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Effect of Drying at 120 °C and 150 °C on Selected Mechanical Properties of Silver Fir (*Abies alba* Mill.)

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Abstract

High-temperature drying can considerably improve drying efficiency. However, information on its impact on the mechanical properties of silver fir during industrial high-temperature drying remains limited. Elevated drying temperatures may induce changes in wood structure that can influence mechanical performance. This study evaluated the effect of high-temperature drying schedules based on industrially applied temperature levels (120 °C and 150 °C) on selected mechanical properties of silver fir (*Abies alba* Mill.). Wood samples were kiln-dried at 120 °C and 150 °C, conditioned to equilibrium moisture content, and tested for impact bending strength, tensile strength perpendicular to the grain, and Janka hardness. Because the experimental material originated from a single silver fir tree, the findings should be interpreted as describing responses within the investigated material rather than as population-level effects for silver fir. The results showed that drying at 150 °C was associated with a tendency toward reduced values of selected mechanical properties; however, the effect of drying temperature was not statistically significant for impact bending strength. ANOVA showed that specimen thickness significantly affected impact bending strength and Janka hardness, whereas drying temperature had a significant effect only on tensile strength perpendicular to the grain. The lowest mean values were observed in the β-150 group, with impact bending strength of 5.4 J·cm^{-2} and tensile strength perpendicular to the grain of 2.3 MPa. The mean oven-dry density was 456.9 kg·m^{-3}, while only weak relationships between density and mechanical properties were observed (r^2 = 0.023–0.178). This suggests that factors related to drying conditions may contribute to variability in mechanical performance beyond the effect of density alone. Thus, the effects of the investigated drying conditions were property-specific rather than consistently attributable to drying temperature. Within the investigated material, these results indicate that the optimization of high-temperature drying schedules should consider both drying parameters and variability in mechanical properties.

Keywords: mechanical properties; *Abies alba*; high-temperature drying; wood drying

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1. Introduction

Industrial wood drying is a critical and energy-intensive stage of timber processing that strongly influences product quality and dimensional stability. Effective moisture removal is necessary to minimize drying defects such as warping, internal checking, and residual

stresses. In recent years, high-temperature drying has attracted considerable attention in both industrial practice and research due to its potential to increase drying rates, shorten production time, and improve kiln efficiency. However, elevated temperatures may also alter the anatomical structure and mechanical properties of wood.

The influence of drying temperature on the physical and mechanical behaviour of wood has been extensively investigated over the past decades. Early studies by MacLean provided fundamental information regarding the effects of heat and steaming conditions on wood properties [1,2]. The thermal behaviour of wood is governed by the physicochemical responses of its principal structural polymers—cellulose, hemicelluloses, and lignin—which undergo temperature-dependent transformations during heating [3]. Subsequent research demonstrated that moisture content and temperature significantly affect the mechanical behaviour of wood, particularly through reversible changes associated with moisture variation [4].

Further studies showed that combined thermal and hygrothermal exposure may induce both reversible and irreversible changes in wood properties. Moisture equilibrium and moisture transport under elevated temperature conditions are important factors controlling drying behaviour, particularly during drying with heated air or superheated steam [5,6]. Permanent changes resulting from prolonged exposure to elevated temperatures have therefore become an important research topic, especially regarding mechanical degradation, dimensional stability, and structural performance [7–12].

Experimental studies have demonstrated that increased drying temperatures may influence wood structure and mechanical behaviour; however, the magnitude of these effects depends on wood species, moisture conditions, drying parameters, and exposure duration [13–17]. Boone and Ward [14] highlighted the importance of appropriate kiln-drying schedules for maintaining timber quality. Johansson et al. [15] demonstrated the influence of high-temperature drying on moisture transport mechanisms, whereas Zhou and Smith [16] reported changes in bending properties following different drying treatments. Bekhta and Niemz [17] further showed that elevated temperatures affect colour, dimensional stability, and selected mechanical properties of spruce wood. According to the review by Oltean et al. [18], moisture loss, internal stress development, and the thermal degradation of cell wall polymers are the principal mechanisms responsible for changes in wood properties during drying. Thermal treatment at elevated temperatures has also been associated with reductions in mechanical performance due to structural changes within the wood matrix [19,20].

Proper kiln-drying practice requires the strict control of process parameters across all stages. The pre-drying phase removes free water while limiting steep moisture gradients that may lead to surface cracking [21]. During the main drying phase, temperature and humidity are regulated to ensure controlled moisture transport within the material. The conditioning phase enables stress relaxation and reduces deformation prior to cooling. Improper drying regimes may significantly deteriorate timber quality; overly rapid drying increases the risk of cracking, while insufficient drying may result in high residual moisture and increased susceptibility to biological degradation [22]. Consequently, precise control of temperature, relative humidity, air velocity, and drying time is essential to maintain the mechanical integrity and dimensional stability of timber products [23].

Silver fir (*Abies alba* Mill.) is a widely distributed European softwood species used in structural timber, furniture production, and interior applications. Its relatively homogeneous structure and favourable processing characteristics make it suitable for engineering applications. However, silver fir is sensitive to drying conditions, particularly elevated temperatures, which may negatively influence its mechanical performance. Despite its

economic importance, information regarding the influence of high-temperature drying on its mechanical performance remains limited compared with Norway spruce or Scots pine.

Therefore, better knowledge of the effects of high-temperature drying on silver fir mechanical properties is required for the development of appropriate industrial drying schedules. High-temperature drying is well-studied in major commercial softwoods, but data for silver fir (*Abies alba* Mill.) remain scarce. Due to its distinct anatomy and permeability, data from other conifers cannot be directly extrapolated, making dedicated investigation necessary. This study investigates the effects of drying at 120 °C and 150 °C on selected mechanical properties of silver fir and evaluates the relationship between wood density and mechanical performance after high-temperature drying.

2. Materials and Methods

2.1. Materials

Silver fir (*Abies alba* Mill.) samples were prepared exclusively from sapwood. The specimens had nominal dimensions of 25 mm and 32 mm in thickness, 120 mm in width, and 350 mm in length. The material was obtained from the Training Forest Enterprise of the Czech University of Life Sciences in Kostelec nad Černými lesy (Czech Republic) and originated from a single silver fir tree. The use of material from one tree reduced the variability associated with differences among trees; however, it also limited the generalizability of the findings and did not allow tree-to-tree variability to be evaluated independently. The selected boards were visually homogeneous and free of defects that could influence mechanical testing. All specimens were free of visible defects such as knots, cracks, and pronounced grain deviations. The average annual ring width was 1.8 ± 0.4 mm. The 25 mm and 32 mm boards were obtained by radial sawing from a comparable radial zone of the same stem to minimize potential differences associated with the pith-to-bark gradient. The relatively low variability in annual ring width indicated relatively uniform growth characteristics within the investigated material.

2.2. Drying

Drying was performed in a Memmert UF110 laboratory kiln (Memmert GmbH+ Co., KG, Schwabach, Germany) equipped with forced convection. Two target drying temperatures were applied, 120 °C and 150 °C, representing intensive high-temperature drying conditions with different levels of thermal exposure.

The drying process consisted of three stages. In the initial stage, samples were preheated at 80 °C for 2 h. Subsequently, the temperature was maintained at 100 °C until the moisture content was estimated to approach the fibre saturation point (FSP). During this stage, a humidified environment was maintained to reduce moisture gradients, internal stresses, and the risk of surface checking. After reaching the FSP, the temperature was increased to the target level (120 °C or 150 °C). Once the final moisture content of 8–10% was achieved, the samples were subjected to controlled cooling to ambient temperature to minimize residual stresses and deformation.

The drying schedules are schematically shown in Figure 1. The symbols α and β denote samples with thicknesses of 25 mm and 32 mm, respectively. Four experimental groups were defined: α-120, β-120, α-150, and β-150 with 30 specimens assigned to each group. The same experimental material was used for the evaluation of selected mechanical properties.

To prevent excessive end-grain moisture loss and associated cracking, sample ends were sealed with a silicone coating prior to drying. Thermocouples were installed to monitor temperature changes in the core and near-surface regions of the samples. Samples were stacked using spruce stickers (24 × 40 mm) to ensure uniform air circulation.

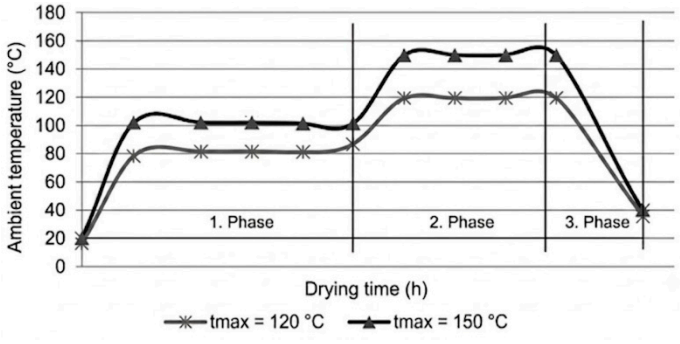

Figure 1. Schematic representation of drying schedules at maximum temperatures of 120 °C and 150 °C.

2.3. Density Determination

Wood density was determined as oven-dry density (ρ_0) following the procedure described in ISO 13061-2 [24]. The oven-dry density was used as a reference density parameter for evaluating relationships with mechanical properties determined at approximately 12% moisture content. The dimensions of the test specimens were measured using a digital calliper with an accuracy of 0.01 mm, and their mass was determined using a precision laboratory balance. To establish the oven-dry condition, samples were dried in a laboratory oven at 103 ± 2 °C until a constant mass was reached. Density was calculated as the ratio of the oven-dry mass to the oven-dry volume. Density was determined after completion of the drying treatments; therefore, the reported oven-dry density represents the density of the thermally treated material and may reflect thermally induced mass loss associated with high-temperature drying.

2.4. Selected Mechanical Properties

After drying, the material was machined into test specimens according to relevant standards. For each experimental group, 30 specimens were conditioned in a climate chamber at 20 ± 2 °C and 65 ± 5% relative humidity until constant mass was achieved. The equilibrium moisture content (EMC) was approximately 12%. All mechanical properties were evaluated at this moisture condition and normalized accordingly. The experimental programme included impact bending strength, tensile strength perpendicular to the grain [25], and Janka hardness measured perpendicular to the grain. Impact bending strength was determined using a Charpy impact testing machine with a 240 mm support span [26]. Janka hardness was measured according to the relevant standard [27] using a steel ball of 11.284 mm diameter pressed to half of its diameter, corresponding to a standardized indentation area of 100 mm^2.

2.5. Statistical Evaluation

All mechanical properties (impact bending strength, tensile strength perpendicular to the grain, and Janka hardness) were evaluated using two-way analysis of variance (ANOVA) to determine the effects of drying temperature, specimen thickness, and their interaction. Relationships between mechanical properties and wood density were assessed using linear regression analysis and Pearson's correlation coefficient (r). Statistical analyses were performed at a significance level of $\alpha = 0.05$ using SPSS software Statistics 26 (IBM Corp., Armonk, NY, USA). No specimens were excluded from the statistical analysis. Because the experimental material originated from a single tree, the results should be interpreted as describing variability within the investigated material rather than population-level variability among silver fir trees. Although the 25 mm and 32 mm boards were obtained by radial sawing from a comparable radial zone of the same stem to minimize potential

radial-position effects, the experimental design does not allow tree-level variability to be evaluated independently.

3. Results

3.1. Impact Bending Strength

The measured average values of impact bending strength in J·cm^{-2} and the basic statistical indicators are presented in Table 1.

Table 1. Impact bending strength—basic statistical indicators.

Regime	Mean	Std. Error	Sample Size (n)	Std. Deviation	Coeff. of Variation (%)	Variance
α-120	9.2	0.30	30	1.67	18.15	2.78
β-120	6.8	0.38	30	2.08	30.59	4.33
α-150	7.5	0.52	30	2.86	38.13	8.16
β-150	5.4	0.29	30	1.60	29.63	2.56

The relationship between oven-dry density and impact bending strength was described using a linear regression model (Equation (1)).

$$IBS = -11.023 + 0.039 \cdot \rho \quad (1)$$

where IBS is the impact bending strength (J·cm^{-2}) and ρ is the wood density (kg·m^{-3}).

Equation (1) describes the linear relationship between oven-dry density and impact bending strength within the investigated dataset. The positive slope indicates that impact bending strength tended to increase with increasing density; however, the low coefficient of determination suggests that density alone explained only a small proportion of the observed variability.

The correlation analysis presented in Table 2 showed only a weak relationship between density and impact bending strength (r^2 = 0.178), indicating that density alone explained only a limited proportion of the variability observed in this mechanical property. To evaluate the influence of drying temperature, specimen thickness, and their interaction on impact bending strength, a two-way analysis of variance (ANOVA) was performed (Table 3). The results showed that drying temperature had no statistically significant effect on impact bending strength (p = 0.461). In contrast, specimen thickness significantly affected impact bending strength (p < 0.001), while the interaction between temperature and thickness was not significant (p = 0.726). These findings indicate that the experimental thickness groups were associated with greater variation in impact bending strength than the applied drying temperatures; however, because the material originated from a single stem, this result should be interpreted within the investigated material. Although the mean values showed a tendency toward lower impact bending strength after drying at 150 °C, this reduction cannot be attributed solely to temperature effects based on the statistical analysis. The observed differences may reflect the combined influence of specimen thickness, material heterogeneity, and variability within the investigated material, while the direct effect of drying temperature was not statistically confirmed. High-temperature exposure may contribute to changes in cell wall polymers, including the degradation of hemicelluloses and other polysaccharides, which have been reported as important mechanisms affecting wood mechanical properties during thermal treatment [18,28]. As shown in Figure 2, higher-density samples tended to exhibit higher impact bending strength; however, this relationship was relatively weak within the investigated material. These results indicate that density was only a limited predictor of impact bending strength within the investi-

gated material, and that other material characteristics may also have contributed to the observed differences.

Table 2. Correlation parameters–dependence of wood impact bending strength on density.

Variable	Mean	Std. Deviation	*r*	r^2	*t*-Value	*p*-Value	N	Intercept (a)	Slope (b)
Density	456.9	27.541	—	—	—	—	—	—	—
Impact bending strength	7.2	2.524	0.422	0.178	5.051	0.001	120	−11.023	0.039

Table 3. Results of two-way ANOVA for the effect of drying temperature and specimen thickness on impact bending strength.

Source of Variation	Sum of Squares (SS)	Degrees of f Reedom (df)	Mean Square (MS)	F-Value	*p*-Value
Intercept	6537.644	1	6537.644	1508.497	<0.001
Temperature	2.366	1	2.366	0.546	0.461
Thickness	117.546	1	117.546	27.122	<0.001
Temperature × Thickness	0.536	1	0.536	0.124	0.726

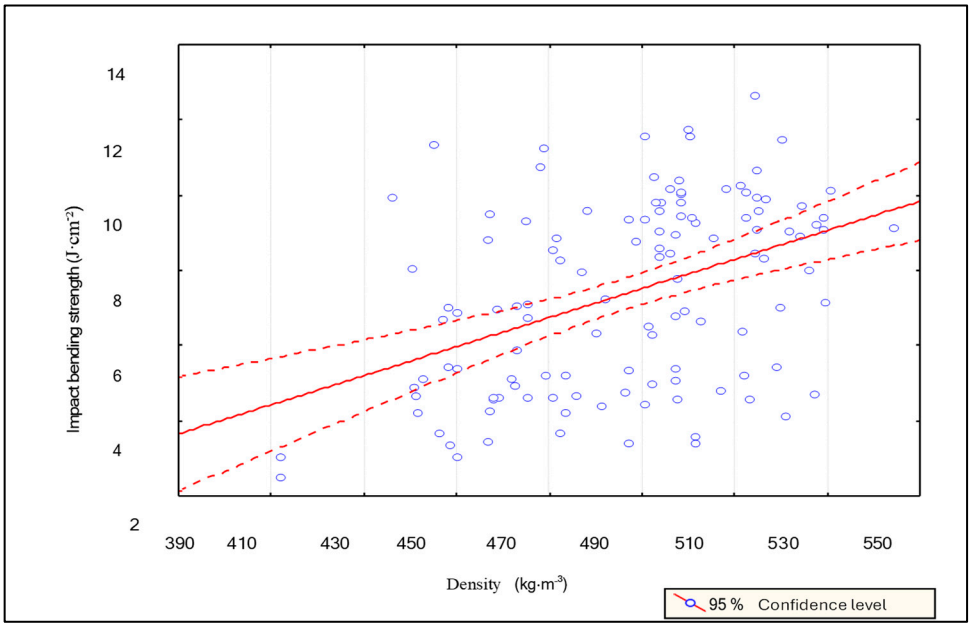

Figure 2. Dependence of impact bending strength on density.

Figure 2 also indicates increased variability in impact bending strength values in some groups exposed to higher drying temperatures, with the highest coefficient of variation observed for the α-150 group (38.13%). The increased dispersion may reflect the combined influence of material heterogeneity, specimen thickness, and thermal exposure conditions. Differences in moisture gradients, internal stress development, and local structural variability may contribute to the observed scatter in mechanical response [18,23]. Therefore, evaluation of average values should be complemented by consideration of variability within individual drying groups. The lowest mean value, observed in the β-150 group (5.4 J·cm^{-2}), highlights the importance of considering variability in mechanical performance when evaluating the effects of intensive drying regimes.

Two-way analysis of variance confirmed a significant effect of thickness on this property (Figure 3). In contrast, drying temperature did not have a statistically significant effect on impact bending strength (p = 0.461), and no significant interaction between

temperature and thickness was observed (p = 0.726). Dried samples with a thickness of 32 mm exhibited the lowest overall toughness values. Although the mean values indicated a tendency toward reduced impact bending strength after exposure to 150 °C, this reduction was not statistically confirmed by the ANOVA results. High-temperature exposure has been reported to influence wood brittleness through changes in cell wall polymers and moisture-related stress development; however, the magnitude of these effects depends on wood species, treatment conditions, and exposure duration. The measured impact bending strength indicates that the tested silver fir retained measurable impact energy absorption capacity after high-temperature drying. However, fracture mechanisms were not directly evaluated in this study. As suggested by Rowell [28], the relatively higher thermal stability of lignin compared with polysaccharides may contribute to the retention of some structural integrity during moderate thermal exposure, which can partially explain the preservation of impact energy absorption capacity observed in the present study.

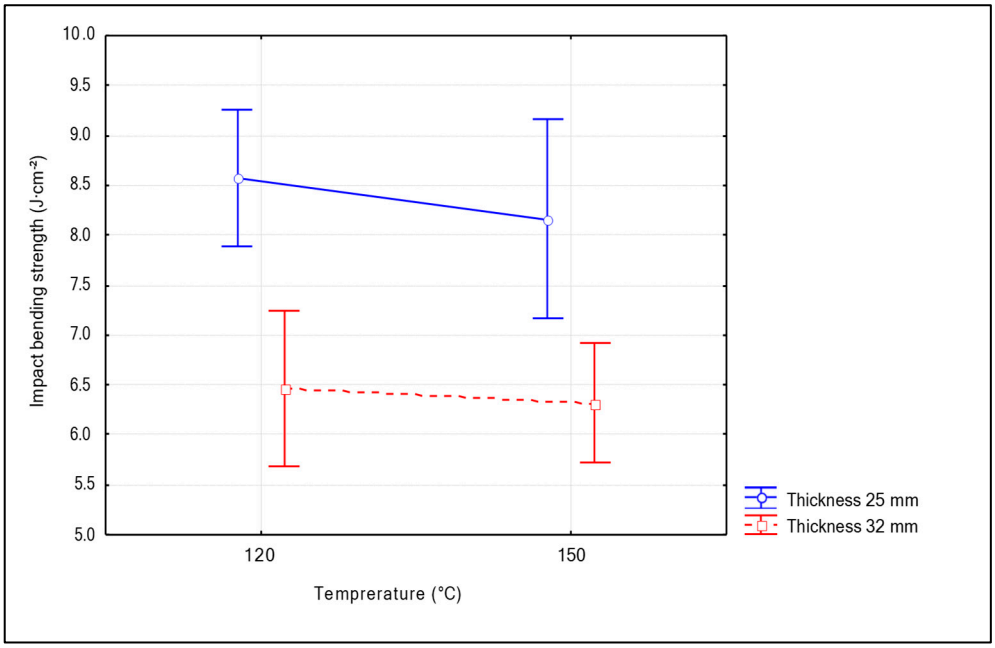

Figure 3. Analysis of variance of impact bending strength relative to temperature.

3.2. Tensile Strength Perpendicular to the Grain

The average values of tensile strength perpendicular to the grain, expressed in MPa, together with the corresponding basic statistical indicators, are summarized in Tables 4 and 5.

The relationship between wood density and tensile strength perpendicular to the grain in the radial direction is described by the linear regression model given in Equation (2):

$$\sigma_T = 1.052 + 0.004 \cdot \rho \quad (2)$$

where σ_T is the tensile strength perpendicular to the grain (MPa) and ρ is the wood density ($kg \cdot m^{-3}$).

Equation (2) describes the relationship between oven-dry density and tensile strength perpendicular to the grain. Although a positive trend was observed, the very low coefficient of determination (r^2 = 0.023) indicates that density alone explained only a negligible proportion of the observed variability. Therefore, the observed variation in tensile strength cannot be adequately explained by density alone and may also reflect other material and drying-related factors.

Table 4. Tensile strength perpendicular to the grain in the radial direction—basic statistical indicators.

Regime	Mean	Std. Error	Sample Size (n)	Std. Deviation	Coeff. of Variance	Variation (%)
α-120	2.9	0.13	30	0.72	24.83	0.52
β-120	3.1	0.12	30	0.64	20.65	0.41
α-150	2.5	0.09	30	0.50	20.00	0.25
β-150	2.3	0.10	30	0.54	23.48	0.29

Table 5. Correlation parameters—dependence of wood tensile strength on density.

Variable	Mean	Std. Deviation	*r*	r^2	*t*-Value	*p*-Value	N	Intercept (a)	Slope (b)
Density	456.9	27.541	—	—	—	—	—	—	—
Tension	2.7	0.659	0.153	0.023	1.677	0.096	120	1.052	0.004

To evaluate the influence of drying temperature, specimen thickness, and their interaction on tensile strength perpendicular to the grain, a two-way analysis of variance (ANOVA) was performed (Table 6). The results showed that drying temperature had a statistically significant effect on tensile strength ($p < 0.001$), whereas specimen thickness ($p = 0.836$) and the interaction between temperature and thickness ($p = 0.648$) were not statistically significant. Experimental measurements showed that tensile strength perpendicular to the grain decreased with increasing drying temperature, with the lowest average value observed after drying at 150 °C (2.3 MPa). This decrease was confirmed by the ANOVA results, which demonstrated a statistically significant effect of drying temperature ($p < 0.001$). Unlike the other mechanical properties, tensile strength exhibited a very weak relationship with wood density ($r^2 = 0.023$), indicating that density had a negligible influence on this property within the investigated range. This weak dependence may indicate that density differences alone were insufficient to explain the variation in tensile strength after thermal exposure. From a practical perspective, the results indicate that density alone is not a reliable predictor of tensile strength perpendicular to the grain after high-temperature drying. However, other anatomical and structural factors may also play a significant role in this process.

Table 6. Results of two-way ANOVA for the effect of drying temperature and specimen thickness on tensile strength perpendicular to the grain.

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-Value	*p*-Value
Intercept	935.096	1	935.096	2545.875	<0.001
Temperature	9.056	1	9.056	24.656	<0.001
Thickness	0.016	1	0.016	0.043	0.836
Temperature × Thickness	0.077	1	0.077	0.210	0.648

Figure 4 illustrates a nearly constant trend of density in relation to tensile strength. Tensile strength values adjusted for average density. Figure 5 shows that tensile strength decreased with rising temperature. Although slightly higher mean tensile strength values were observed for thicker samples at 120 °C, specimen thickness did not have a statistically significant effect according to ANOVA. The 25 mm thick samples exhibited lower tensile strength compared to the thicker samples, which may be related to differences in crack development and the associated failure mechanism during testing. Although differences in fracture appearance were observed, the influence of crack development was not quantified in this study and may only partially explain the observed differences in tensile strength.

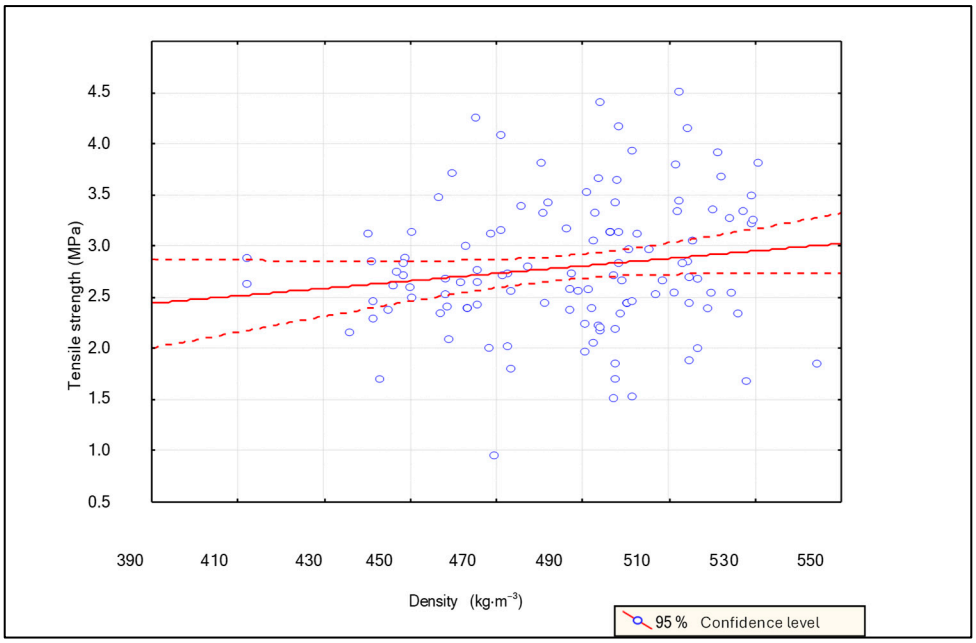

Figure 4. Dependence of tensile strength on density.

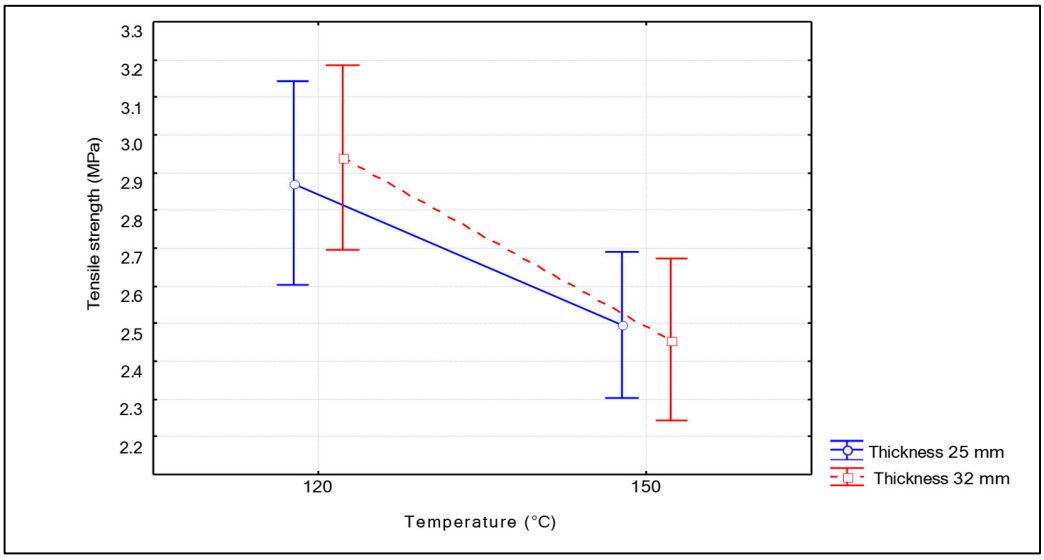

Figure 5. Effect of temperature on tensile strength perpendicular to the grain.

3.3. Janka Hardness

The average values of Janka hardness and the corresponding basic statistical indicators are presented in Table 7. The correlation parameters describing the relationship between density and Janka hardness are summarized in Table 8.

The relationship between wood density and Janka hardness is described by the linear regression model given in Equation (3):

$$H_J = 2.255 + 0.023 \cdot \rho \quad (3)$$

where H_J is the Janka hardness (MPa) and ρ is the oven-dry density (kg·m^{-3}).

Table 7. Janka hardness—basic statistical indicators.

Regime	Mean	Std. Error	Sample Size (n)	Std. Deviation	Coeff. of Variation (%)	Variance
α-120	14.3	0.36	30	1.96	13.71	3.83
β-120	12.5	0.27	30	1.50	12.00	2.24
α-150	12.9	0.32	30	1.77	13.72	3.15
β-150	11.7	0.18	30	1.00	8.55	1.01

Table 8. Correlation parameters—dependence of wood hardness on density.

Variable	Mean	Std. Deviation	*r*	r^2	*t*-Value	*p*-Value	N	Intercept (a)	Slope (b)
Density	456.9	27.541	—	—	—	—	—	—	—
Hardness	12.8	1.839	0.339	0.115	3.908	0.001	120	2.255	0.023

Equation (3) expresses the relationship between oven-dry density and Janka hardness. As shown in Figure 6, Janka hardness showed a positive trend with increasing density; however, the relatively low coefficient of determination (r^2 = 0.115) indicates that density explained only a limited proportion of the variability in Janka hardness after high-temperature drying.

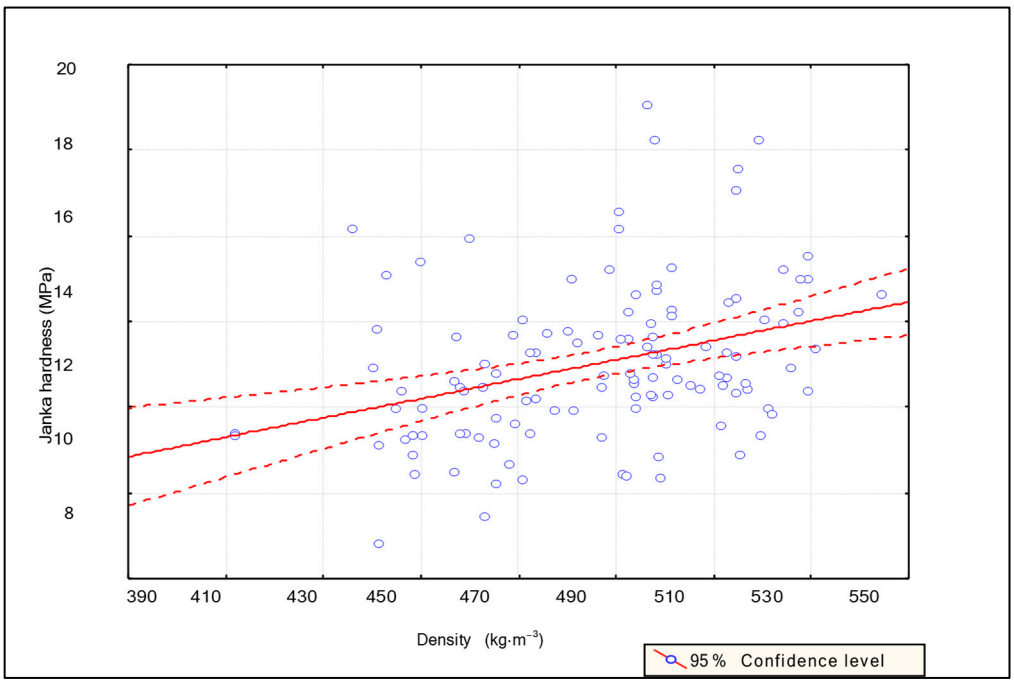

Figure 6. Dependence of Janka wood hardness on density.

It should be noted that the regression equations were derived exclusively from the experimental data obtained in this study and are valid only within the density range of the tested specimens (approximately 390–555 kg·m^{-3}). Therefore, the intercept values should not be interpreted as physically meaningful predictions outside the investigated density range, and the equations should not be used for extrapolation beyond the observed data.

The ANOVA results (Table 9) showed that specimen thickness had a statistically significant effect on Janka hardness ($p < 0.001$), whereas the effect of drying temperature (p = 0.089) and the temperature–thickness interaction (p = 0.421) were not statistically

significant. The observed differences between the experimental thickness groups were statistically more pronounced than the temperature effect. However, because the material originated from a single stem, this finding should be interpreted within the investigated material and does not by itself establish a general thickness effect for silver fir wood. The lowest average value was observed in the β-150 group (11.7 MPa), indicating a tendency toward reduced hardness after higher thermal exposure; however, this reduction was not statistically confirmed by the ANOVA results.

Table 9. Two-way ANOVA results for Janka hardness.

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-Value	*p*-Value
Intercept	20,361.260	1	20,361.260	7688.576	<0.001
Temperature	7.770	1	7.770	2.934	0.089
Thickness	39.760	1	39.760	15.015	<0.001
Temperature × Thickness	1.730	1	1.730	0.652	0.421

The relatively weak relationship between density and hardness ($r = 0.339$, $r^2 = 0.115$) suggests that density explained only a limited proportion of the variability in hardness after high-temperature drying. From a practical perspective, the observed tendency toward reduced hardness after high-temperature drying should be considered in applications where resistance to indentation is important.

Figure 7 shows that samples with smaller thickness (25 mm) exhibited higher hardness values. Although lower hardness values were observed after drying at 150 °C, the temperature effect and the temperature–thickness interaction were not statistically significant. The observed tendency toward reduced hardness at higher temperatures may be associated with thermally induced changes in wood polymers, particularly degradation of hemicelluloses reported during high-temperature exposure. However, the present statistical analysis did not confirm a significant temperature effect, and these mechanisms were not directly evaluated in this study.

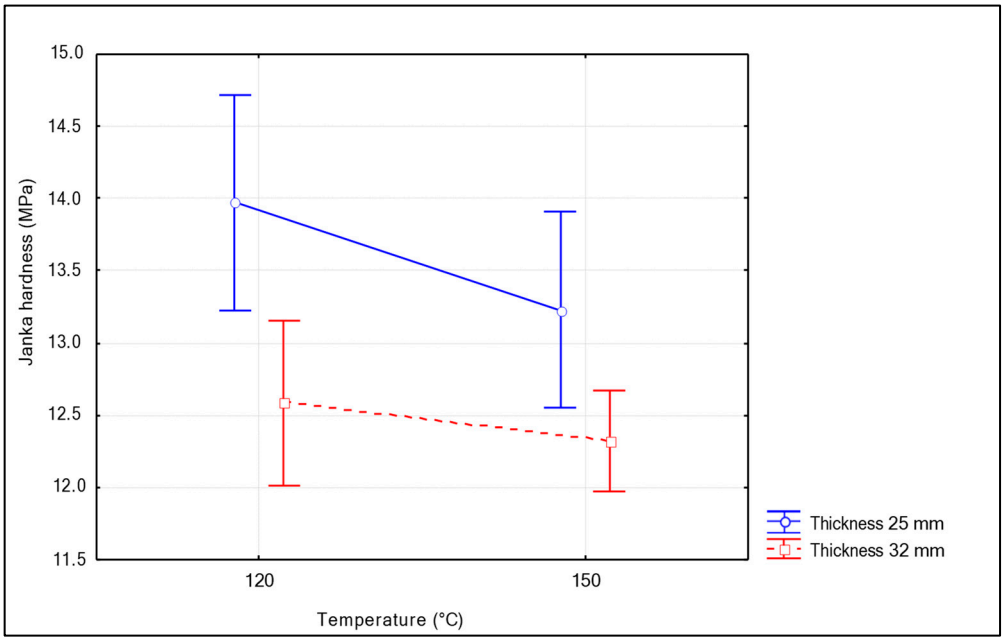

Figure 7. Influence of drying temperature on Janka hardness for different specimen thicknesses.

4. Discussion

High-temperature drying is an established approach in industrial wood processing because it can significantly reduce drying time and increase production efficiency. However, elevated temperatures must be carefully controlled, as excessive thermal exposure may affect wood structure, dimensional stability, and mechanical behaviour. Previous studies have shown that these effects depend on wood species, moisture conditions, drying temperature, and duration of exposure [29,30].

The present study showed that high-temperature drying influenced the mechanical behaviour of silver fir (*Abies alba* Mill.), although the response differed among the evaluated properties. Drying at 150 °C resulted in lower average values of impact bending strength, tensile strength perpendicular to the grain, and Janka hardness compared to drying at 120 °C. However, the statistical analysis demonstrated that the effect of temperature was significant only for tensile strength perpendicular to the grain, while impact bending strength and Janka hardness were affected mainly by specimen thickness. These results indicate that the influence of high-temperature drying should be evaluated separately for individual mechanical properties.

The decrease in impact bending strength was the most pronounced numerical change observed in this study. The mean value decreased from 9.2 J·cm^{-2} in the α-120 group to 5.4 J·cm^{-2} in the β-150 group. Nevertheless, drying temperature did not have a statistically significant effect ($p = 0.461$), whereas specimen thickness showed a significant influence ($p < 0.001$). Therefore, the lower values observed after drying at 150 °C cannot be attributed solely to temperature increase. Differences in specimen thickness, moisture transport, internal stress development, and natural variability of wood structure may have contributed to the observed variation. During drying, specimen dimensions influence moisture redistribution and stress development within wood, which may subsequently affect the final mechanical response of the material [31].

The tendency toward reduced impact bending strength after higher thermal exposure is consistent with previous studies reporting changes in mechanical properties after heat treatment of wood. Thermal exposure may cause the degradation of less stable wood components, particularly hemicelluloses, and may modify interactions within the lignin–carbohydrate matrix, which can influence toughness and fracture behaviour [32,33]. Similar reductions in mechanical performance have been reported after thermal treatment of different wood species; however, the magnitude of these changes depends strongly on species and treatment conditions [30,34,35]. Since chemical composition and fracture mechanisms were not analyzed in the present study, these explanations should be considered as possible mechanisms rather than directly confirmed causes.

Tensile strength perpendicular to the grain showed the highest sensitivity to drying temperature. The mean value decreased from 3.1 MPa at 120 °C to 2.3 MPa after drying at 150 °C, and this difference was confirmed by ANOVA ($p < 0.001$). In contrast to impact bending strength, specimen thickness had no significant effect on this property. This suggests that, within the investigated material, tensile strength perpendicular to the grain was more strongly associated with drying temperature than with the experimental specimen thickness.

The reduction in tensile strength may be related to structural changes occurring within the wood cell wall and the middle lamella. Elevated temperatures can induce chemical modifications of wood polymers, including the degradation of hemicelluloses and changes in lignin-related structures, which may reduce the ability of wood to resist transverse loading [32,33]. Previous research has also demonstrated that thermal degradation influences the viscoelastic behaviour and mechanical response of wood across the grain

at elevated temperatures [36]. These findings support the observed decrease in tensile strength perpendicular to the grain after drying at 150 °C.

The slightly higher tensile strength observed in some groups dried at 120 °C, which should be interpreted cautiously. Although the β-120 group reached the highest average value, this does not indicate an improvement caused by moderate thermal exposure. The difference may reflect the inherent variability of wood material and the interaction between drying conditions and anatomical characteristics. Similar variability in the response of wood to thermal treatment has been reported for different species and processing conditions [34].

Janka hardness exhibited a different behaviour compared to tensile strength. Although the lowest average hardness was measured in the β-150 group (11.7 MPa), drying temperature was not statistically significant ($p = 0.089$), while specimen thickness had a significant effect ($p < 0.001$). Therefore, the observed reduction in hardness at 150 °C represents a tendency rather than a confirmed deterioration caused by temperature alone. Thermal treatment may influence hardness through changes in wood polymers and cell wall structure; however, the extent of these changes depends on treatment intensity and material characteristics [35,37,38].

The relationship between density and mechanical properties was relatively weak in all evaluated cases. Although higher density was associated with higher impact bending strength and Janka hardness, the coefficients of determination remained low ($r^2 = 0.023–0.178$). This indicates that density alone was not sufficient to predict mechanical performance after high-temperature drying. Thermal exposure introduces additional factors affecting wood behaviour, including the chemical modification of cell wall components, redistribution of moisture, and development of internal stresses [23,32,39].

Within the investigated material, increasing drying temperature from 120 °C to 150 °C was associated with reductions in selected mechanical properties, although the statistical significance of the temperature effect depended on the property evaluated. The statistically confirmed decrease in tensile strength perpendicular to the grain suggests that this property may be particularly sensitive to intensive drying conditions. However, because impact bending strength and Janka hardness were not significantly affected by temperature, the suitability of high-temperature drying should be assessed using multiple quality indicators rather than a single mechanical parameter.

The main limitations of this study are the use of material originating from a single silver fir tree and the absence of a conventional drying reference treatment. The single-tree design limits the generalizability of the findings because the observed variation represents variability within the investigated material and cannot be considered representative of the broader silver fir population. The 25 mm and 32 mm boards were obtained by radial sawing from a comparable radial zone of the same stem to minimize potential differences associated with the pith-to-bark gradient. Nevertheless, because all material originated from a single stem, the independent contribution of specimen thickness cannot be completely separated from tree-specific anatomical variation. This limitation is particularly relevant for impact bending strength and Janka hardness, for which specimen thickness showed a statistically significant effect. The observed thickness effects should therefore be interpreted as effects associated with the experimental thickness groups rather than as general thickness effects applicable to silver fir wood. Future studies should include material from multiple trees and explicitly control or record the radial position of specimens within the stem to improve statistical independence and generalizability. The absence of a conventional drying reference treatment is another limitation, as it prevents the direct quantification of the differences between high-temperature and conventional kiln drying. Future research should therefore combine multiple-tree sampling with conventional drying

controls, chemical analyses, microscopic observations, and fracture evaluation to better explain the mechanisms responsible for changes in mechanical behaviour.

5. Conclusions

The results provide further insight into the response of the investigated silver fir (*Abies alba* Mill.) material to high-temperature drying and may contribute to the evaluation of drying conditions while considering potential changes in mechanical performance. The study demonstrated that increasing the drying temperature from 120 °C to 150 °C was associated with reductions in the mean values of impact bending strength, tensile strength perpendicular to the grain, and Janka hardness; however, the statistical significance of this effect differed among the evaluated properties.

The most pronounced numerical reduction was observed for impact bending strength, where the average value decreased to 5.4 $J \cdot cm^{-2}$ after drying at 150 °C; however, this difference was not statistically confirmed as an effect of drying temperature. Instead, specimen thickness showed a stronger statistical influence on this property. The results indicate that the mechanical response observed within the investigated silver fir material was associated with a combination of thermal exposure, specimen dimensions, and natural variability of wood structure.

Tensile strength perpendicular to the grain was the most sensitive property to drying temperature, showing a statistically significant decrease from 3.1 MPa at 120 °C to 2.3 MPa at 150 °C. In contrast, Janka hardness showed only a decreasing tendency with increasing temperature, while the effect of specimen thickness was statistically more pronounced.

The relationship between oven-dry density and mechanical properties was relatively weak (r^2 = 0.023–0.178), indicating that density alone was not sufficient to predict mechanical performance after high-temperature drying. These findings highlight the importance of considering both material characteristics and drying conditions when evaluating the suitability of high-temperature drying schedules.

From an application perspective, the use of a 150 °C drying regime should be carefully evaluated when the preservation of mechanical performance is required, particularly because tensile strength perpendicular to the grain showed a statistically significant temperature-related response in the investigated material. The results suggest that individual mechanical properties should be evaluated separately, as their sensitivity to elevated temperatures differs.

Further research should include conventional drying regimes as reference treatments, intermediate temperature levels, and additional structural properties such as bending strength, modulus of elasticity, and compressive strength parallel to grain. Complementary analyses of chemical changes and fracture mechanisms would also help to clarify the processes responsible for the observed changes in mechanical behaviour.

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