the total color change of the wood.

The color change observed in the controls indicates that untreated beeches also undergo noticeable alteration after accelerated photo-aging, attributable mainly to the photo-oxidative reactions of lignin and wood extractives [40,41], consistent with previously reported changes in the surface chemistry of wood under artificial weathering [42]. In contrast, the much higher ΔE^* of the impregnated specimens was not due solely to aging but also to the presence of corn oil, whose characteristic yellowish hue alters the way the surface interacts with incident light; as a result, the naturally light-colored beech surface acquires different optical characteristics after impregnation.

Notably, the two impregnation times produced very similar outcomes. This observation consists of the absence of statistically significant differences in weight percentage gain (WPG) between the 30 and 60 min treatments, indicating that comparable oil uptake resulted in similar color changes. These findings suggest that most of the surface modification occurred during the initial stage of impregnation, while extending the treatment time to 60 min provided only limited additional effect.

The individual CIE color coordinates further clarify the nature of the observed color changes. All groups exhibited negative ΔL values, indicating surface darkening after artificial weathering, as shown in Table 2. However, this reduction in lightness was considerably greater in the corn oil-impregnated specimens than in the controls. The positive Δa values indicate a shift toward the red region, while the positive Δb^* values demonstrate a pronounced shift toward yellow. Both chromatic shifts were substantially stronger in the impregnated specimens, particularly along the yellow–blue axis, which is consistent with the characteristic yellowish color of corn oil. The similar ΔL^* , Δa^* , and Δb^* values recorded for the 30- and 60-min treatments further support the limited influence of extending the impregnation duration, as presented at Figure 8.

Table 2. Color changes (ΔL^* , Δa^* , Δb^* , and ΔE^*) of the control and corn oil-impregnated beech wood following artificial weathering.

Treatment	ΔL^*	Δa^*	Δb^*	ΔE^*
60 min	-14.37 ± 1.73^a	3.71 ± 1.17^b	10.95 ± 0.75^b	18.48 ± 1.86^a
30 min	-15.30 ± 1.77^a	4.95 ± 1.45^a	11.62 ± 0.97^a	19.87 ± 2.14^a
Control	-2.55 ± 1.49^b	0.96 ± 0.40^c	4.42 ± 1.51^c	5.31 ± 1.79^b

Values are presented as mean $\pm$ standard deviation. Different superscript letters within the same column indicate statistically significant differences according to Tukey's HSD test ($p < 0.05$). $n = 15$ for each impregnated group; $n = 5$ for the control group. The asterisk (*) in ΔE^* signifies that the measurement is based on the standardized $L^* a^* b^*$ (CIELAB) color space, where the individual coordinates L^* , a^* , b^* also carry asterisks to denote normalized, perceptually uniform color values.

Comparison of pairwise color differences confirmed this pattern: the control–30-min difference was 2.25 ± 1.01 , and the control–60-min difference was 3.20 ± 1.31 , indicating that extending the impregnation time causes only limited additional change in color response, as presented at Figure 9.

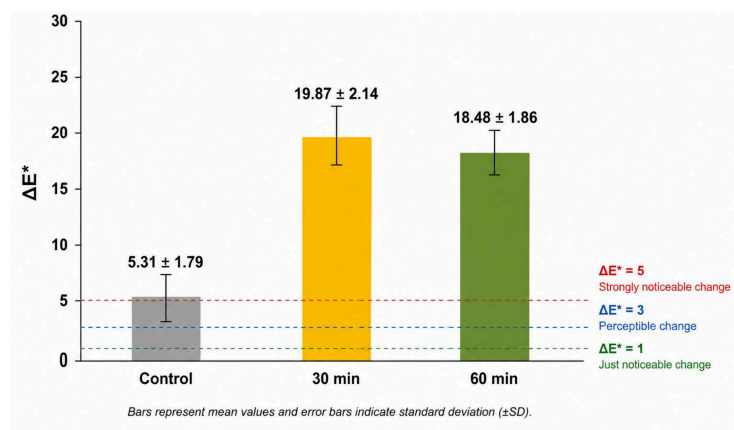


Figure 8. Total color difference (ΔE^*) of the non-impregnated and corn oil-impregnated beech wood specimens after accelerated aging in a Xenon chamber. Values are presented as the mean $\pm$ standard deviation. The asterisk (*) in ΔE^* signifies that the measurement is based on the standardized $L^* a^* b^*$ (CIELAB) color space, where the individual coordinates L^* , a^* , b^* also carry asterisks to denote normalized, perceptually uniform color values.

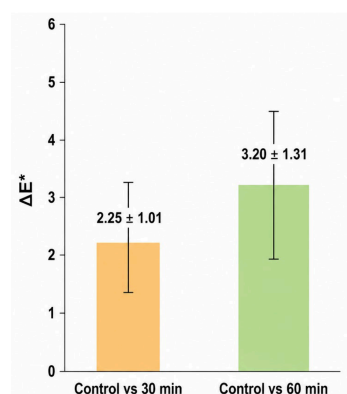


Figure 9. Color difference (ΔE^*) between the controls and specimens impregnated for 30 and 60 min. The control–30-min difference was 2.25 ± 1.01 , and the control–60-min difference was 3.20 ± 1.31 . The asterisk (*) in ΔE^* signifies that the measurement is based on the standardized $L^* a^* b^*$ (CIELAB) color space, where the individual coordinates L^* , a^* , b^* also carry asterisks to denote normalized, perceptually uniform color values.

Overall, corn oil impregnation substantially affects the aesthetic appearance of beech after artificial weathering. Although impregnation resulted in more pronounced color change relative to the non-impregnated specimens, this outcome reflects the expected presence of the natural oil rather than degradation of the wood structure and instead confirms the durable integration of corn oil into the surface zone of the material.

3.4. Hardness of Corn Oil-Impregnated Beech Before and After Aging

Before artificial weathering, all experimental groups exhibited the same hardness value (89.00 ± 0.00), indicating that corn oil impregnation did not directly affect the surface hardness. After artificial weathering, the controls and the 60-min specimens retained this value, while the 30-min specimens showed a marginal decrease to 88.85 ± 0.39 —approximately 0.17%, effectively negligible. ANOVA did not reveal statistically significant differences between the three groups ($F = 1.39$, $p = 0.263$).

The stability of hardness indicates that corn oil primarily affected the physical and surface properties of the wood without substantially altering its mechanical behavior. The oil most likely settled mainly within the vessels and cell cavities, without significantly affecting the cell walls that largely determine hardness. Artificial weathering did not

produce measurable hardness loss, suggesting that photo-oxidative changes were confined to the outermost surface layers of the wood, as presented at Figure 10.

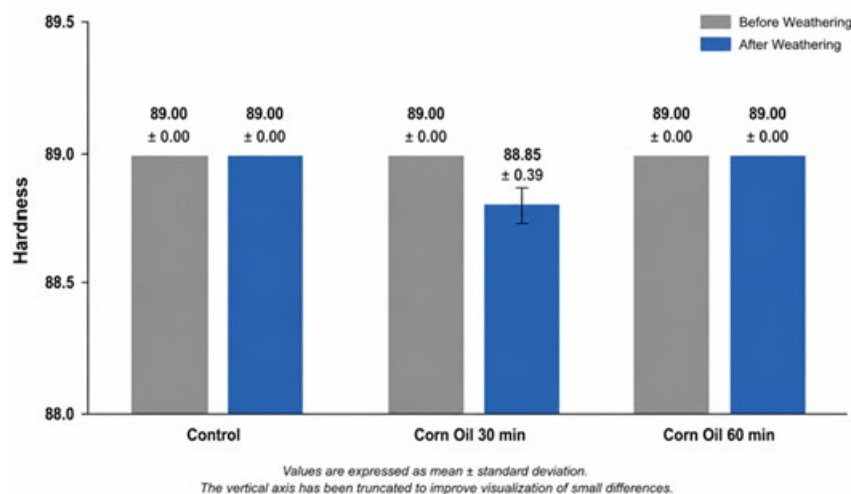


Figure 10. Surface hardness of the non-impregnated and corn oil-impregnated beech wood specimens before and after accelerated aging. Values are presented as the mean ± standard deviation.

3.5. Surface Roughness of Corn Oil-Impregnated Beech Before and After Aging

In the axial direction, artificial weathering increased the surface roughness mainly in the control specimens: R_a rose from 2.29 ± 0.89 to $3.60 \pm 0.67 \mu\text{m}$, R_q from 2.90 ± 1.16 to $4.60 \pm 1.04 \mu\text{m}$, and R_z from 12.16 ± 4.71 to $20.65 \pm 5.66 \mu\text{m}$. Evaluating R_a , R_q , and R_z jointly is standard practice for characterizing wood surface roughness, as it captures both the average and extreme deviations of the surface profile [43]. In comparison, changes in the impregnated specimens were smaller: R_a remained essentially unchanged in the 30-min group ($3.03 \pm 1.13 \rightarrow 3.06 \pm 1.07 \mu\text{m}$), while the 60-min group showed a modest increase ($2.88 \pm 0.96 \rightarrow 3.26 \pm 1.08 \mu\text{m}$), clearly lower than the controls. ANOVA of the final values, however, revealed no statistically significant differences between the three groups for any parameter (R_a : $F = 0.53$, $p = 0.592$; R_q : $F = 0.65$, $p = 0.531$; R_z : $F = 0.58$, $p = 0.566$), likely due to the wide dispersion of the measurements.

A similar pattern was observed in the radial direction, where roughness values were generally higher, as expected given the anatomical structure and fiber orientation. The control specimens again showed the highest final values (R_a : $5.37 \pm 1.32 \rightarrow 7.58 \pm 0.69 \mu\text{m}$; R_z : $32.53 \pm 7.77 \rightarrow 42.44 \pm 5.38 \mu\text{m}$), while both impregnation groups showed a smaller increase. Nevertheless, differences between groups again did not reach statistical significance (R_a : $F = 2.11$, $p = 0.138$; R_q : $F = 0.52$, $p = 0.599$; R_z : $F = 1.07$, $p = 0.356$).

The more pronounced increase in surface roughness observed in the control specimens suggests that untreated wood surfaces were more susceptible to degradation during artificial weathering, as it presented at Figure 11. Corn oil, which is generally classified as a semi-drying vegetable oil, may have contributed to the partial protection of the wood surface by forming a thin residual oil layer and filling superficial vessels and surface irregularities after impregnation. This residual surface layer may have reduced the direct exposure of the wood to radiation and consequently limited the increase in roughness after weathering. Nevertheless, because the differences between the experimental groups were not statistically significant, this observation should be interpreted as a tendency rather than conclusive evidence. The absence of additional improvement after extending the impregnation time from 30 to 60 min suggests that most of the protective effect was achieved during the initial stage of impregnation, in agreement with the behavior observed for the other evaluated properties.

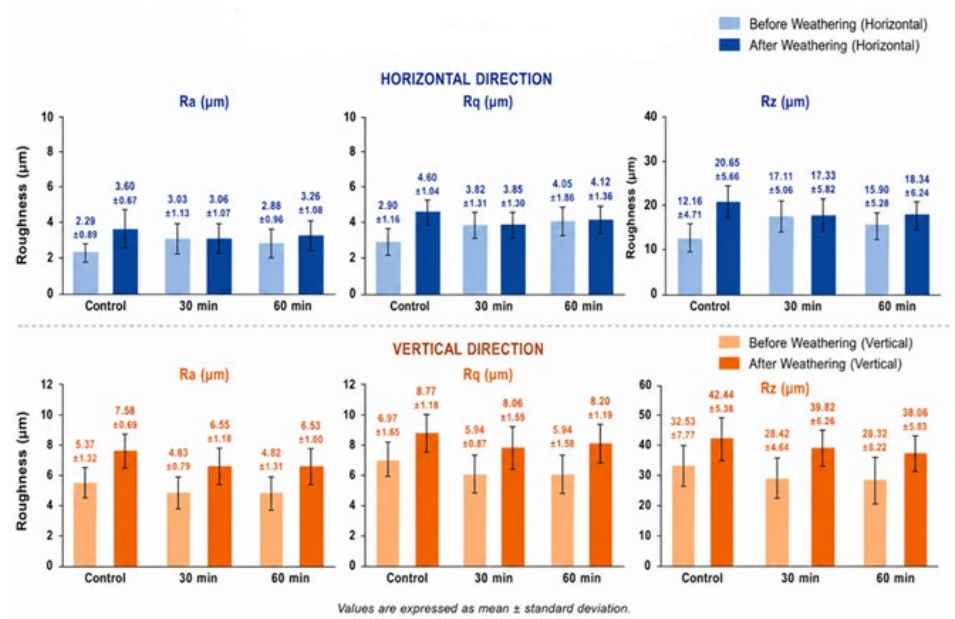


Figure 11. Surface roughness parameters Ra, Rq, and Rz in the horizontal and vertical directions, before and after artificial weathering. Values are presented as the mean ± standard deviation.

3.6. Contact Angle

The effect of corn oil impregnation on the surface wettability of beech wood was evaluated by sessile drop contact angle measurements before and after artificial weathering. The images qualitatively support the trends observed in the quantitative measurements presented in Figure 12. Representative contact angle images illustrating the typical wetting behavior of untreated and corn oil-impregnated specimens are shown in Figure 13.

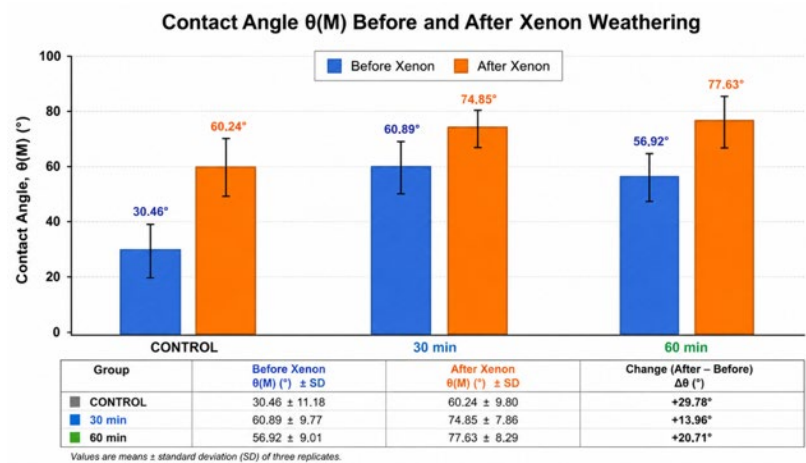


Figure 12. Static contact angle (θM) before and after accelerated aging. Values are presented as the mean ± standard deviation.

Before artificial weathering, the control specimens exhibited the lowest mean contact angle ($30.46^{\circ} \pm 11.18^{\circ}$), characteristic of a relatively hydrophilic surface. This behavior is consistent with the findings of Kúdela et al. [28], who reported that untreated beech wood exhibits relatively low water contact angles due to its high affinity for polar liquids, and with the observations of Kúdela [29], who demonstrated that lower contact angle values correspond to the improved wettability of wood surfaces. The impregnated specimens showed markedly higher values, nearly double those of the controls: $60.89^{\circ} \pm 9.77^{\circ}$ for the 30-min group and $56.92^{\circ} \pm 9.01^{\circ}$ for the 60-min group. The increase in contact angle indicates a reduction in surface wettability, in agreement with the general relationship between

contact angle and wetting behavior described by Kúdela [29]. ANOVA (Table 3) confirmed that differences between the three groups were statistically significant ($F = 24.94$, $p < 0.001$), confirming that corn oil impregnation significantly increased the surface hydrophobicity.

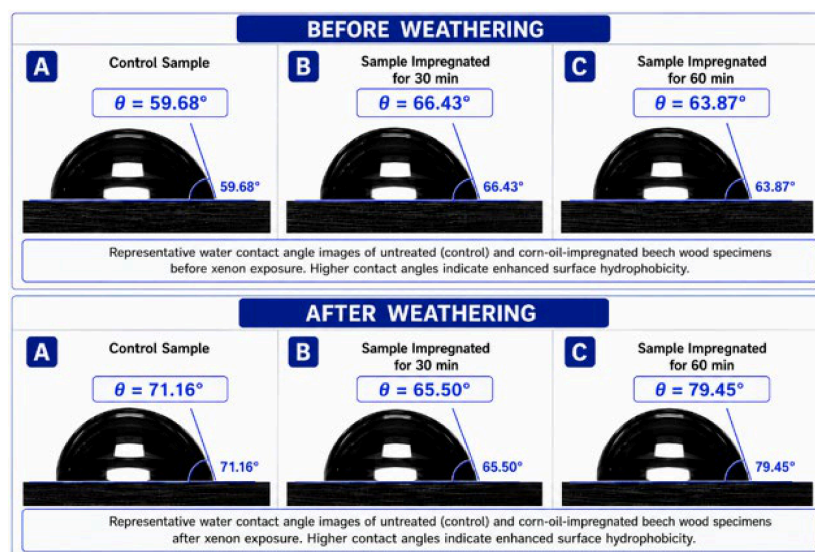


Figure 13. Representative water contact angle images of beech wood specimens before and after artificial weathering for the non-impregnated (control) and corn oil-impregnated specimens. A: Control Sample, B: Sample Impregnated for 30 min, C: Sample Impregnated for 60 min.

Table 3. Summary of ANOVA results (control versus 30- and 60-min impregnation) for the surface properties of beech wood after artificial weathering.

Property	Control	30 min	60 min	F	p
ΔE (color difference)	5.31 ± 1.79	19.87 ± 2.14	18.48 ± 1.86	106.92	<0.001
Hardness (final)	89.00 ± 0.00	88.85 ± 0.39	89.00 ± 0.00	1.39	0.263
Ra horiz. (final)	3.60 ± 0.67	3.06 ± 1.07	3.26 ± 1.08	0.53	0.592
Rz horiz. (final)	20.65 ± 5.66	17.33 ± 5.82	18.34 ± 6.24	0.58	0.566
Ra vert. (final)	7.58 ± 0.69	6.55 ± 1.18	6.53 ± 1.00	2.11	0.138
Rz vert. (final)	42.44 ± 5.38	39.82 ± 6.26	38.06 ± 5.83	1.07	0.356
Contact angle (before)	30.46 ± 12.94	60.89 ± 7.85	56.92 ± 7.41	24.94	<0.001
Contact angle (after)	60.24 ± 7.41	74.85 ± 5.59	77.63 ± 15.80	4.45	0.020

After accelerated aging, the contact angle increased in all groups: the controls reached $60.24^\circ \pm 9.80^\circ$, while the 30- and 60-min groups reached $74.85^\circ \pm 7.86^\circ$ and $77.63^\circ \pm 8.29^\circ$, respectively. Differences between groups also remained statistically significant after aging ($F = 4.45$, $p = 0.020$). The persistence of higher contact angle values in the impregnated specimens suggests that the treatment maintained a less wettable surface even after weathering. Similar increases in water contact angle following the surface modification of beech wood have been reported by Kúdela et al. [31], who attributed this behavior to changes in the physicochemical characteristics of the wood surface.

Representative measurements followed the same trend: before aging, the contact angle was 25.50° for the control and 66.70° and 70.00° for the 30- and 60-min specimens, respectively; after aging, values rose to 52.80° , 83.40° , and 107.70° , as presented in Table 3. The untreated specimens exhibited predominantly hydrophilic behavior, whereas the

impregnated specimens showed moderate hydrophobic behavior before weathering and highly hydrophobic behavior after weathering [44,45]. This trend is consistent with the observations of Kúdela [29], who demonstrated that increasing water contact angle values corresponded to reduced wettability and lower affinity of wood surfaces for polar liquids.

The higher contact angles observed after impregnation indicate a reduction in surface wettability and an increase in surface hydrophobicity. This behavior is likely associated with the presence of corn oil retained within the near-surface wood structure, and to some extent, with a residual oil layer remaining on the surface after impregnation. As corn oil is considered a semi-drying vegetable oil, such a residual layer may partially reduce the direct interaction between water droplets and the wood cell wall, contributing to the observed increase in contact angle. According to Kúdela et al. [28], changes in the physicochemical condition of the beech wood surface are accompanied by corresponding changes in wettability and surface free energy, emphasizing the sensitivity of water contact angle to surface modifications.

The interpretation of the wettability results should also be considered in relation to the characteristics of corn oil. Corn oil is generally classified as a semi-drying vegetable oil, and following impregnation, a thin residual oil layer may remain on the wood surface. This residual layer, together with the oil retained within surface vessels and lumina, may contribute to the increased hydrophobicity observed after treatment by reducing the direct interaction between water droplets and the wood cell wall. Therefore, the observed increase in contact angle is likely associated with both the penetration of oil into the wood structure and the presence of residual oil on the specimen surface.

Although increased surface hydrophobicity may reduce the adhesion of waterborne coatings, it may be advantageous for applications where improved water repellency and reduced moisture uptake are desired. Therefore, corn oil impregnation should primarily be regarded as a bio-based wood modification treatment rather than as a surface preparation for subsequent coating application.

Overall, the results indicate that corn oil impregnation significantly reduced the surface wettability and increased the hydrophobicity of beech wood. The further increase in contact angles after artificial weathering may reflect changes in the surface layers of the wood, combined with the presence of residual corn oil and the slight increase in surface roughness observed during aging. Kúdela et al. [30] demonstrated that variations in the surface condition of beech wood, such as those produced by milling and sanding, significantly affect wettability and the thermodynamic characteristics of the surface, highlighting that contact angle measurements are highly sensitive to changes in surface morphology and physicochemical properties. Likewise, Kúdela et al. [31] showed that modifying the surface of beech wood results in measurable changes in contact angle and surface free energy. Although the modification method employed in the present study differs from that investigated by Kúdela et al. [31], both studies demonstrate that alterations of the wood surface can substantially influence its wetting behavior. A comparable improvement in hydrophobicity has been reported for beech wood impregnated with other vegetable oils, such as rapeseed oil [17], supporting the potential of vegetable oils as bio-based wood modification agents for improving moisture resistance. Although the increased hydrophobicity may reduce the compatibility of the wood surface with subsequent waterborne coatings, the primary objective of corn oil impregnation in the present study was to enhance the wood's resistance to moisture rather than to improve coating performance. Therefore, the observed reduction in surface wettability represents a desirable effect for applications where increased water repellency and durability are required.

4. Discussion

The present study demonstrated that vacuum impregnation with corn oil effectively modified the surface and hygroscopic behavior of European beech wood. FTIR spectroscopy confirmed the successful penetration of corn oil into the wood structure through the appearance of characteristic triglyceride absorption bands, while the high weight percentage gain (WPG > 45%) obtained after both impregnation durations demonstrated the high uptake capacity of beech under vacuum conditions. Together, these findings indicate that the impregnation process enabled effective oil retention within the wood structure, providing the basis for the subsequent changes observed in wettability, water absorption, dimensional stability, and surface performance. The absence of statistically significant differences in WPG between the 30- and 60-min treatments further suggests that most accessible voids within the wood were already occupied during the first stage of impregnation, limiting the additional benefit of prolonged treatment.

The improvements in hygroscopic behavior can be explained by the physical mode of action of vegetable oil impregnation. Corn oil penetrated the vessels, lumina, and superficial cell-wall regions, partially occupying spaces normally available for water movement. In addition, the slight reduction observed in the O–H absorption region of the FTIR spectra suggests that oil deposition reduced the accessibility of hydrophilic hydroxyl groups, particularly those associated with cellulose, which is the principal component governing moisture sorption in wood. This behavior is consistent with the classical bulking effect described for non-volatile impregnating agents, whereby cell-wall occupancy reduces the availability of sorption sites and consequently limits moisture uptake and moisture-induced dimensional changes. The markedly lower water absorption and reduced radial and tangential swelling observed in the impregnated specimens are therefore consistent with both the FTIR observations and the high WPG values obtained in the present study.

The surface-related properties showed a similarly coherent response. Corn oil impregnation substantially increased the static contact angle before artificial weathering, indicating a clear reduction in surface wettability. Following Xenon exposure, contact angle increased further in all groups, although the impregnated specimens consistently remained more hydrophobic than the untreated controls. This behavior is attributed not only to the intrinsic hydrophobic nature of the oil, but also to the presence of a residual oil layer covering part of the wood surface after impregnation. Corn oil is generally classified as a semi-drying vegetable oil and may therefore function as a thin protective coating that partially shields the wood surface from direct environmental exposure. The relatively limited increase in surface roughness observed after weathering supports this interpretation, although the statistical analysis indicates that these differences should be regarded as tendencies rather than conclusive evidence because of the natural variability of wood and the relatively small number of control specimens.

Artificial weathering produced a considerably greater color change in the impregnated specimens than in the untreated controls. However, this increase should not be interpreted as evidence of accelerated degradation. Instead, the color difference mainly reflects the inherent yellow color of corn oil and the optical modification of the wood surface following oil penetration. The similarity of the color changes obtained after 30 and 60 min of impregnation is fully consistent with the absence of statistically significant differences in WPG, indicating that comparable oil uptake resulted in comparable optical modification. This agreement between color development and impregnation efficiency further supports the conclusion that extending the treatment time beyond 30 min provides only limited additional benefit.

Unlike wettability and hygroscopic behavior, surface hardness remained essentially unchanged following impregnation and artificial weathering. This finding indicates that

corn oil primarily modifies the physical characteristics of the wood surface without significantly altering the structural integrity of the cell wall responsible for mechanical resistance. The non-destructive Shore D measurements therefore suggest that the treatment improves moisture-related properties while preserving the original hardness of beech wood.

The results obtained from FTIR spectroscopy, WPG determination, contact angle measurements, water absorption, dimensional swelling, color evaluation, and roughness analysis consistently indicate that vacuum impregnation with corn oil acts mainly through a physical modification mechanism rather than chemical alteration of the wood polymers. The convergence of these independent measurements provides strong evidence that the oil successfully penetrates the porous structure of beech wood, reduces its affinity with water, and improves dimensional stability without adversely affecting hardness.

From a practical perspective, the results suggest that corn oil may represent a promising bio-based impregnation medium for applications where improved moisture resistance and dimensional stability are required while maintaining the mechanical characteristics of wood. Although oil-treated surfaces are generally less suitable for the subsequent application of water-based coatings because of their reduced wettability, the treatment may be advantageous in applications where the impregnated wood is intended for use without additional finishing layers. Future research should evaluate the long-term behavior of corn oil under natural outdoor exposure, its resistance to biological degradation, and its compatibility with alternative coating systems.

5. Conclusions

The present study demonstrated that vacuum impregnation with corn oil is an effective bio-based treatment for enhancing the hygroscopic and surface properties of European beech wood. High oil uptake was achieved under both impregnation durations, resulting in reduced surface wettability, lower water absorption, improved dimensional stability, and enhanced resistance to moisture-related degradation while preserving the surface hardness of the wood.

The absence of statistically significant differences in weight percentage gain (WPG) and in most of the evaluated properties between the 30- and 60-min treatments indicates that the majority of the beneficial effects of impregnation are achieved within the first 30 min. From a practical perspective, the shorter treatment duration therefore represents the most efficient processing condition, reducing treatment time while maintaining comparable performance.

The combined evaluation of FTIR spectroscopy, WPG, surface wettability, color, roughness, hardness, water absorption, and dimensional stability indicate that corn oil operates primarily through a physical modification mechanism by reducing the accessibility of water to the wood structure and limiting moisture-induced dimensional changes. These findings demonstrate the potential of corn oil as a sustainable and environmentally friendly impregnation medium for enhancing the service performance of beech wood.

Further research should focus on long-term natural weathering, biological durability, and the compatibility of corn oil-impregnated wood with protective coating systems to further assess its suitability for industrial applications.

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Abbreviations

The following abbreviations are used in this manuscript: WPG, weight percentage gain; FTIR, Fourier transform infrared spectroscopy; ANOVA, analysis of variance; HSD, honestly significant difference; ISO, International Organization for Standardization; ASTM, American Society for Testing and Materials; EN, European Standard.

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