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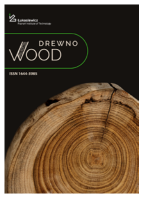

Comparative Investigation of Physical and Mechanical Properties of Some Wood Species in Different Climatic Conditions

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In this study, samples of oriental beech (*Fagus orientalis* L.), hornbeam (*Carpinus betulus* L.), and alder (*Alnus glutinosa* L.) wood, which are widely used in furniture production and other sectors of the woodworking industry, were comparatively examined under different climatic conditions, and their interchangeability was investigated. For this purpose, test specimens prepared from the three wood species were subjected to tests at 20 °C/65%, 40 °C/35%, and 10 °C/50% temperature and relative humidity conditions, and their physical and mechanical properties were determined. As a result, among the diffuse-porous wood species examined, the density of hornbeam wood was found to be 0.76 g/cm³, while that of beech wood was 0.73 g/cm³. The bending strength was determined as 129.4 N/mm² for hornbeam wood, with the closest value observed in beech wood at 121.2 N/mm². Similarly, the modulus of elasticity in bending of hornbeam and beech wood was found to be at comparable levels. However, the highest impact strength was measured in beech wood at 82.4 kJ/m², while the lowest was in hornbeam wood at 56.6 kJ/m², with alder wood exhibiting an intermediate value of 67.3 kJ/m². When the hardness values of the wood species were examined, it was observed that beech wood (29.2 N/mm²) and alder wood (25.1 N/mm²) exhibited similar hardness resistance. Therefore, it can be concluded that hornbeam and beech wood can be used interchangeably for load-bearing applications, whereas for applications requiring hardness and impact strength, beech and alder wood species may be preferred as substitutes for one another. Thus, when the use of one of these three wood species is required, sourcing based on availability and ease of transportation may provide an economic advantage.

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Introduction

Wood materials used in the woodworking industry can be used interchangeably depending on their availability on the market and for economic reasons. However, when used interchangeably, it is very important to consider whether they have similar performance values in terms of the current climatic conditions at the end-use location and the static or dynamic loads to which they will be exposed. Therefore, it is necessary to know the resistance of different wood materials to physical and mechanical effects under the same conditions.

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Although wooden furniture has been produced in various forms for centuries, it has not been designed considering its structural properties (Eckelman 1966). Although the physical and mechanical properties of many wood species are known, they are mainly those determined under standard measurement conditions. Therefore, there are not yet sufficient studies on the structural properties of wood in other conditions (temperature, humidity, etc.) than standard ones, and some of the studies conducted in recent years are as follows. Wood is a natural material whose use has been increasing day by day due to its many superior properties from the past to the present (Kurtoğlu 2000; Ors and Keskin 2001; Khalil *et al.* 2010; Bülbül *et al.* 2024). In order for a furniture system or furniture joints to be structurally designed and analyzed in accordance with engineering rules, the physical and mechanical properties of the wood material must first be known (Kasal 2004). Thus, the first step in furniture design is to determine the physical and mechanical properties of the materials used in production. The next steps are to determine whether the elements and/or joints are reliable by comparing the internal stresses that will occur in the constructions of the joints and other components that make up the furniture's structural system under the effect of external compelling forces with the acceptable safety stresses determined for the materials (Eckelman 1991).

The places where wooden products are designed and manufactured, and the places where they are used, often show significant differences in terms of climate conditions. The moisture value of wood, which has a hygroscopic structure, also changes accordingly (Kurtoğlu 2016). Similarly, global climate conditions also have these differences. Therefore, arranging the material to be used in the production of wooden products according to the climate conditions of the place of use will both allow the products to have a long life and ensure the sustainability of forest products.

By conducting several experiments, it was understood that the Taguchi design method is the appropriate analysis method for determining the elastic modulus of wood materials. It can be said that this methodology provides an accurate and effective method for determining the effective parameters on the mechanical properties of wood (Güneş et al. 2024).

It is desired that the amount of moisture that wooden products will contain is between 5% and 19% depending on the place of use. It has been stated that moisture above these rates causes problems such as decay (Görgün and Ünsal 2023) and that every 1% increase in moisture in wooden materials causes a decrease in mechanical strength by up to 4% (Bozkurt and Göker 2023).

Oriental beech or eastern beech belongs to the family Fagaceae. It is a deciduous broad-leaved tree which reaches a height of 30–40 meters. In rare instances, trees up to 50 meters in height can be found. Stem diameter can reach about 1 m at breast height. Height growth of oriental beech at early ages is slow. The maximum growth rate is usually achieved at the age of 30–40 years, but under shelter, this could take longer, even 60 years. The wood of oriental beech is heavy, hard, and highly resistant to shock. This feature makes it suitable for steam bending. The wood is also a source of fuelwood and can be used for constructions, particleboard, furniture, flooring, veneer, mining poles, railway tiles, and paper. In Turkey, the species is distributed in Thrace and in the south of the Marmara Sea and throughout the Black Sea regions, where it is possible to find oriental beech both as pure stands and mixed forests with conifers and other deciduous broadleaves. There are also isolated natural populations of the species north-east of the Mediterranean Sea on the Nur Mountains (Kandemir and Kaya 2009).

Hornbeam wood is known to be a quality material used in products requiring solid wood, especially in the furniture sector. It is frequently used, especially in furniture production and structural wood applications. Hornbeam, which can also be used as fuel, does not require delicate and soft conditions. Due to its solid structure and durability, it meets wood's needs in many areas, from the toy sector to the ship sector. Hornbeam and beech wood are often confused due to their appearance similarity. However, their structures and physical properties are different from each other. Hornbeam wood is white, heavy, and quite hard, and does not break easily. For this reason, it is also more difficult to process. Hornbeam wood is used in wooden systems and elements that require strength under pressure. It is used in the production of products such as gear wheels, lathe tools, ship keels, wooden machine parts, mine poles, shoe molds, levers, wooden sports equipment, wooden kitchen tools and utensils, agricultural tools, and shuttles (Özbayram and Alkiz 2019).

Fast-growing alder wood grows especially on-stream banks (Giardina *et al.* 1995) and in humid stands (Vares et al. 2004). Alder is widespread in the Eastern Black Sea region and the Caucasus (Ayan and Sıvacıoğlu 2006) and is a rapidly growing species. It is operated with a management period of 20 to 50 years (Hamzeh'ee et al. 2008). Another important industrial forest wood species in terms of ecology and economy, which is widespread in the Black Sea region and the Caucasus, is the eastern beech (Ertekin et al. 2015). They are operated with a management period of 100 to 140 years (Pak and Gulci 2017). In the areas where both species are distributed, the total annual rainfall is over 2500 mm/m^2 (Varkouhi *et al.* 2017).

Wooden parts, such as those for aircraft, buses, machines, sports equipment, ladders, tool handles, and some structural elements used in construction, are always subject to dynamic loads rather than static loads. Shock strength, which is the type of strength that the material shows against dynamic forces, is a type of strength that occurs in a very small time, such as one thousandth of a second. High shock strength represents flexibility, while low shock strength represents brittleness (Bozkurt 1987; Kaya and Bülbül, 2023).

This study aims to experimentally determine the resistance of beech, hornbeam, and alder woods—which are appearance similar but differ in their physical and mechanical properties—to physical and mechanical stresses under three distinct climate regimes (20 °C/65%, 40 °C/35%, and 10 °C/50%), and to assess the potential interchangeability of these species. It is anticipated that facilitating such interchangeability will confer both economic and sustainability benefits.

Materials and methods

1. Material

In this study, considering their widespread use in the solid wood furniture industry in Turkey, oriental beech (*Fagus orientalis* L.), hornbeam (*Carpinus betulus* L.), and alder (*Alnus glutinosa* L.) were used. Wood materials were obtained completely randomly from the furniture industry factories in the Siteler district, Ankara. In the procurement of lumber, factors such as naturally dried, dry, solid, natural colored, flawless, parallel grained, untwisted grained, not damaged by insects or fungi were taken into consideration.

2. Preparation of Samples and Testing Method

A sufficient amount of air-dried wooden blocks from all three wood types were cut in the machine shop of the Department of Woodworking Industrial Engineering of the Faculty of Technology of Gazi University, in the dimensions and quantities given in Table 1. All prepared samples were first kept in the air conditioning chamber at 20 °C/65% relative humidity until they reached a constant weight to determine the physical and mechanical properties for 6 different tests and measurements under 3 different climate conditions. Ten of these samples were taken from the air conditioning chamber, tested, and the properties were measured, and the physical and mechanical values under these climate conditions were determined. Then, the second climate condition of the climate chamber was set to 40 °C/35% and the remaining samples were kept until they reached constant weight in this second climate condition and 10 samples were tested/measured, and finally, the third condition of the climate chamber was set to 10 °C/50% and the samples were kept until they reached constant weight and tests and measurements were applied to the samples.

The experimental samples in this study were conditioned according to the climate conditions specified in the experiment, in a Climatized Testing Chamber capable of controlling temperature between +10ºC and +80ºC and relative humidity between 10% and 95%, based on the geographical conditions of a region like Turkey, located in the middle of the temperate zone in the northern hemisphere where all four seasons are experienced. The conditioning process continued until the specimens reached a constant weight, as determined by measurements taken every 6 hours using a precision balance with an accuracy of 0.01 g.

- 20 °C/65%: Expresses the natural dryness degree in open air conditions for wood material and is accepted to represent spring and autumn weather conditions as climate.
- 40 °C/35%: Expresses a higher dryness degree for wood material and is accepted to represent summer weather conditions as climate.
- 10 °C/50%: Expresses a low dryness degree again for wood material and is accepted to represent winter weather conditions as climate.

The testing and the values at the end of each climate condition in these three conditions were measured consecutively. It is accepted that a wood type has experienced a one-year usage cycle and reflects the physical and mechanical changes that occur in the material during this cycle. To determine the changes in some physical and mechanical properties of these three wood types, the tests and measurements given in Table 1 were carried out on a 5-ton capacity universal testing machine (Instron 5969).

The wood species supplied in log form were conditioned in the workshop environment until equilibrium with the ambient air was achieved. Subsequently, test specimens were prepared according to the relevant standards. The prepared specimens were conditioned at 20±2 °C and 65±5% relative humidity (RH) until reaching a constant weight. After conditioning, the specimens from all three wood species were individually taken from the conditioning chamber and tested. This procedure minimized the adverse effects of environmental conditions on the specimens during testing. Following this process, the specimens were consecutively exposed to three different climatic conditions, and the physical and mechanical behaviors of the three wood species were determined sequentially. The changes experienced by the wood species over a one-year usage cycle were identified, and the variations under successive environmental conditions were compared.

Table 1. Experimental design for the tests and the number of specimens required to determine the mechanical and physical properties based on wood species and climatic conditions

Wood species	Climate Condition	Tests	Dimension (mm)	Number of samples	Total number of samples	Standard no
Eastern beech hornbeam alder	20 °C 65%	Density	20×20×20	10	30	TS ISO 13061-2 (2021)
		Wood moisture content	20×20×20	10	30	TS ISO 13061- 1 (2021)
		Bending strength	20×20×350	10	30	TS EN 310 (1999)
		Modulus of elasticity	20×20×300	10	30	TS EN 310 (1999)
		Impact /shock strength	20×20×300	10	30	TS ISO 13061 10 (2021)
		Brinell hardness (Tangential surface)	50×50×50	10	30	TS ISO 13061-12 (2021)
	40 °C 35%	Density	20×20×20	10	30	TS ISO 13061-2 (2021)
		Wood moisture content	20×20×20	10	30	TS ISO 13061- 1 (2021)
		Bending strength	20×20×350	10	30	TS EN 310 (1999)
		Modulus of elasticity	20×20×300	10	30	TS EN 310 (1999)
		Impact /shock strength	20×20×300	10	30	TS ISO 13061 10 (2021)
		Brinell hardness (Tangential surface)	50×50×50	10	30	TS ISO 13061-12 (2021)
	10 °C 50%	Density	20×20×20	10	30	TS ISO 13061-2 (2021)
		Wood moisture content	20×20×20	10	30	TS ISO 13061- 1 (2021)
		Bending strength	20×20×350	10	30	TS EN 310 (1999)
		Modulus of elasticity	20×20×300	10	30	TS EN 310 (1999)
		Impact /shock strength	20×20×300	10	30	TS ISO 13061 10 (2021)
		Brinell hardness (Tangential surface)	50×50×50	10	30	TS ISO 13061-12 (2021)
Total					540	

3. Data analysis

SPSS 26 (IBM Corp., 2019) and MSTAT-C (Michigan State University, 1989) programs were preferred to analyze the data obtained by experimental methods. First, normality tests were performed on the raw data using these programs, and after confirming the normality of the data, multi-way analysis of variance (MANOVA) and multiple comparisons were carried out based on a 95% confidence level.

Results and discussion

In all three wood types, the average values in the 20 °C/65% climate condition were accepted as the control value, and the values in other conditions were proportioned to them, and the change percentages were determined.

1. Physical properties

The density and moisture values determined in the wood samples that were kept consecutively in different climate conditions are given in Tables 2 and 3.

2. Equilibrium moisture

According to Table 2, it was determined that the equilibrium moisture value of each wood sample changed in each climate condition, and the equilibrium moisture values of all three wood samples in the same climate condition were very close to each other. In this case, it can be said that all three wood types will show similar working behavior against moisture changes in the three climate conditions. In addition, it is seen that in all three wood types, the equilibrium moisture decreased due to drying in the 40°C/35% condition, and although the relative humidity of the environment increased again in the 10°C/50% condition, the equilibrium moisture increased somewhat in parallel, but did not reach the level of control repeat values.

Due to its hygroscopic nature, wood continuously exchanges moisture with its environment depending on the climatic conditions in which it is located. These effects of moisture and temperature are among the primary deteriorative factors for wood-based materials (Kollmann and Cote, 1968; Švajlenka et al., 2019). This exchange continues until the equilibrium moisture content is reached. In general, under conditions of 25 °C temperature and 60% relative humidity, the equilibrium moisture content of European wood species is around 11–12%, whereas for tropical wood species this value can range between 9% and 15%. Furthermore, it has been noted that wood species dried at high temperatures have lower equilibrium moisture contents (Villiere, 1966). Therefore, the fact that the equilibrium moisture content determined in this study under 40°C temperature and 35% relative humidity conditions was lower can be said to be consistent with the literature.

3. Density

It is known that the density of wood changes according to the amount of basic solids (cellulose and extra substances) in the unit volume content or the rate of moisture. It is known that increasing density, depending on the amount of basic solids, positively affects the mechanical properties of the material and increases the strength values. However, increasing density, depending on the increase in the moisture content, decreases the strength values. Table 3 shows the density change depending on moisture in three wood types under three climate conditions.

From Table 3, it is seen that the density value of each wood sample in each climate condition changes according to the humidity balance of the ambient condition. This result agrees with many literature results; the values in the 40 °C/35% condition decrease the density due to drying compared to the control values, and the relative humidity of the environment increases again in the 10 °C/50% condition, but the density increases somewhat in parallel, but does not reach the level of the control repeat values. This situation can be explained by a decreasing density depending on the equilibrium humidity. Therefore, it can be said that in the study, the density values of the wood species changed depending on the relative humidity of the air, and the effect of temperature was less significant.

It has been reported that wood density increases after 60 °C due to the plasticization of components such as cellulose and lignin (Li *et al.* 2019;). Additionally,

Table 2. Equilibrium moisture statistics of samples from three wood species

Wood species	Climate condition	Xmin (%)	Xmax (%)	Xmean (%)	ss.	% Change
	20 °C/65%	12.16	12.72	**12.44**	0.23	-
Hornbeam	40 °C/35%	6.02	7.69	6.98	0.53	-43.8
	10 °C/50%	10.68	11.45	11.07	0.32	-11
	20 °C/65%	10.94	12.49	**12.05**	0.55	-
Beech	40 °C/35%	5.22	7.42	6.32	1.06	-47.5
	10 °C/50%	9.94	11.14	10.72	0.47	-11
	20 °C/65%	11.84	12.54	**12.22**	0.27	-
Alder	40 °C/35%	6.07	8.2	7.03	0.74	-42.4
	10 °C/50%	10.46	11.22	10.9	0.30	-10.9

Table 3. Density statistics of samples from three wood species in three different climate conditions

Wood species	Climate condition	Xmin (g/cm³)	Xmax (g/cm³)	Xmean (g/cm³)	ss.	% Change
Hornbeam	20 °C/65%	0.66	0.83	**0.74**	0.061	-
	40 °C/35%	0.64	0.74	0.68	0.033	-8
	10 °C/50%	0.69	0.73	0.71	0.078	-4
Beech	20 °C/65%	0.68	0.79	**0.73**	0.047	-
	40 °C/35%	0.62	0.71	0.67	0.032	-8.2
	10 °C/50%	0.63	0.78	0.71	0.057	-4
Alder	20 °C/65%	0.59	0.61	**0.59**	0.007	-
	40 °C/35%	0.51	0.62	0.56	0.038	-5
	10 °C/50%	0.54	0.61	0.58	0.026	-1.6

climate temperature has been shown to affect wood density in standing trees, and this is considered an important factor influencing the sustainability of wood (Gindl *et al.* 2001; Wang *et al.* 2002; Švajlenka, and Pošiváková, 2025). However, no studies have been found regarding the effect of climatic conditions on the wood density of sawn timber.

Mechanical properties

1. Bending strength

The bending strength of each wooden sample changes depending on the equilibrium humidity in each climatic condition. This result overlaps with many literature results; the bending strength and change rates in hornbeam and beech samples are very close to each other, and the bending strength of alder is lower and changes. It seems that the ratio is different from these. In this case, it can be said that hornbeam and beech wood species will show similar bending strength behavior against humidity changes in three climatic conditions.

Multiple variance analysis of the bending strengths of all three wood types stored consecutively under different climatic conditions is given in Table 5.

According to Table 5, it was determined that the wood type was significant in terms of its effect on bending strength, while the change in climate conditions and their binary interaction were not significant. It was determined that the tree species affected the bending strength the most, and although the effect of climate condition and bilateral interaction was very low, it was not statistically significant. However, it can be said that the change in bending strength in all three wood types is due to the difference in moisture balance in climatic conditions. Although the values of hornbeam and beech differ slightly in terms of bending strength, it is understood that they are close to each other and may show similar behavior in terms of strength. Alder comes after the two other species.

The softening of the hemicellulose and lignin present in wood material occurs at temperatures between 30°C and 70°C at a moisture content of 10% (Kelley *et al.* 1987). Along with this, a decrease in mechanical properties such as bending strength

Table 4. Statistical values of bending strength of samples from three wood species

Wood species	Climate condition	Xmin (N/mm²)	Xmax (N/mm²)	Xmean (N/mm²)	ss.	% Change
Hornbeam	20 °C/65%	105.0	161.7	**129.4**	16.8	-
	40 °C/35%	92.9	165.8	135.4	24.7	4.6
	10 °C/50%	91.6	161.2	126.4	23.0	-2.3
Beech	20 °C/65%	105.2	147.5	**121.2**	14.3	-
	40 °C/35%	104.4	150.3	124.8	14.7	2.9
	10 °C/50%	111.2	131.3	121.2	18.9	-
Alder	20 °C/65%	70.2	98.3	**84.8**		-
	40 °C/35%	82.3	118.5	100.4	24.0	18.3
	10 °C/50%	66.8	97.6	84.8	11.2	-

Table 5. Multiple variance analysis of the effects of wood type and climate condition on bending strength

Source	Sum of squares	df	Mean of squares	F	(p < 0.05)
Wood type (A)	13711.867	2	6855.934	18.238	0.000
Climatic condition (B)	2245.607	2	1122.804	2.987	0.061
A × B	3103.645	4	775.911	2.064	0.101
Error	16915.722	45	375.905		
Total	770447.270	54			
Corrected error	35976.841	53			

has been observed (Zhou et al. 2012). Therefore, it has been stated that temperature has a significant effect on the mechanical properties of wood material (Li et al. 2023), and the general trend is that mechanical strengths are higher at lower temperatures (Bergman et al. 2010).

2. Modulus of elasticity in bending

From Table 6, it has been determined that the elastic modulus of each wooden sample changes depending on the equilibrium humidity in each climatic condition. The elastic modulus of hornbeam is higher than the other two wood types, and the modulus of beech and alder samples are very close to each other and lower than hornbeam. In this case, it can be stated that all three wood types will show similar elastic behavior against changes in humidity in outdoor conditions. Multiple variance analysis of the elastic modulus of wood species in different climatic conditions under three climatic conditions is given in Table 7.

According to Table 7, only the wood type was significant in terms of its effect on the elastic modulus, and the climate condition and binary interaction change were not significant. Although it was seen that the tree species affected the elasticity modulus the most, and that the climate condition and the bilateral interaction affected it at a very low level, it was determined that it was not statistically significant. Although the values of hornbeam are high, beech and redwood differ in terms of elasticity modulus, it is understood that they are close to each other and lower, but may show similar behavior in terms of elasticity.

In studies conducted at 12% moisture content, the modulus of elasticity in bending was found to be 9100 N/mm² for alder wood, 11,900 N/mm² for beech wood, and 12,990 N/mm² for hornbeam wood (Kretschmann, 2010; Cziczer and Báder, 2024). It has been determined that the modulus of elasticity in bending of wood-based composite materials decreases as the temperature increases at different temperature levels (between -40°C and +40°C) (Xi et al. 2023). The elastic deformation of wood occurs primarily as a result of external forces rather than changes in its chemical structure (Fu et al. 2025). However, an increase in ambient temperature may damage the chemical structure of wood, which in turn can lead to a reduction in its modulus of elasticity. The values of the modulus of elasticity in bending obtained in the

Table 6. Statistical data on the modulus of elasticity in bending of three wood species stored consecutively in different climatic conditions

Wood species	Climate condition	Xmin (N/mm²)	Xmax (N/mm²)	Xmean (N/mm²)	ss.	% Change
Hornbeam	20 °C/65%	11424.2	17118.7	**13908.9**	1801.4	-
	40 °C/35%	11744.4	17274.2	14509.7	1428.4	4.3
	10 °C/50%	10533.1	15845.1	13815.4	1942.6	-0.006
Beech	20 °C/65%	10244.4	13596.6	**11396.4**	1427.4	-
	40 °C/35%	10252.3	13749.4	12000.5	1860.2	5.3
	10 °C/50%	10580.4	12055.3	11317.5	1913.5	-0.006
Alder	20 °C/65%	8367.2	12048.2	**10761.5**	1261.9	-
	40 °C/35%	9817.8	13252.7	11534.5	1747.1	7.2
	10 °C/50%	8917.6	11479.6	10460.9	932.5	-2.7

Table 7. Multiple variance analysis of the effects of wood type and climate condition on the modulus of elasticity in bending

Source	Sum of squares	df	Mean of squares	F	(p < 0.05)
Wood Type (A)	40344954.674	2	20172477.337	7.110	0.002
Climatic condition (B)	8941648.029	2	4470824.015	1.576	0.218
A x B	28654619.328	4	7163654.832	2.525	0.054
Error	127679399.879	45	2837319.997		
Total	8684421539.799	54			
Corrected error	205620621.910	53			

present study were found to be consistent with those reported in the literature. However, it can be stated that the modulus of elasticity in bending decreases as the relative humidity of the air increases, which can be considered a result of the effect of moisture content. The differences in bending strength and modulus of elasticity in bending between the wood species can be attributed to the differences in the density values of the respective species.

3. Impact strength (Shock)

One of the important features of wood material in terms of its usage values is its impact (shock) strength. Statistical values of the shock strength of three wood species under different climatic conditions are given in Table 8.

The impact strength value of each wood sample varies in each climatic condition, the impact strength of hornbeam is lower than the other two wood species, and the impact strength values of beech and alder samples are found to be quite close to each other. In this case, it can be said that beech and alder will show similar dynamic bending behavior against the changes in humidity that will occur in open-air conditions in the places where they are used.

Multiple variance analysis of the impact strength of consecutive on-hold wood species in different climatic conditions is given in Table 9.

According to Table 9, the interaction between wood type and climate condition was significant in terms of its effect on impact strength, while the change in climate condition was not significant. It has been determined that the impact strength is affected mostly by the tree species and then by the climate interaction, and although it is seen that the climate condition affects it at a very low level, it is not statistically significant. In terms of impact strength, it can be said that all three wood types become brittle and weaken against the shock effect in the 40 °C/35% environment, where the temperature increases and relative humidity decreases, and in the 10 °C/50% condition. Although the temperature decreases and the relative humidity increases, the equilibrium humidity remains low, further reducing the impact strength.

It was determined that the impact strength of spruce and pine wood at different temperatures (between -60°C and +20°C) and moisture contents reached the highest energy absorption capacity at -60°C when the moisture content was 12%, whereas at 70% moisture content, the highest energy absorption capacity was observed at +20°C (Kollmann, 1982). In another study,

Table 8. Statistical data on the impact strength of three wood species stored consecutively in different climatic conditions

Wood species	Climate condition	Xmin (kJ/m²)	Xmax (kJ/m²)	Xmean (kJ/m²)	ss.	% Change
Hornbeam	20 °C/65%	24.1	89.1	**56.6**	16.5	-
	40 °C/35%	22.7	73.1	47.5	17.7	-16
	10 °C/50%	28.2	62.2	45.2	21.8	-20
Beech	20 °C/65%	66.8	98.1	**82.4**	14.2	-
	40 °C/35%	34.2	93.4	70.6	23.1	-14
	10 °C/50%	39.2	86.2	68.3	16.2	-17
Alder	20 °C/65%	51.7	80.4	**67.3**	9.8	-
	40 °C/35%	49.4	97.1	64.1	17.8	-4.7
	10 °C/50%	27.3	84.2	51.3	22.4	23.7

Table 9. Multiple variance analysis of impact strengths of wood types under different climatic conditions

Source	Sum of squares	df	Mean of squares	F	(p < 0.05)
Wood type (A)	5756.937	2	2878.468	8.692	0.001
Climate condition (B)	754.960	2	377.480	1.140	0.329
A x B	4693.130	4	1173.282	3.543	0.013
Error	14902.956	45	331.177		
Total	235668.736	54			
Corrected error	26107.982	53			

it was stated that fracture toughness increased as the moisture content decreased (Kretschmann and Green, 1996). In wood material, the moisture content remained almost constant between -30°C and +30°C, but was found to be lower after +60°C and +90°C. Additionally, it was reported that the impact strength decreased as temperature increased between -30°C and +30°C, whereas it remained almost constant between +30°C and +90°C (Baumann et al., 2020). It can be said that the temperatures measured in the present study are partially consistent with the literature and that the obtained results show similarities with those reported in previous studies.

4. Brinell hardness

Table 10 indicates that the hardness of each wood sample varies in three climatic conditions, with beech being the hardest, and the hardness of hornbeam is higher than the other two wood types. Multiple variance analysis of the hardness of consecutively held wood species in different climatic conditions is given in Table 11.

From Table 11, it was determined that the interaction between wood type and climate condition was not significant in terms of its effect on hardness, but the change in wood type and climate condition was significant. Although it was seen that the tree species affected the hardness the most, followed by the climate condition, and the bilateral interaction affected it the least, it was determined that it was not statistically significant. In terms of the effect of climatic conditions, the highest hardness in all three wood types was found in the 40 °C/35% condition, followed by similar values in the other two climatic conditions. It can be assumed that the reason why it is high in the 40 °C/35% climate condition is that the wood dries thoroughly, and the fibrous tissue becomes rigid in high temperatures and decreasing relative humidity.

As the amount of wood substance present within a unit volume of wood increases, the hardness value also increases. Therefore, at a given moisture content, the hardness value increases with the increase in specific gravity of the wood. Furthermore, as the moisture content increases from 0% up to the fiber saturation point, the hardness value decreases, and beyond the fiber saturation point, no significant change occurs (Göker and As, 1991). In the present study, it can be stated that in all three wood species, the hardness values were higher under conditions of high temperature and low relative humidity, and that this was due to the combined effect of temperature and moisture content.

Table 10. Statistical data on Brinell hardness values of three wood types in different climatic conditions

Wood species	Climate condition	Xmin (N/mm²)	Xmax (N/mm²)	Xmean (N/mm²)	ss.	% Change
Hornbeam	20 °C/65%	35.1	56.8	**41.7**	7.6	-
	40 °C/35%	32.1	55.5	47.9	8.5	14.8
	10 °C/50%	38.6	47.6	41.7	3.6	-
Beech	20 °C/65%	24.3	36.9	**29.2**	4.2	-
	40 °C/35%	33.4	44.4	40.6	4.6	39
	10 °C/50%	23.8	34.3	30.1	3.9	-
Alder	20 °C/65%	20.5	29.6	**25.1**	3.6	-
	40 °C/35%	22.2	33.2	27.7	3.5	10.3
	10 °C/50%	19.9	26.2	23.1	2.5	-7.9

Table 11. Multiple variance analysis on Brinell hardness values of consecutively on hold wood types in different climatic conditions

Source	Sum of squares	df	Mean of squares	F	($p < 0.05$)
Wood type (A)	4237.616	2	2118.808	82.060	0.000
Climate condition (B)	665.580	2	332.790	12.889	0.000
A x B	110.707	4	27.677	1.072	0.382
Error	1161.906	45	25.820		
Total	64925.064	54			
Corrected error	6175.810	53			

Conclusions

Hornbeam, oriental beech, and alder woods are known to be widely preferred interchangeably in the manufacturing sector due to their visual similarities and various advantages. However, the following conclusions have been drawn based on the results of this study.

1. In terms of density, hornbeam and beech are in the same group as each other according to the averages of all three climatic conditions (representing the seasonal environment), and they change between 4% and 8% in response to climate change, while alder is in the second group with a density around 20% lower than these. In this case, hornbeam and eastern beech can be used interchangeably, with alder being recommended as the second choice, because they have and are visually similar to each other, and are also in the same group in terms of density.
2. While hornbeam and beech are close to each other and higher in terms of bending strength and elastic modulus according to the averages of all three climatic conditions (representing the seasonal environment), alder is in the second group with 33% lower strength and elasticity values. In this case, hornbeam and beech can be used interchangeably, with alder being recommended as the second choice, as they are very similar in appearance and density and are in the same group in terms of bending strength.
3. In terms of impact (shock) strength, beech wood has the highest impact strength based on the average values of the three different climatic conditions (representing seasonal environment).
4. It was determined that the Brinell hardness value, which is an important indicator of resistance against effects such as scratching and impact, is higher in hornbeam wood compared to beech and alder wood.
5. Considering the mechanical properties of the three wood species studied, it is not recommended to use one of these species as a substitute for another, due to the significant differences between them. However, it is recommended to investigate the mechanical properties if they are to be used in the production of industrial timber, such as Glulam (GL) or Cross-Laminated Timber (CLT), through various structural adhesives.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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