Determination of Some Physical and Mechanical Properties of Uludağ Fir Wood (*Abies nordmanniana* subsp. *bornmuelleriana*) Grown in Different Site Classes

Halil İbrahim Şahin,[a,*] and Fatih Baştar [b]

Physical, mechanical, and quality characteristics of Uludağ fir (*Abies nordmanniana* subsp. *bornmuelleriana*) wood, which occurs naturally in Turkey, were determined. The effect of site classes (SCs) on these characteristics was investigated. Uludağ fir trees growing naturally in the Şerif Yüksel Forest Management District and belonging to different site classes (I, II, and III) were considered. The physical and mechanical properties of the test samples were determined in accordance with relevant standards, and differences between SCs were evaluated using statistical methods. SCs were found to have a statistically significant effect on the physical and mechanical properties of Uludağ fir wood ($p<0.05$). The highest performance in terms of physical and mechanical properties was generally observed in samples from Class II. Static quality (SQ) values ranged from 9.52 to 10.9, while dynamic quality (DQ) values ranged from 1.77 to 1.98. Based on DQ values, samples from all quality classes fell into the group of wood exhibiting high elastic properties; based on SQ values, they were classified as high-quality wood. The findings highlight the impact of SCs on the quality characteristics of Uludağ fir wood, providing important scientific data for quality-focused raw material selection, sustainable forest management, and the planning of wood usage areas.

DOI: 10.15376/biores.21.3.8489-8508

Keywords: Uludağ fir; Site class; Physical properties; Mechanical properties; Static and dynamic quality values

*Contact information: a: Department of Wood Mechanics and Technology, Faculty of Forestry, Düzce University, 81620, Düzce, Turkey; b: Directorate of Western Black Sea Forestry Research Institute, BOLU, Turkey; *Corresponding author: halilibrahimsahin@duzce.edu.tr*

INTRODUCTION

Wood is a material with high sustainability ratings because it is recyclable, reusable, environmentally friendly, and naturally renewable (Dong *et al.* 2022; Abdolmaleki *et al.* 2025). It is considered a green building material due to its carbon sequestration throughout its life cycle (Li *et al.* 2018). According to environmental impact assessments, wood structures exhibit a global warming potential that is 81 to 94% lower than that of concrete buildings and 76 to 91% lower than that of steel buildings (Wang *et al.* 2024).

Wood and engineered wood products are widely used in various construction applications (He *et al.* 2024). Furthermore, their excellent strength-to-weight ratios, thermal insulation, and acoustic properties make them suitable for a wide range of applications in buildings, from structural beams to windows, door frames, wall and flooring materials, and furniture (Asdrubali *et al.* 2017; Reh *et al.* 2022).

Wood is a hygroscopic material due to the abundance of hydroxyl groups associated with its cell wall polymers. It undergoes dimensional changes depending on ambient temperature and relative humidity (Brischke *et al.* 2017). Therefore, to minimize the effects of movement after installation, lumber intended for exterior use should be dried to an equilibrium moisture content of approximately 15% (Engelund *et al.* 2013; Sargent 2019).

Wood quality is significantly influenced not only by the species' genetic characteristics but also by the growing environment, site class (SC), climatic conditions, silvicultural practices, growth rate, and the wood's anatomical structure (Rocha *et al.* 2019). Therefore, even among individuals of the same species, significant differences in density, dimensional stability, and mechanical properties may arise depending on growing conditions (Pretzsch and Rais 2016; Clough *et al.* 2017; Schimleck *et al.* 2018; Barrette *et al.* 2023; Jones *et al.* 2024; Wentzel *et al.* 2024). Various techniques are used to determine wood quality in applications such as historic structures, packaging, biofuels, coatings, furniture, lumber, and flooring. These techniques can be classified as visual (macroscopic) grading, chemical, physical, and mechanical tests, non-destructive methods, and microscopic analyses. Numerous studies utilizing these techniques can be found in the literature (Azzi *et al.* 2025; Liu *et al.* 2025; Nwoanjia *et al.* 2025).

SC is one of the fundamental site condition indicators that reflects the productivity capacity of forest land and is widely used in forest planning. SCs serve as an important decision-support tool in forestry practices such as determining the growth potential of stands, establishing management horizons, planning thinning programs, and selecting appropriate tree species (Vissage *et al.* 2019). SC is not merely an indicator reflecting growth performance; it also reflects the combined effects of numerous environmental factors such as climate, soil, topography, and biotic interactions (Lockhart 2013). For this reason, it is important to investigate SCs not only in terms of stand productivity but also regarding their potential effects on the technological properties of wood.

Uludağ fir (*Abies nordmanniana* subsp. *bornmuelleriana*), one of Turkey's most important native conifer species, is used primarily as a construction material, for carpentry, and in various industrial applications. Ecologically, this species enhances biodiversity, supports wildlife, prevents soil erosion, and contributes to water regulation and carbon sequestration. These trees are essential for maintaining forest health, providing ecosystem services, and supporting climate regulation (Gülsoy 2024).

Numerous studies have been conducted on coniferous species in the literature. These studies have reported that growing conditions and silvicultural practices influence wood density, modulus of elasticity, and mechanical properties. However, a significant portion of the existing studies has focused on materials obtained from a single growing environment or has evaluated only specific physical or mechanical properties (Beets *et al.* 2018; Barrette *et al.* 2023). In particular, there is very limited information regarding the comprehensive effect of different SCs on the physical properties, mechanical performance, and quality indicators of wood from naturally occurring Uludağ fir populations. Therefore, evaluating Uludağ fir wood from different SCs within the same research framework in terms of density, dimensional stability, mechanical properties, and quality values will fill an important scientific gap.

Hypotheses

Based on this identified knowledge gap in the current literature, the following research hypotheses have been formulated to evaluate the effect of different SCs on the physical, mechanical, and quality characteristics of Uludağ fir wood:

H1. It is proposed that there are statistically significant differences in the physical properties (density, shrinkage, and swelling behavior) of Uludağ fir (*Abies nordmanniana* subsp. *bornmuelleriana*) wood grown in different SCs.

H2. It is proposed that SCs have a statistically significant effect on the mechanical properties of Uludağ fir wood (modulus of rupture (MOR), modulus of elasticity (MOE), impact bending strength (IBS), and compressive strength parallel to the grain (CS)).

H3. It is proposed that there are statistically significant differences in the DQ and SQ values of Uludağ fir wood grown in different SCs.

In the literature, there are very limited studies examining the relationships between SCs and the physical, chemical, mechanical, and anatomical properties of wood, as well as other technological characteristics (Bektas *et al.* 2003; Gundogan *et al.* 2005). However, no study in the literature has been found that comprehensively evaluates the effect of SCs on the physical, mechanical, and quality properties of Uludağ fir wood.

The purpose of this study was to conduct a comparative analysis of physical, mechanical, and quality characteristics of Uludağ fir wood grown at three different SCs in the Aladağ region of Bolu Province, Turkey, and to determine the effect of SCs on wood quality. The findings are intended to provide a scientific basis for decision-makers in the quality-oriented classification of Uludağ fir wood and in selecting suitable raw materials for various applications (indoor and outdoor applications, veneer, lumber, furniture, construction, etc.).

This article is one of the few that comprehensively evaluates the effect of different SCs on the wood quality of Uludağ fir in terms of physical, mechanical, and quality characteristics. Furthermore, the findings are expected to contribute to a better understanding of the relationship between growing conditions and wood properties, thereby establishing a scientific foundation for sustainable forestry practices and wood raw material management.

EXPERIMENTAL

Materials

The Uludağ fir wood samples used in the study were obtained from the Aladağ Forest Management Directorate, Şerif Yüksel Forest Management Chiefdom of Bolu Regional Forest Directorate. Since the study primarily addressed the effects of SCs on physical and mechanical properties, care was taken to ensure that environmental and stand characteristics other than SCs (such as elevation, aspect, slope, breast height diameter, stand type, and canopy closure) were as similar as possible across each SC (Table 1). The areas from which the experimental trees were sourced were selected from stands within the same forest management district, at similar elevations (1500-1600 m), and with similar topographic characteristics.

In this study, the SCs of the sample plots were determined based on the management plan of the Şerif Yüksel Forest Management Chiefdom and the SC tables developed by Eraslan *et al.* (1984) for the Uludağ fir. Accordingly, SC I represents high site productivity, SC II represents moderate site productivity, and SC III represents relatively lower site productivity. The determination of SCs was based on the average top height criterion; in the study area, the top height was set at 38 to 42 m for SC I, 34 to 38 m for SC II, and 30 to 34 m for SC III.

Since the fir stands in the study area were managed based on diameter classes rather than age classes, diameter was used as the criterion for selecting sample trees instead of age. Therefore, to ensure comparability among SCs, sample trees within similar diameter ranges were selected. This approach was adopted to ensure that differences between SCs stem as much as possible from site conditions and to reduce sampling-related variability. The target diameter for fir trees in these regions was set at 72 cm; sample trees were selected from the 68 to 76 cm diameter class, comprising trees from three different SCs (SC I-SC III), with a total of 24 sample trees 8 from each plot-harvested and removed from the field. Figure 1 shows the trees from which the experimental samples were obtained.

Fig. 1. Images of sampled areas and trees (a: SC I, b: SC II, and c: SC III)

The height of the felled trees was measured with digital height gauges, and the diameter at breast height was determined from a height of 1.30 m with the help of calipers. In addition, 8- to 10-cm-thick disks were taken from 0.30 m to determine tree age. General information about the area and trees from which the experimental samples were obtained.

Table 1. Information About the Sample Area and Trees

Region	Tree No.	Height (m)	Age (year)	Diameter (cm)	Elevation (m)	Closure (%)	Slope (%)	Aspect
SC I	1	38.8	177	68	1549	70 to 75	9 to 17 (middle)	South West
	2	38.9	151	70	1549			
	3	38.1	108	68	1549			
	4	39.5	228	68	1549			
	5	38.6	236	74	1549			
	6	39.6	221	76	1549			
	7	39.4	183	74	1550			
	8	40.1	215	72	1550			

SC II	1	35.5	216	68	1573	70 to 75	9 to 17 (middle)	South West
	2	34.4	123	72	1580			
	3	35.6	211	68	1577			
	4	34.5	187	73	1576			
	5	34.2	86	72	1574			
	6	35.2	230	73	1573			
	7	36.3	222	73	1579			
	8	34.1	141	72	1578			
SC III	1	32.4	289	72	1576	70 to 75	9 to 17 (middle)	South West
	2	31.8	159	70	1576			
	3	31.5	242	72	1578			
	4	30.2	123	70	1580			
	5	30.9	185	70	1581			
	6	31.7	260	74	1581			
	7	32.2	234	68	1582			
	8	31.3	189	76	1583			

SC I: Side Class I; SC II: Side Class II; SC III: Side Class III

Methods

Test samples to be used for physical and mechanical test specimens were taken from 2 m sections of tree trunks between 2 to 4 m from the root according to the TS 4176 (1984) standard. North directions were marked on the 2 m trunk sections cut from the trees and tree numbers were written on each of them. The obtained logs were first de-capped and then sawn into 3- and 6-cm-thick timber in a private sawmill, following the standards. The sawing process was carried out in accordance with TS ISO 3129 (2021). The sawn timbers were renumbered and stacked in a covered area to reach the desired equilibrium humidity by placing slats between them. The moisture content of the timber was continuously checked. The timbers whose moisture content reached the fiber saturation point were processed with band saw, circular saw, and planing machines to obtain test samples. Care was taken to ensure that the test specimens did not contain defects such as cracks, knots, *etc.* Defective specimens were replaced with new ones. When preparing small-sized specimens, the splinters formed on the edges and corners were removed with sandpaper. The numbering process was completed by writing the SC and the test numbers of each test on the prepared test specimens with a ballpoint pen. Figure 2 shows the procedures related to the measurement of physical properties.

Moisture content, air dry density (AD) and oven dry density values (OD), bulk density value (BD), shrinkage and swelling percentages in radial, tangential, and longitudinal directions, volumetric shrinkage, and swelling percentages were determined from the physical properties of Uludağ fir wood of different SCs. Analyses of physical properties were carried out on 20 x 20 x 30 mm^3 test specimens. TS ISO 13061-1 (2021) standard was followed in determining the moisture values of wood and TS ISO 13061-2 (2021) standard was followed in determining the density values.

Fig. 2. Images from the work and procedures for density and sorption experiments (a,d: for shrinkage and swelling measurements, b-c: for density test)

Measurement of the shrinkage and swelling percentages in the longitudinal, radial, and tangential directions of the samples used in wood-water relations was carried out in accordance with TS ISO 13061-13 (2024), TS ISO 13061-14 (2024), TS ISO 13061-15 (2021), and TS ISO 13061-16 (2021) standards, respectively.

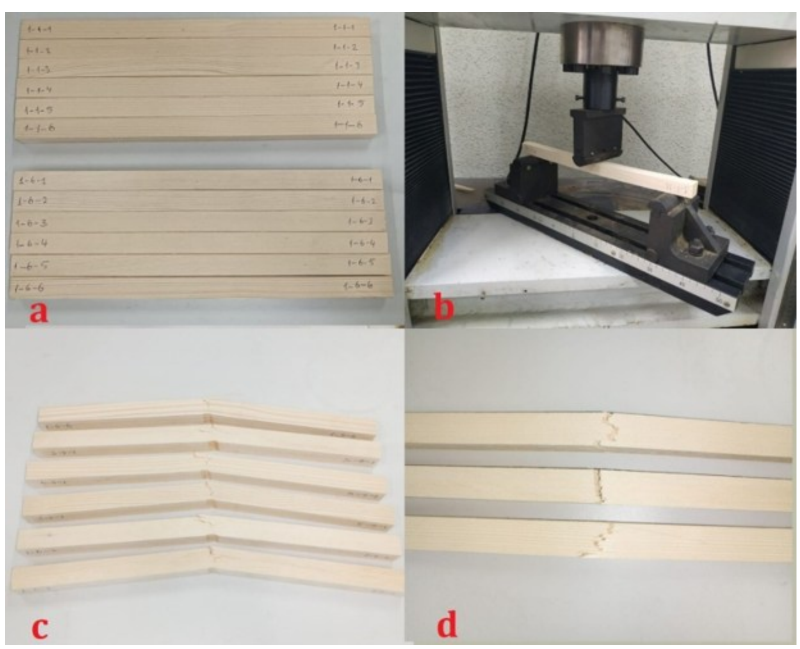

Fig. 3. MOR and MOE test specimens and analysis procedure images (a: MOR and MOE test specimens, b: MOR and MOE analysis image, c-d: fracture images after MOR and MOE analysis)

A 50 kN ton universal testing machine was used in the tests to determine the mechanical properties. Modulus of rupture (MOR) and modulus of elasticity (MOE), impact bending strength (IBS), and compressive strength parallel to grain (CS) were calculated from the mechanical properties. The MOR and MOE tests were performed in accordance with TS ISO 13061-3 (2021) and TS ISO 13061-4 (2021) standards, respectively. The CS value was determined according to TS ISO 13061-17 (2019) standard and IBS values were determined according to TS ISO 13061-10 (2021) standard. Test specimens with dimensions of 20 x 20 x 360 mm^3 for MOR and MOE, 20 x 20 x 30 mm^3 for CS, and 20 x 20 x 300 mm^3 for IBS were used for the analysis of mechanical properties. A total of 240 test specimens, 30 specimens from each tree, were used to determine each physical and mechanical properties. Figure 3 shows the procedures related to the measurement of MOR and MOE tests.

Statistical Analysis

The data were analyzed using SPSS 22 statistical package program. One-way analysis of variance (ANOVA) was used to determine whether there were statistical differences between the SCs in terms of physical and mechanical properties. In case of significant differences between the groups, Duncan's test was applied. Confidence level was taken as 0.05 (95%) in all comparisons.

RESULTS AND DISCUSSION

Physical Properties

The mean AD, OD, and BD values (X), standard deviation, minimum, and maximum values and homogeneity groups obtained as a result of statistical analysis are shown in Table 2.

Table 2. AD, OD, and BD Values of Uludağ Fir wood of Different SCs (g/cm^3)

Properties	Site Class (SC)	X	HG	S	X_{Min}	X_{Max}	F-ratio	P-value
Air dry density (AD)	SC I	0.401*	A**	0.04	0.310	0.530	23.60	0.000
	SC II	0.426	C	0.04	0.360	0.670		
	SC III	0.409	B	0.04	0.330	0.560		
Oven dry density (OD)	SC I	0.376	A	0.04	0.290	0.490	19.29	0.000
	SC II	0.397	C	0.04	0.330	0.620		
	SC III	0.383	B	0.04	0.310	0.520		
Bulk density (BD)	SC I	0.332	A	0.03	0.260	0.430	24.25	0.000
	SC II	0.352	C	0.03	0.300	0.550		
	SC III	0.341	B	0.04	0.280	0.470		

*: The average of 240 samples was used for each test; **: there is no statistical difference between the averages shown with the same letters in the column for each experimental group ($p < 0.05$); X: mean value; HG; homogeneity group, S: standard deviation values; X_{min}: minimum value; X_{max}: maximum value

In general, the differences between the mean AD, OD, and BD values obtained from all three SCs were statistically significant at a 95% confidence level ($p < 0.05$; Table 2). Therefore, Duncan's test was applied to determine which SCs were responsible for the significant differences. According to the results of the Duncan test, it was determined that the average AD, OD, and BD values obtained in all three SCs were different from each other (Table 2). The highest averages for AD, OD, and BD values were obtained from the SC II, while the lowest values were generally observed in the SC I (Table 2). These results demonstrate that differences in the productivity of the growing environment had a measurable effect on wood density.

Wood density is a property that is influenced not only by a tree's genetic characteristics but also by factors such as growing conditions, growth rate, annual ring width, and the earlywood-to-latewood ratio. In particular, differences in SC can alter wood density by affecting the trees' cambial activity and cell wall development (Schimleck *et al.* 2018; Barrette *et al.* 2023).

In this study, the higher wood density values observed in SC II indicate that growth conditions in this site not only promoted rapid diameter increase but also resulted in a denser wood structure. Although it is generally thought that rapid growth in high-quality sites may reduce wood density, this can vary depending on species, age, competitive conditions, and annual ring structure. Indeed, studies conducted in different growing environments indicate that changes in density cannot be explained by growth rate alone; both the growing environment and tree characteristics must be evaluated together (Kimberley *et al.* 2017; Barrette *et al.* 2023).

The density findings obtained fell within the ranges reported in previous studies on Uludağ fir wood. While Sofuoglu *et al.* (2023) reported the density of Uludağ fir wood as 0.410 g/cm³ under 12% moisture content conditions, AD values obtained in the present study, depending on the SCs, ranged from 0.401 to 0.426 g/cm³. In addition, As *et al.* (2001) reported that AD density values of fir wood obtained from different growing regions ranged from 0.429 to 0.450 g/cm³.

It is well known that variations in density values are significant in terms of mechanical properties and performance in use. This is because density is one of the quality indicators that significantly affects the strength and quality of wood, its dimensional stability, susceptibility to biological decay, machinability, and end-use applications (Romagnoli *et al.* 2014; Barreiros *et al.* 2024). Therefore, identifying differences in SC is important, particularly for the classification of fir wood intended for structural use.

The mean tangential, radial, longitudinal, and total volumetric shrinkage values of Uludağ fir wood grown in three different SCs and the homogeneity groups obtained from statistical analysis are shown in Table 3. According to the results of simple analysis of variance, the difference between the mean tangential, radial, longitudinal, and volumetric shrinkage percentages obtained from all three SCs was found statistically significant at the 95% confidence level ($p < 0.05$; Table 3). In general, in terms of volumetric shrinkage rates, there was no difference between the amount of shrinkage obtained in SC II and III. The SC I gave a higher shrinkage rate than the others (Table 3).

In this study, the volumetric shrinkage values determined for Uludağ fir wood ranged from 11.4% to 12.0%. As *et al.* (2001), in their study on different fir species, reported that volumetric shrinkage values ranged from 10.7% to 13.0%. The obtained values are consistent with the characteristic properties of fir wood's dimensional change behavior.

Table 3. Volumetric Shrinkage Percentages of Uludağ Fir Wood of Different SCs (%)

Shrinkage	Site Class (SC)	X	HG	S	X_{Min}	X_{Max}	F-ratio	P-value
Tangential	SC I	7.50	*A*	0.99	4.11	11.1	21.47	0.000
	SC II	7.53	*A*	0.83	5.24	11.7		
	SC III	7.13	*B*	0.85	4.14	8.76		
Radial	SC I	4.01	*A*	1.15	1.91	9.17	17.16	0.000
	SC II	3.66	*C*	0.77	1.42	5.98		
	SC III	3.79	*B*	0.60	2.33	5.66		
Longitudinal	SC I	0.49	*A*	0.32	0.03	3.35	7.70	0.000
	SC II	0.42	*B*	0.14	0.10	0.85		
	SC III	0.47	*A*	0.15	0.13	0.98		
Volumetric shrinkage	SC I	12.0	*A*	1.7	8.30	17.1	13.45	0.000
	SC II	11.6	*B*	1.2	7.30	15.1		
	SC III	11.4	*B*	1.0	8.23	14.0		

Dimensional changes occurring during wood drying are primarily governed by water loss in the cell walls and the anatomical structure. In this study, it was observed that tangential shrinkage values were higher than radial shrinkage values across all SCs. Previous studies have indicated that tangential shrinkage is approximately 1.5 to 2.5 times greater than radial shrinkage (Spear and Walker 2006; Schulgasser and Witztum 2015; Xue *et al.* 2018). This phenomenon is attributed to the anisotropic anatomical structure of wood, including its annual ring structure, earlywood-latewood ratio, distribution of medullary rays, and the arrangement of cell wall microfibrils. In addition to differences in density, microstructural characteristics also play a decisive role in the dimensional changes of wood (Almeida *et al.* 2014; Bonarski *et al.* 2015; Schulgasser and Witztum 2015; Xue *et al.* 2018; Zhang *et al.* 2021; Amer *et al.* 2022). When evaluating differences among SCs, the high shrinkage values observed in Class I may be associated with a more heterogeneous wood structure. Wide annual rings formed under rapid growth conditions and changes in the earlywood ratio can influence the wood's drying behavior (Zhang *et al.* 2021).

The mean tangential, radial, longitudinal, and total volumetric swelling values of Uludağ fir wood of different SCs and the homogeneity groups obtained as a result of statistical analysis are shown in Table 4. The tangential, radial, longitudinal, and volumetric swelling values of Uludağ fir wood also differed statistically depending on the quality classes ($p<0.05$). In general, there was no significant difference between the volumetric swelling percentages obtained in SC I and SC II (Table 4).

An analysis of the swelling values determined for Uludağ fir wood revealed that, across all quality classes, the swelling values in the tangential direction were higher than those in the radial and longitudinal directions. This result stems from the wood's natural anisotropic structure. Özan *et al.* (2017) reported tangential and radial swelling values in Uludağ fir wood as 7.3% and 3.9%, respectively, while Korkut and Bektaş (2008) similarly noted that the tangential swelling values for control samples were high.

Table 4. Volumetric Swelling Percentages of Uludağ Fir Wood of Different SCs (%)

Swelling	Site Class (SC)	X	HG	S	X_{Min}	X_{Max}	F-ratio	P-value
Tangential	SC I	8.17	*A*	1.15	4.90	11.14	15.00	0.000
	SC II	8.60	*C*	0.99	5.71	11.08		
	SC III	8.34	*B*	1.07	4.54	11.46		
Radial	SC I	4.22	*B*	1.06	1.74	9.27	20.69	0.000
	SC II	3.96	*A*	0.89	2.08	9.33		
	SC III	4.37	*C*	0.71	2.39	6.32		
Longitudinal	SC I	0.96	*A*	0.26	0.36	1.75	414.7	0.000
	SC II	0.56	*C*	0.13	0.30	0.88		
	SC III	0.75	*B*	0.17	0.36	1.18		
Volumetric swelling	SC I	13.3	*AB*	1.7	8.28	18.5	3.19	0.000
	SC II	13.1	*A*	1.4	8.57	17.9		
	SC III	13.5	*B*	1.2	8.54	16.7		

Like the shrinkage results, the swelling behavior is also closely related to the wood's anisotropic structure. In this study, as a result of the wood's natural structure, the tangential swelling values were found to be higher than those in the radial and longitudinal directions across all SCs. Cell arrangement, annual ring structure, and the organization of microfibrils in the cell walls exhibit directional variations in dimensional changes (Jankowska *et al.* 2016; Elaieb *et al.* 2019). Particularly with regard to wood-water relationships, high-density woods generally have a higher bound water content. Consequently, it is suggested that their dimensional stability may vary. However, this relationship is not linear. The anatomical characteristics of the wood and the characteristics of the growing environment also play significant roles (Zhang *et al.* 2021).

Mechanical Properties

The mean values of MOR, MOE, IBS, and CS of Uludağ fir wood belonging to different SCs and the homogeneity group values obtained as a result of statistical analysis are shown in Table 5. According to the results of the simple analysis of variance, the difference between the mean values of MOR, MOE, IBS, and CS obtained from all three SCs was found to be significant ($p < 0.05$; Table 5). Therefore, the Duncan test was applied to determine which SCs were responsible for the significant differences. An analysis of the Duncan test results for mechanical properties revealed that all SCs differed from one another in terms of MOR and MOE. It was determined that SC II differed from the others in terms of IBS, while SC I differed from the others in terms of CS (Table 5).

As shown in Table 5, the MOR values for SC I-SC III were 62.0, 71.2, and 66.5 N/mm², respectively, with the highest values observed in SC II. MOR is one of the fundamental mechanical properties that indicate the load-bearing capacity of wood. This value results from the combined effect of density, fiber angle, annual ring structure, and cell wall properties. In particular, research conducted in recent years on coniferous species indicates a strong relationship between wood density and MOR. In general, it has been reported that an increase in wood density leads to an increase in mechanical strength properties (Schimleck *et al.* 2018; Tumenjargal *et al.* 2020; Park *et al.* 2024).

Table 5. Results of Mechanical Properties of Uludağ Fir Wood of Different SCs

Mechanical Properties	Site Class (SC)	X	HG	S	X_{Min}	X_{Max}	F-ratio	P-value
MOR (N/mm^2)	SC I	62.0	*A*	10.1	36.4	85.8	48.46	0.000
	SC II	71.2	*C*	9.7	35.7	96.1		
	SC III	66.5	*B*	10.9	25.0	101.8		
MOE (N/mm^2)	SC I	7360	*A*	1294	4530	11393	47.84	0.000
	SC II	8447	*C*	1176	5307	11920		
	SC III	8096	*B*	1255	4478	13097		
IBS (kgm/cm^2)	SC I	0.281	*A*	0.09	0.12	0.56	19.01	0.000
	SC II	0.353	*B*	0.03	0.16	0.59		
	SC III	0.296	*A*	0.09	0.16	0.57		
CS (N/mm^2)	SC I	38.1	*A*	5.0	25.8	53.1	133.5	0.000
	SC II	45.0	*B*	4.47	30.9	59.6		
	SC III	44.3	*B*	5.6	27.2	61.9		

MOR: Modulus of rupture; MOE: Modulus of elasticity; IBS: Impact bending strength; CS: compressive strength parallel to grain

In this study, the higher MOR values obtained for SC II can be explained by the fact that fir wood in this group has higher density values, resulting in a more rigid cell structure. However, mechanical strength cannot be explained by density alone; anatomical characteristics such as fiber orientation, the earlywood/latewood ratio, and the microfibril angle in the cell wall also play a decisive role. In particular, the microfibril arrangement in the S2 layer-the main component of the secondary cell wall has a significant effect on wood stiffness and MOR (Ramage *et al.* 2017; Li *et al.* 2021).

Upon examining the reported MOR values for Uludağ fir, it was observed that the results obtained in this study fell within the ranges reported in the literature. While Uysal *et al.* (2022) reported the MOR of Uludağ fir wood as 65.0 N/mm², Pelit *et al.* (2018) reported a value of 66.9 N/mm². The higher MOR observed in the SC II in the present study demonstrates the effect of growing conditions on wood quality and highlights the need to consider SC differences when evaluating mechanical performance.

The MOE values for SC I-SC III were determined to be 7,360, 8,447, and 8,096 N/mm², respectively. The highest MOE was found in SC II, while the lowest value was observed in SC I. Upon examining the reported MOE values for Uludağ fir, it was observed that the results obtained in this study fell within the ranges reported in the literature. However, variations in the MOE values obtained in different studies may stem from differences in growing conditions, cambial age, annual ring characteristics, wood density, and cell wall microstructure. It has been reported that, particularly in coniferous species, the MOE is closely related to wood density and the microfibril angle in the secondary cell wall, and that these properties can vary depending on the growing environment and tree development (Schimleck *et al.* 2018; Vega *et al.* 2020; Dahlen *et al.* 2023). Similarly, Schimleck *et al.* (2018) reported that density and fiber properties have significant effects on elastic behavior in determining wood quality in coniferous species.

The IBS values of Uludağ fir wood were determined to be 0.281, 0.353, and 0.296 kgm/cm² for SC I, II, and III, respectively (Table 5). It was observed that the values for SC II were higher than those for the other SCs. IBS reflects the wood's capacity to absorb energy under sudden loads and is significantly influenced by density, fiber continuity, and anatomical defects. In particular, fiber straightness, knot formation, and cell wall properties are the key factors determining dynamic strength (Ramage *et al.* 2017).

In this study, the higher IBS values obtained in SC II can be explained by the more favorable anatomical structure and density characteristics developed in this group. It is noted that the effect of the growing environment on the mechanical performance of wood must be evaluated not only in terms of growth rate but also in conjunction with the microstructural properties of the resulting wood (Barrette *et al.* 2023).

CS values were determined to be 38.1, 45.0, and 44.3 N/mm² for the SC I, II, and III, respectively. The lowest value was observed in the SC I group, while SC II and III yielded similar results (Table 5). CS is one of the key mechanical properties that determine wood's load-bearing capacity along the fiber direction. Fundamentally, cell wall thickness and the microstructural arrangement of the cell wall can influence wood density. Particularly in coniferous species, the orientation of cellulose microfibrils and the microfibril angle in the S2 layer (the thickest section of the secondary cell wall) play a decisive role in the wood's stiffness and mechanical behavior along the fiber direction (Barnett and Bonham 2004; Bader *et al.* 2019; Maaß *et al.* 2020).

The fact that both the density and CS values were higher for SC II and III supports the relationship between wood density and mechanical strength. Wood density is considered an important indicator of many mechanical properties, particularly CS. An increase in wood density is generally associated with higher strength values (Arriga *et al.* 2023). Some researchers have stated that mechanical properties of wood can be determined by utilizing its density (Almeida *et al.* 2016, 2017). However, it is noted that this relationship cannot be explained solely by changes in density; cell wall structure, annual ring characteristics, fiber orientation, and the anatomical organization of wood also influence mechanical performance (Kimberley *et al.* 2017; Schimleck *et al.* 2018; Li *et al.* 2021).

The mean DQ and SQ values of Uludağ fir wood of different SCs and the homogeneity groups obtained from statistical analysis are shown in Table 6. According to the results of simple analysis of variance, the differences between the mean DQ and SQ values obtained from all three SCs were found to be significant ($p < 0.05$; Table 5). Therefore, Duncan's test was applied to determine which SCs were responsible for the significant differences. In terms of DQ values, there was no difference between the values obtained in SC I and SC III, while the DQ value in SC II was higher than the others. SQ values were found to be different from each other in all three SCs.

Statistically significant differences were found between DQ and SQ values of Uludağ fir wood grown in different site classes ($p<0.05$; Table 6). According to the results of the Duncan test, while SC I and III fell into the same homogeneity group in terms of DQ, SC II formed a separate group and exhibited higher values. In terms of SQ values, however, all three SCs were found in distinct homogeneity groups (Table 6).

Table 6. Results of Quality Properties of Uludağ Fir Wood of Different SCs

Quality Properties	Site Class (SC)	X	HG	S	X_{Min}	X_{Max}	F-ratio	P-value
Dynamic quality (DQ)	SC I	1.77	*A*	0.50	0.79	3.94	9.09	0.000
	SC II	1.98	*B*	0.71	0.48	4.74		
	SC III	1.79	*A*	0.50	0.67	3.32		
Static quality (SQ)	SC I	9.52	*A*	1.15	6.00	13.20	79.5	0.000
	SC II	10.6	*B*	1.30	6.70	14.50		
	SC III	10.9	*C*	1.30	6.60	14.40		

DQ values are calculated by evaluating IBS and AD values together and provide information about the wood's behavior under sudden loads. In this study, the DQ values for the first, second, and third SCs were determined to be 1.77, 1.98, and 1.79, respectively. The fact that the highest DQ value was obtained in the SC II can be attributed to the wood from this growing environment having both higher density and higher IBS values. The fact that all DQ values obtained in this study were found in the group of wood exhibiting high elastic properties indicates that Uludağ fir wood possesses a structure capable of absorbing a certain level of energy against sudden load impacts. It has been reported that, particularly in coniferous species, increases in density, improvements in cell wall organization, and enhancements in mechanical strength properties increase wood's capacity to absorb energy from impact forces (Ramage *et al.* 2017; Schimleck *et al.* 2018; Barrette *et al.* 2023).

When SQ values were examined, values of 9.52, 10.62, and 10.88 were obtained for SC I, II, and III, respectively. The lowest SQ value was determined in SC I, while the highest value was found in SC III (Table 6). In contrast to DQ, it is noteworthy that the SC III yielded the highest SQ value. This is because the SQ calculation evaluates both the CS and the density values together. In this study, although the CS in SC III was similar to that of the SC II, the higher density value may have contributed to the increase in the SQ value. The relationship between wood density and mechanical performance is recognized as an important parameter in SQ assessments, particularly for coniferous species (Schimleck *et al.* 2018; Li *et al.* 2021).

A comprehensive evaluation of mechanical properties has shown that the differences observed among SCs are not limited to a single mechanical property. It also indicates a systematic variation that affects the overall performance of the wood. In particular, the fact that higher values were obtained for MOR, MOE, and IBS in SC II, while the SQ index was found to be higher in SC III, demonstrates that the growing environment can influence wood quality through various mechanical parameters. This situation indicates that SCs are an important factor determining not only growth performance but also the engineering properties of wood. Recent studies indicate that evaluating wood quality based on a single mechanical property is insufficient. They report that considering stiffness, density, strength, and quality indices collectively provides a more comprehensive picture of wood's utilization potential (Schimleck *et al.* 2018; Drew *et al.* 2022; Barrette *et al.* 2023).

CONCLUSIONS

1. This article has shown that the physical, mechanical, and quality properties of Uludağ fir wood grown in different site classes (SCs) varied significantly, depending on the growing environment.
2. In terms of physical properties, the highest density values were found in SC II, while in terms of dimensional stability, lower values of volumetric shrinkage were observed in SC III. This finding indicates that differences in SC have a decisive effect on the physical properties of the wood.
3. When mechanical properties were examined, the SC II generally exhibited the highest performance in terms of modulus of rupture (MOR), modulus of elasticity (MOE), internal bond strength (IBS), and compressive strength parallel to the grain (CS). These results support the relationship between density and mechanical performance.
4. Dynamic quality (DQ) and static quality (SQ) assessments showed that performance also varied among the SCs. SC II scored higher in DQ, while SC III scored higher in SQ. However, all quality classes fell within an acceptable quality range.
5. When physical, mechanical, and quality characteristics were evaluated together, it was determined that SCs had a significant effect on the technological properties of Uludağ fir wood. Therefore, it is recommended that SC information be taken into account in the quality-based evaluation of wood raw materials.
6. This study identified significant effects of SCs on the physical, mechanical, and quality characteristics of Uludağ fir wood. However, it should be noted that wood properties may be influenced not only by SCs but also by age, annual ring characteristics, fiber morphology, cell wall structure, microfibril angle, genetic traits, and other site-specific factors. Therefore, evaluating samples obtained from different elevation levels and geographic regions in conjunction with these variables in future studies will contribute to a more comprehensive understanding of the relationship between SC and wood quality. Furthermore, it is believed that the findings from this study can be utilized in the development of wood quality prediction models and in sustainable raw material planning efforts.

ACKNOWLEDGMENTS

This article was prepared from part of the project (Physical and Mechanical Properties section) numbered 08.7101/2018-2022-2023 and titled “Determination of the technological properties of the wood of the same diameter Uludağ Fir (*Abies nordmanniana* subsp. *bornmuelleriana*) grown in different bonitets (Aladağ sample)” supported by the General Directorate of Forestry, Western Black Sea Forestry Research Institute Directorate, Turkey.

REFERENCES CITED

Abdolmaleki, H., Ahmadi, Z., Hashemi, E., and Talebi, S.(2025). "A review of the circular economy approach to the construction and demolition wood waste: A 4 R principle perspective," *Cleaner Waste Systems* 2025, article 100248. https://doi.org/10.1016/j.clwas.2025.100248

Almeida, G., Huber, F., and Perré, P. (2014). "Free shrinkage of wood determined at the cellular level using an environmental scanning electron microscope," *Maderas. Ciencia y Tecnología* 16(2), 187-198. https://doi.org/10.4067/S0718-221X2014005000015

Almeida, T. H., Almeida, D. H., Christoforo, A. L., Chahud, E., Branco, L. A. M. N., and Lahr, F. A. R. (2016). "Density as estimator of strength in compression parallel to the grain in wood," *International Journal of Materials Engineering* 6(3), 67-71. https://doi.org/10.5923/j.ijme.20160603.01

Almeida, T. H., Almeida, D. H., Araújo, V. A., Silva, S. A. M., Christoforo, A. L., and Lahr, F. A. R. (2017). "Density as estimator of dimensional stability quantities of Brazilian tropical woods," *BioResources* 12(3), 6579-6590. https://doi.org/10.15376/biores.12.3.6579-6590

Amer, M., Kabouchi, B., Rahouti, M., and Famiri, A. (2022). "Experimental study of physical properties and impact bending strength of clonal Eucalyptus wood," *International Journal of Thermophysics* 43(11), article 163. https://doi.org/10.1007/s10765-022-03087-w

Arriaga, F., Wang, X., Íñiguez-González, G., Llana, D. F., Esteban, M., and Niemz, P. (2023). "Mechanical properties of wood: A review," *Forests* 14(6), article 1202. https://doi.org/10.3390/f14061202

As, N., Koç, H., Doğu, D., Atik, C., Aksu, B., and Erdinler, S. (2001). "Türkiye'de yetişen endüstriyel öneme sahip ağaçlarin anatomik, fiziksel, mekanik ve kimyasal özellikleri [Anatomical, physical, mechanical and chemical properties of industrial trees grown in Turkey]," *İstanbul Üniversitesi Orman Fakültesi Dergisi* 51(1), 71-88. [In Turkish] https://doi.org/10.17099/jffiu.15049

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

Azzi, Z., Al Sayegh, H., Metwally, O., and Eissa, M. (2025). "Review of nondestructive testing (NDT) techniques for timber structures," *Infrastructures* 10(2), article 28. https://doi.org/10.3390/infrastructures10020028

Báder, M., Németh, R., and Konnerth, J. (2019). "Micromechanical properties of longitudinally compressed wood," *European Journal of Wood and Wood Products* 77, 341-351. https://doi.org/10.1007/s00107-019-01392-0

Barnett, J. R., and Bonham, V. A. (2004). "Cellulose microfibril angle in the cell wall of wood fibres," *Biological Reviews* 79(2), 461-472. https://doi.org/10.1017/s1464793103006377

Barreiros, R. M., Godinho, E. Z., Pereira, L. C., Dias, K. B., and Caneppele, F. D. L. (2024). "Methods in determining basic density of wood," *Wood Material Science & Engineering* 19(4), 918-919. https://doi.org/10.1080/17480272.2023.2291141

Barrette, J., Achim, A., and Auty, D. (2023). "Impact of intensive forest management practices on wood quality from conifers: Literature review and reflection on future challenges," *Current Forestry Reports* 9, 101-130. https://doi.org/10.1007/s40725-023-00181-6

Beets, P. N., Kimberley, M. O., Oliver, G. R., and Pearce, S. H. (2018). "Predicting wood density of growth increments of Douglas-fir stands in New Zealand," *New Zealand Journal of Forestry Science* 48(1), 8. https://doi.org/10.1186/s40490-018-0112-z

Bektas, I., Alma, M. H., As, N. and Gundoğan, R. (2003). "Relationship between site index and several mechanical properties of Turkish Calabrian pine (*Pinus brutia* Ten.)," *Forest Products Journal* 53(2), 27-31.

Bonarski, J. T., Kifetew, G., and Olek, W. (2015). "Effects of cell wall ultrastructure on the transverse shrinkage anisotropy of Scots pine wood," *Holzforschung* 69(4), 501-507. https://doi.org/10.1515/hf-2014-0075

Brischke, C., Meyer-Veltrup, L., and Bornemann, T. (2017). "Moisture performance and durability of wooden facades and decking during six years of outdoor exposure," *Journal of Building Engineering* 13, 207-215. https://doi.org/10.1016/j.jobe.2017.08.004

Clough, B. J., Curzon, M. T., Domke, G. M., Russell, M. B., and Woodall, C. W. (2017). "Climate-driven trends in stem wood density of tree species in the eastern United States: Ecological impact and implications for national forest carbon assessments," *Global Ecology and Biogeography* 26(10), 1153-1164. https://doi.org/10.1111/geb.12625

Dahlen, J., Auty, D., Eberhardt, T. L., Schimleck, L., and Pokhrel, N. R. (2023). "Determination of ring-level dynamic modulus of elasticity in loblolly pine from measurements of ultrasonic velocity and specific gravity," *Forestry: An International Journal of Forest Research* 96(4), 588-604. https://doi.org/10.1093/forestry/cpac063

Dong, X., Gan, W., Shang, Y., Tang, J., Wang, Y., Cao, Z., Xie, Y., Liu, J., Bai, L., Li, J., and Rojas, O. J. (2022). "Low-value wood for sustainable high-performance structural materials," *Nature Sustainability* 5(7), 628-635. https://doi.org/10.1038/s41893-022-00887-8

Drew, D. M., Downes, G. M., Seifert, T., Eckes-Shepard, A., and Achim, A. (2022). "A review of progress and applications in wood quality modelling," *Current Forestry Reports* 8(4), 317-332. https://doi.org/10.1007/s40725-022-00171-0

Elaieb, M. T., Shel, F., Jalleli, M., Langbour, P., and Candelier, K. (2019). "Physical properties of four ring-porous hardwood species: Influence of wood rays on tangential and radial wood shrinkage," *Madera y Bosques* 25(2), article e12521695. https://doi.org/10.21829/myb.2019.2521695

Engelund, E. T., Thygesen, L.G., Svensson, S., and Hill, C. A. S. (2013). "A critical discussion of the physics of wood-water interactions," *Wood Science and Technology* 47, 141-161. https://doi.org/10.1007/s00226-012-0514-7

Eraslan, İ., Yüksel, Ş., and Giray, N. (1984). "Batı Karadeniz Bölgesindeki Değişik Yaşlı Koru Ormanlarının Optimal Kuruluşları Hakkında Araştırmalar," Tarım Orman ve Köyişleri Bakanlığı Orman Genel Müdürlüğü [Research on the Optimal Establishment of Different Old-Growth Forests in the Western Black Sea Region, Ministry of Agriculture, Forestry and Rural Affairs, General Directorate of Forestry], Ankara, Turkey. [In Turkish]

Gülsoy, S. K. (2024). "Chemical composition and fiber properties of wood of fir species naturally growing in Türkiye: A literature review," in: *International Studies and Evaluations in The Field of Agriculture, Forestry and Aquaculture Sciences*, Özrenk K., Bolat A. (eds.), Serüven Publishing, Ankara, Türkiye, pp. 221-234.

Gundogan, R., Bektas, I., Alma, M. H., and Yuksel, A. (2005). "Relationship between site index and some physical properties of Calabrian pine," *Forest Products Journal* 55(1), 45-48.

He, S., Zhao, X., Wang, E. Q., Chen, G. S., Chen, P. Y., and Hu, L. (2023). "Engineered wood: sustainable technologies and applications," *Annual Review of Materials Research* 53, 195-223. https://doi.org/10.1146/annurev-matsci-010622-105440

Jankowska, A., Drożdżek, M., Sarnowski, P., and Horodeński, J. (2016). "Effect of extractives on the equilibrium moisture content and shrinkage of selected tropical wood species," *BioResources* 12, 597-607. https://doi.org/10.15376/biores.12.1.597-607

Jones, G., Ulan, M., Liziniewicz, M., Lindeberg, J., and Adamopoulos, S. (2024). "Relating estimates of wood properties of birch to stem form, age and species," *Journal of Forestry Research* 35(1), 14. https://doi.org/10.1007/s11676-023-01669-4

Kimberley, M. O., McKinley, R. B., Cown, D. J., and Moore, J. R. (2017). "Modelling the variation in wood density of New Zealand-grown Douglas-fir," *New Zealand Journal of Forestry Science* 47(1), 15. https://doi.org/10.1186/s40490-017-0096-0

Korkut, S., and Bektas, I. (2008). "The effects of heat treatment on physical properties of Uludag fir (*Abies bornmuelleriana* Mattf.) and Scots pine (*Pinus sylvestris* L.) wood," *Forest Products Journal* 58(3), 95-99.

Li, D., Zhao, Y., Zhang, L., Chen, X., and Cao, C. (2018). "Impact of quality management on green innovation," *Journal of Cleaner Production* 170, 462-470. https://doi.org/10.1016/j.jclepro.2017.09.158

Li, M. Y., Ren, H. Q., Wang, Y. R., Gong, Y. C., and Zhou, Y. D. (2021). "Comparative studies on the mechanical properties and microstructures of outerwood and corewood in *Pinus radiata* D. Don," *J. Wood Sci.* 67, 60. https://doi.org/10.1186/s10086-021-01992-6

Liu, H., Zheng, Y., and Ke, M. (2025). "Study on the effects of vacuum heat treatment on the physical, mechanical, and chemical properties of *Dalbergia latifolia* Roxb wood," *Wood Material Science & Engineering* 21(2), 1164-1174. https://doi.org/10.1080/17480272.2025.2471003

Lockhart, B. R. (2013). "Site index determination techniques for southern bottomland hardwoods," *Southern J. Applied Forestry* 37(1), 5-12. https://doi.org/10.5849/sjaf.09-027

Maaß, M. C., Saleh, S., Militz, H., and Volkert, C. A. (2020). "The structural origins of wood cell wall toughness," *Advanced Materials 32*(17), article 1907693. https://doi.org/10.1002/adma.201907693

Nwoanjia, J., Biwôlé, J. J. E., Mfomo, J. Z., Fongnzossie, E. F., Pizzi, A., Essiane, S. N., and Biwole, A. B. (2025). "Physical, mechanical and chemical properties as a decision-support tool to promote alternative woods: Case of Dabema (*Piptadeniastrum africanum*) in Cameroon," *Journal of Renewable Materials* 13(5), 901-914. https://doi.org/10.32604/jrm.2025.02024-0005

Özan, Z. E., Onat, S. M., and Aydemir, D. (2017). "The effects of thermal treatment on the some properties of Scots pine and Uludağ fir woods," *Journal of Bartin Faculty of Forestry* 19(1), 187-193. https://doi.org/10.24011/barofd.313318

Park, Y., Kim, C. K., Jeong, H., Lee, H. M., Kim, K. M., Lee, I. H., Kim, M. J., and Kwon, G. B. (2024). "Evaluation of the basic properties for the Korean major domestic wood species: I. Korean red pine (*Pinus densiflora*) in Pyeongchang-gun, Gangwon-do," *Journal of the Korean Wood Science and Technology* 52(1), 87-100. https://doi.org/10.5658/WOOD.2024.52.1.87

Pelit, H., Budakçı, M., and Sönmez, A. (2018). "Density and some mechanical properties of densified and heat post-treated Uludağ fir, linden and black poplar woods," *European J. Wood Wood Products* 76 (1), 79-87. https://doi.org/10.1007/ s00107-017-1182-y

Pretzsch, H. and Rais, A. (2016). "Wood quality in complex forests versus even-aged monocultures: Review and perspectives," *Wood Science and Technology* 50, 845-880. https://doi.org/10.1007/s00226-016-0827-z

Ramage, M., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., Li Yu, G. W., Fleming, P., Densley-Tingley, D., Alwood, J., *et al.* (2017). "The wood from the trees: The use of timber in construction," *Renewable and Sustainable Energy Reviews* 68(1), 333-359. https://doi.org/10.1016/j.rser. 2016.09.107

Reh, R., Kristak, L., and Antov, P. (2022). "Advanced eco-friendly wood-based composites," *Materials* 15(23), article 8651. https://doi.org/10.3390/ma15238651

Rocha, M. F. V., Veiga, T. R. L. A., Soares, B. C. D., Araújo, A. C. C. D., Carvalho, A. M. M., and Hein, P. R. G. (2019). "Do the growing conditions of trees influence the wood properties?," *Floresta e Ambiente* 26(3), article e20180353. https://doi.org/10.1590/2179-8087.035318

Romagnoli, M., Cavalli, D., and Spina, S. (2014). "Wood quality of chestnut: Relationship between ring width, specific gravity, and physical and mechanical properties," *BioResources* 9(1), 1132-1147. https://doi.org/10.15376/biores.9.1.1132-1147

Sargent, R. (2019). "Evaluating dimensional stability in solid wood: A review of current practice," *Journal of Wood Science* 65(1), 36. https://doi.org/10.1186/s10086-019-1817-1

Schimleck, L., Antony, F., Dahlen, J., and Moore, J. (2018). "Wood and fiber quality of plantation-grown conifers: A summary of research with an emphasis on loblolly and radiata pine," *Forests* 9(6), article 298. https://doi.org/10.3390/f9060298

Schulgasser, K., and Witztum, A. (2015). "How the relationship between density and shrinkage of wood depends on its microstructure," *Wood Science and Technology* 49(2), 389-401. https://doi.org/10.1007/s00226-015-0699-7

Sofuoglu, S. D., Tosun, M., and Atılgan, A. (2023). "Determination of the machining characteristics of Uludağ fir (*Abies nordmanniana* Mattf.) densified by compressing," *Wood Material Science & Engineering* 18(3), 841-851. https://doi.org/10.1080/17480272.2022.2080586

Spear, M., and Walker, J. (2006). "Dimensional instability in timber," in: *Primary Wood Processing, Principles and Practice*, Springer, Berlin, Germany, pp. 95-120. https://doi.org/10.1007/1-4020-4393-7_4

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

TS 4176 (1984). "Wood-Sampling sample trees and logs for determination of physical and mechanical properties of wood in homogeneous stands," Turkish Standards Institution, Ankara, Turkey.

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

TS ISO 13061-2 (2021). "Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 2: Determination of density for physical and

mechanical tests," Turkish Standards Institution, Ankara, Turkey.
TS ISO 13061-3 (2021). "Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 3: Determination of ultimate strength in static bending," Turkish Standards Institution, Ankara, Turkey.
TS ISO 13061-4 (2021). "Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 4: Determination of modulus of elasticity in static bending," Turkish Standards Institution, Ankara, Turkey.
TS ISO 13061-10 (2021). "Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 10: Determination of impact bending strength," Turkish Standards Institution, Ankara, Turkey.
TS ISO 13061-13 (2024). "Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 13: Determination of radial and tangential shrinkage," Turkish Standards Institution, Ankara, Turkey.
TS ISO 13061-14 (2024). "Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 14: Determination of volumetric shrinkage," Turkish Standards Institution, Ankara, Turkey.
TS ISO 13061-15 (2021). "Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 15: Determination of radial and tangential swelling," Turkish Standards Institution, Ankara, Turkey.
TS ISO 13061-16 (2021). "Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 16: Determination of volumetric swelling," Turkish Standards Institution, Ankara, Turkey.
TS ISO 13061-17 (2019). "Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 17: Determination of ultimate stress in compression parallel to grain," Turkish Standards Institution, Ankara, Turkey.
Tumenjargal, B., Ishiguri, F., Takahashi, Y., Nezu, I., Baasan, B., Chultem, G., Aiso-Sanada, H., and Yokota, S. (2020). "Bending properties of dimension lumber produced from Siberian larch (*Larix sibirica*) in Mongolia," *Journal of Wood Science* 66, 17. https://doi.org/10.1186/s10086-020-01863-6
Uysal, M., Eren, O., Karatay, H., and Memiş, D. (2022). "Investigation of bending properties of cross laminated timber made of Uludağ fir and black pine," *Turkish Journal of Forestry* 23(4), 313-319. https://doi.org/10.18182/tjf.1166361
Vega, M., Hamilton, M., Downes, G., Harrison, P. A., and Potts, B. M. (2020). "Radial variation in modulus of elasticity, microfibril angle and wood density of veneer logs from plantation-grown *Eucalyptus nitens*," *Annals of Forest Science* 77, 65. https://doi.org/10.1007/s13595-020-00961-1
Vissage, J. S., Greer, T. R., Jr., and Brandeis, T. J. (2019). "Site class and site index: Two estimates of site quality for the Southern Research Station Forest Inventory and Analysis Program," e-Res. Note SRS-025, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, USA. https://doi.org/10.2737/SRS-RN-25
Wang, Q., Wang, Z., Feng, X., Zhao, Y., and Li, Z. (2024). "Mechanical properties and probabilistic models of wood and engineered wood products: A review of green construction materials," *Case Studies in Construction Materials* 21, article e03796. https://doi.org/10.1016/j.cscm.2024.e03796
Wentzel, M., Pesenti, H., Droppelmann, F., and Rolleri, A. (2024). "Thinning wood properties of *Nothofagus alpina* under three different silvicultural conditions," *Maderas Ciencia y Tecnología* 26 (7), 1-16.

https://doi.org/10.22320/s0718221x/2024.07

Xue, Q., Sun, W., Fagerstedt, K., Guo, X., Dong, M., Wang, W., and Cao, H. (2018). "Effects of wood rays on the shrinkage of wood during the drying process," *BioResources* 13(3), 7086-7095. https://doi.org/10.15376/biores.13.3.7086-7095

Zhang, S. Y., Ren, H., and Jiang, Z. (2021). "Wood density and wood shrinkage in relation to initial spacing and tree growth in black spruce," *Journal of Wood Science* 67, 30. https://doi.org/10.1186/s10086-021-01965-9

Article submitted: February 13, 2025; Peer review completed: March 15, 2025; Revised version received: July 18, 2026; Accepted: July 20, 2026; Published: July 24, 2026.
DOI: 10.15376/biores.21.3.8489-8508