RING WIDTH, PHYSICAL AND MECHANICAL PROPERTIES OF ELDAR PINE (CASE STUDY ON MARZANABAD SITE)

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The present study aims at investigating the variation in average ring width, physical properties (oven-dry density, basic density, volumetric shrinkage, maximum moisture content, percentage of cell wall, percentage of porosity) and mechanical strength (modulus of rupture, modulus of elasticity and compression parallel to the grain) of eldar pine tree wood (*Pinus eldarica Medw*.), cultivated in the north of Iran (Marzanabad site). To carry out the measurements, the test specimens were prepared from three stands and 3 logs at breast height, based on ASTM–D143 standard. The testing samples were cut along radial axis, from pith to bark, to determine annual ring width and physical properties, mature wood being used to measure mechanical strength characteristics. The results showed that oven-dry density, basic density, volumetric shrinkage and percentage of cell wall increased along radial direction from pith to bark, while ring width, maximum moisture content and porosity decreased. The average density at 12% moisture content was of 578.35 kg m^{-3}, the modulus of rupture (MOR) – of 73.77 MPa, modulus of elasticity (MOE) – of 6.73 GPa, and compression parallel to the grain – 43.82 MPa. The relationships between ring width and wood density, and between density at 12% moisture content and mechanical strength properties were determined by regression analyses. Positive relationships were found between density at 12% moisture content and mechanical strength properties, while the annual ring width showed a negative correlation with wood density. Overall, eldar pine trees growing in this site have low wood quality, according to the static quality and reference **p** value (ratio of static bending strength and compression strength parallel to the grain).

Keywords: *Pinus eldarica*, ring width, physical properties, mechanical characteristics

INTRODUCTION

Due to increasing wood consumption and the development of pulp and paper production, plantations of fast-growing tree species, managed in short rotations, have a growing importance for the sustainability of industrial wood raw material. Softwoods, especially fast-growing pine species, have a higher priority for plantation forestry due to their capability of adaptation to a wide range of ecological conditions and various usage areas. Therefore, since 1956, Iranian Parks and Forestry officials have imported approximately 48 foreign fast-growing softwood species into Iran and planted them under different ecological conditions.[1] *Pinus eldarica* is one of the softwood species planted in many parts of Iran, and it has shown good adaptation to environmental conditions. Debazac and Tomasson consider *Pinus eldarica* to be a subspecies of *Pinus brutia*,[2] while Critchfiled and Little consider it as a variety of *Pinus brutia*.[3]

Wood properties have been reported to depend on such factors as climate, origin, ecological conditions, as well as tree part, varying among and within species.[4] Wood properties, such as density and fiber length, determine the end-product quality in industrial processes and are positively correlated with tear strength.[5]

Wood density is one of the most important properties[6] and a commonly used indicator of wood quality and cell size, since it attests timber strength, stiffness, ease of drying, machining, hardness and it is related to tracheid properties, pulp yield and paper-making properties.[7-9] It is affected by the proportion of cell wall material in the wood (cell wall thickness), cell diameter, and chemical content of the wood and hence, it is dependent on the ratio of cell wall thickness and cell diameter.[10,11]

Basic density is closely related to end-use quality parameters, such as pulp yield, structure and timber strength.[12] Indeed, in many conifers, the basic density of the latewood zone is more than twice that of earlywood; thus, any increase in the proportion of latewood inevitably leads to an increase in whole-ring basic density.[7,13] In a study carried out by Kiaei in 2011 on the anatomical, physical and mechanical properties of eldar pine in Kelardashat region, it was found that the wood basic density, wood oven-dry density, fiber length and cell wall thickness increased along the radial axis from pith to bark.[14]

There is an increasing demand for new species from fast-growth plantations as alternative timbers for coniferous wood, but there is little or no information about the wood properties of eldar pine. Thus, the objectives of this study are: a) to investigate the variations of ring width and physical properties along the radial axis, from the pith toward the bark of *Pinus eldarica* grown in the Marzanabad region, b) to examine the mechanical strength properties of *Pinus eldarica*, c) to determine the relationship between annual ring width and wood density, and between wood density and mechanical strength properties in eldar pine growing under fast-growth conditions in Iran.

EXPERIMENTAL

Materials and methods

All the pine trees (*Pinus eldarica Medw*.) were randomly selected, taking into account stem straightness and the absence of obvious decay; pine wood was according to TS 2476, as defect-free, clear, and normally grown (without zone lines, reaction wood, decay, insect damage or fungal infection) wood from a plantation in the north of Iran, Marzanabad region. The experimental area is located at an average altitude of 500 m, and has the following geographical coordinates: 36° 27' N, 51° 18' E. The mean annual rainfall in the experimental area is of about 350 mm/year; the average annual temperature is of 14.4 °C, and prevailing wind direction is northward. The soil is silty clay loam. Three trees were cut from the same site. These trees have been grown for 35 years on the site. The characteristics of the studied eldar pine trees are listed in Table 1.

Physical properties

From each tree, sample logs of 30 cm length were taken at breast height. 25 mm thick rough boards were radially sawn in the four directions of the radius. Then test specimens were cut from these rough boards with the dimensions of 20 × 20 × 20 mm according to ASTM D143-94 used for measuring the oven-dry density, basic density, volumetric shrinkage, maximum moisture content, percentage of cell wall, and percentage of porosity.

The specimens were soaked in distilled water for 72 h to ensure that their moisture content was above the fiber saturation point. Then their dimensions were measured in the three principal directions with a digital caliper to the nearest 0.001 mm. Specimens were weighed to the nearest 0.001 g for saturated weight and the saturated volume was calculated based on these dimension measurements. Finally, the samples were oven-dried at 103 ± 2 °C to 0% moisture content. After cooling in desiccators, the oven-dry weights of the specimens were measured. The values of the wood oven-dry density and basic density, volumetric shrinkage, maximum moisture content, percentage of cell wall, and percentage of porosity were calculated using the following equations:

$D_o = (M_o \div V_o) \times 100$

$D_b = (M_o \div V_s) \times 100$

$\beta_v = (V_s - V_o)/V_s \times 100$

$M_{max} = (1.5 - D_b) \div (1.5 \times D_b)$ (%)

where D_o, M_o, V_o, D_b, V_s, β_v and M_{max} are oven-dry density, dried weight, basic density, dried volume, volumetric shrinkage, saturated volume of the specimen and maximum moisture content, respectively.

$V_c = D_o \div D_c \times 100$

$V_H = 100 - V_c$

where V_c is the percentage of cell wall (%), D_o is oven-dry density (g cm^{-3}), D_c is oven-dry density of the cell wall (1.5 g cm^{-3}) and V_H is percentage of porosity.

Mechanical properties

Sample boards with dimensions of 25 × 25 × 410 mm and 25 × 25 × 100 mm were cut from logs, according to ASTM-D143-94, for measuring static bending (MOR and MOE) and the compression strength parallel to the grain. The specimens were taken from mature wood. The age demarcation point between juvenile and mature wood was estimated at around 25 years.[15]

Following the air-drying process, small and clear specimens were cut from the boards to determine compression parallel to the grain and static bending (modulus of rupture and modulus of elasticity). The prepared samples were then conditioned at the temperature of 20±2 °C and at 65±5% relative humidity until the specimens reached an equilibrium moisture content of about 12%. The load was applied in the tangential direction. The dimensions of the samples were measured with a digital caliper and weights were determined in order to obtain wood density values at 12% moisture content. Then the values of mechanical strength properties were corrected (transformed to 12% moisture content) by using the following strength conversion equation:

$$\delta_{12} = \delta_m \times [1 + \alpha (M_2 - 12)]$$

where δ_{12} is strength at 12% moisture content (N/mm^2), δ_m – strength at moisture content deviated from 12% (N/mm^2), M_2 – moisture content during test (%), α – constant value showing the relationship between strength and moisture content (α = 0.05, 0.04, 0.02) for the compression strength parallel to the grain, modulus of rupture and modulus of elasticity, respectively.

Table 1
Characteristics of studied *Pinus eldarica* trees

Tree No.	Diameter (cm)	Height (m)
1	23.76	13.0
2	27.49	14.0
3	24.34	12.9

Statistical analysis

To determine the effect of cambial age on ring width and the effect of radial direction on the physical properties (oven-dry density, basic density, volumetric shrinkage, maximum moisture content, percentage of cell wall, and percentage of porosity), statistical analysis was conducted using the SPSS programming method in conjunction with the analysis of variance (ANOVA) techniques. Duncan's multiple range test (DMRT) was used to test the statistical significance at α levels of 0.05 and 0.01. A linear regression model was used to analyze the relationship among the various properties of the wood.

RESULTS AND DISCUSSION

Ring width

Table 2 shows the results of the descriptive statistics for the annual ring width of eldar pine wood. The results showed that annual ring width increased rapidly with cambial age up to about 10 years and decreased gradually thereafter (Figure 1). The analysis of variance (ANOVA) indicates that there is a significant difference between annual ring width and cambial age (radial direction from pith to bark) in eldar pine (Table 3).

The average annual ring width of eldar pine has been found to be of 3.31±2.41 mm for this site, which is higher than the annual ring width found for Azadi (2.60 mm), Chitgar (2.75 mm) and Sorkh-Hesar (2.70 mm)[16] and lower than those for Garagpas-Kelardashat (3.68 mm)[14] and Chatan (4.95 mm).[17] A greater variation in the ring width level on different sites is due to the changes in weather conditions (temperature and rainfall) during the growth period. The climate has a significant effect on ring width and on the anatomical characteristics of wood.[18-20] For example, Safdari[16] stated that precipitation in August on 3 different sites had a very positive influence on the ring width of eldar pine trees in Tehran.

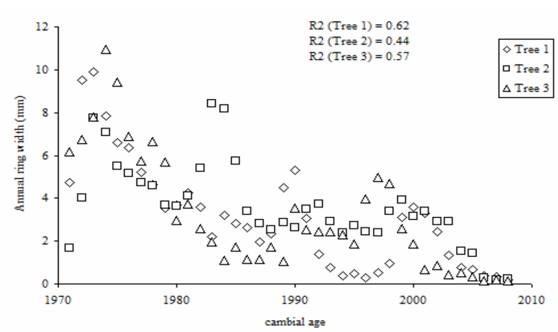


Figure 1: Ring width variation along radial axis (cambial age) in eldar pine

Table 2
Descriptive statistics of annual ring width in eldar pine wood

Wood properties	Mean	Maximum	Minimum	Standard deviation
Ring width (mm)	3.31	10.95	0.12	2.41

Physical properties

Table 4 shows the results of the descriptive statistics for the oven-dry density, basic density and volumetric shrinkage of eldar pine wood. The mean oven-dry density was of 0.471 g cm^{-3}, basic density – of 0.424 g cm^{-3} and volumetric shrinkage – of 9.62% in this material. The oven-dry density, basic density and volumetric shrinkage values increased along the radial axis from pith to bark (Figure 2). The results of statistical analysis indicate that there were significant differences among the physical properties of the samples along the radial axis (Table 5).

Table 3
Analysis of variance (ANOVA) for cambial age (radial axis) and ring width

Ring width	Sum of squares	df	Mean square	F
Among groups	481.821	37	13.022	5.431*
Within groups	182.217	76	2.398	
Total	664.038	113		

*Significant at 0.01; df – degree of freedom

Table 4
Analysis of variance (ANOVA) for physical properties along radial axis

Physical properties		Sum of squares	df	Mean square	F
Oven-dry density	Among groups	0.056	3	0.019	3.555*
	Within groups	0.229	44	0.005	
	Total	0.285	47		
Basic density	Among groups	0.044	3	0.015	3.355*
	Within groups	0.194	44	0.004	
	Total	0.238	47		
Volumetric shrinkage	Among groups	48.475	3	16.158	13.296*
	Within groups	53.471	44	1.215	
	Total	101.947	47		

*Significant at 0.01; df – degree of freedom

Table 5
Average and descriptive statistics of wood density and shrinkage of eldar pine

Along radial axis from pith to bark	Oven-dry density (g cm^{-3})	Basic density (g cm^{-3})	Volume shrinkage (%)
1 (near to pith)	0.415±0.045 [a]	0.378±0.042 [a]	8.31±0.836 [a]
2	0.474±0.072 [ab]	0.420±0.067 [ab]	9.14±1.10 [ab]
3	0.487±0.075 [b]	0.437±0.071 [b]	10.04±1.04 [b]
4 (near to bark)	0.507±0.088 [b]	0.461±0.079 [b]	11.01±1.36 [c]
Descriptive statistics			
Mean	0.471	0.424	9.62
Maximum	0.72	0.66	13.77
Minimum	0.35	0.32	7.12
Standard deviation	0.078	0.071	1.47

The values marked with different letters are significantly different, mean ± standard deviation

Table 6
Comparison of eldar pine physical properties with those of other pine species

Species	Oven-dry density (kg m^{-3})	Volumetric shrinkage (%)
Studied species	471	9.62
P. ponderosa	420	9.7
P. radiata	440	10.7
P. taeda	540	12.3
P. sylvestris	503	-
P. banksiana	460	10.3
P. contorta	430	11.1
P. elliottii	660	12.1

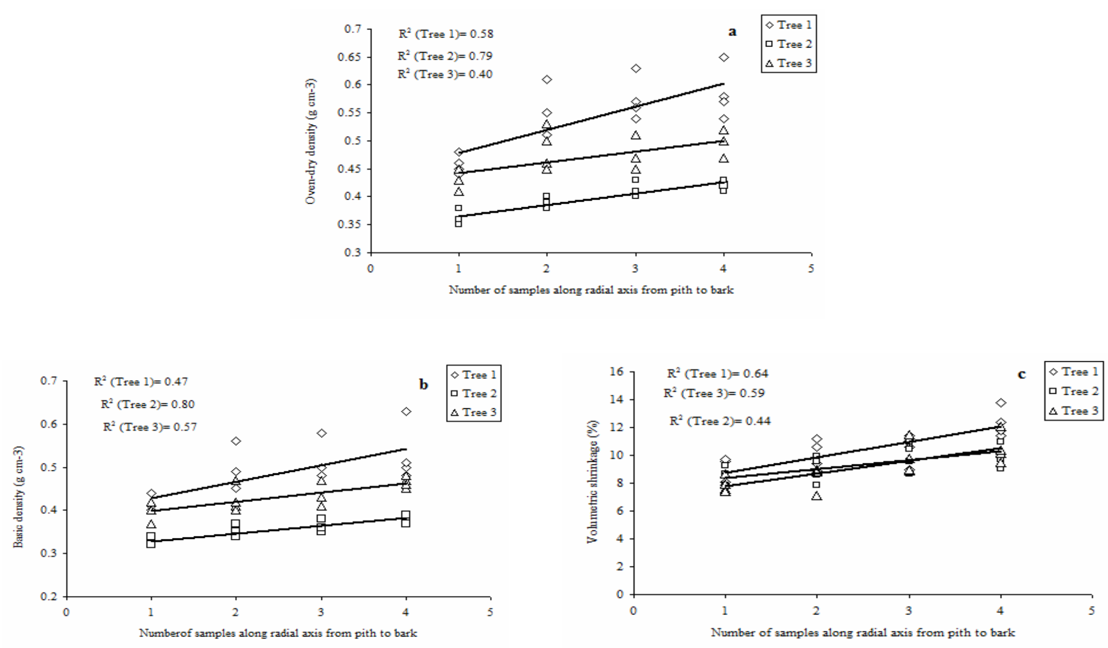


Figure 2: Oven-dry density (a), basic density (b) and volumetric shrinkage (c) variation from pith to bark

Some researchers have reported wood density increases with age or distance from the pith. This is supported by the fact that juvenile wood is usually known to be of a lower density than mature wood, because of few latewood cells. In softwoods and hardwoods, the ultramicroscopic structure, chemical composition, anatomical, physical and mechanical properties of juvenile wood are different from those of mature wood. Earlywood cells found in a high proportion in juvenile wood have a thin wall layer, which is one of the reasons for lower density.[15,20-23] The increase in wood density is due to the increase in cell wall thickness and existence of juvenile wood around the pith during the juvenile period of the tree.

The oven-dry density of eldar pine is 2-12% higher than the density of *P. contorta*, *P. banksiana*, *P. radiate* and *P. ponderosa*, from North America, while it is 5-28% lower than that of *P. sylvestris*, *P. taeda* and *P. elliottii*, from Latvia and North America. The volumetric shrinkage of the studied species is 1-21% lower than the volumetric shrinkage of the other pine trees mentioned (Table 6).[24-25]

Table 7 shows the results of descriptive statistics for the moisture content, percentage of cell wall, percentage of porosity of eldar pine wood. The mean of maximum moisture content was found to be of 175.09%, the cell wall – of 31.30% and percentage of porosity – of 68.69% in this material. The cell wall percentage values increased along the radial axis from pith to bark, while the maximum moisture content and percentage of porosity decreased (Figure 3). The results of statistical analysis indicate that there were significant differences among the mentioned traits of the samples along the radial axis (Table 8). Simpson reported that the maximum moisture content in lumber is important due to its influence in controlling kiln-drying schedules.[26] From a practical standpoint, when determining kiln schedules, the largest number of moisture samples should be selected from the slowest drying materials. In addition, porosity is linearly and inversely related to wood maximum moisture content and wood density, respectively.[27]

The water existing in wood is either bound (in the cell wall) or free (in the cell cavity). As bound water, it is bonded (via secondary or hydrogen bonds) within the wood cell walls. As free water, it is simply present in the cell cavities. When wood dries, most free water separates at a faster rate than bound water due to the higher accessibility and the absence of secondary bonding. The moisture content at which the cell walls are still saturated, but virtually contain no water in the cell cavities, is called the fiber saturation point. The fiber saturation point usually varies between 21 and 28%. The fiber saturation point is calculated by dividing volumetric shrinkage to basic density.[28] In the present study, the fiber saturation point of eldar pine has been found to be of 23.88% for the Marzanabad region.

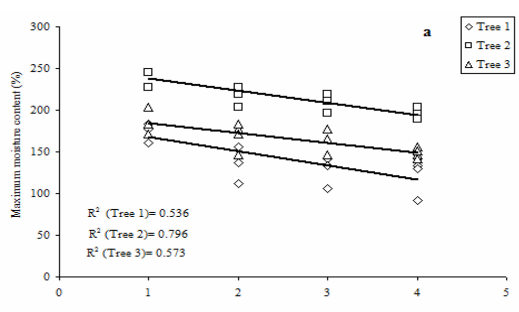
Relationship between wood density and volumetric shrinkage

Regression analysis showed that oven-dry density (R^2 = 0.23) and basic density (R^2 = 0.21) had a significantly positive correlation with volumetric shrinkage (Figure 4, Table 9). It is well known that wood is an anisotropic material, which presents differential dimensional changes in different structural directions. The degree of shrinkage and swelling is affected by the amount of moisture gained or lost by the wood, when the moisture content fluctuates between zero and the fibre saturation point.[29] Kollman and Cote explained that shrinkage differs in three different directions, due to the influence of wood rays and different arrangements of fibrils in cell walls.[30]

Table 7
Average and descriptive statistics of maximum moisture content, percentage of cell wall and porosity of eldar pine

Along radial axis from pith to bark	Maximum moisture content (%)	Percentage of cell wall (%)	Percentage of porosity (%)
1 (near to pith)	200.92±31.70 ^{a}	27.72±4.85 ^{a}	72.27±3.01 ^{b}
2	176.34±37.30 ^{a}	31.61±4.85 ^{b}	68.38±4.85 ^{a}
3	167.24±36.52 ^{ab}	32.44±5.01 ^{b}	67.55±5.01 ^{a}
4 (near to bark)	155.84±33.06 ^{b}	33.44±4.96 ^{b}	66.55±4.96 ^{a}
	Descriptive statistics		
Mean	175.09	31.30	68.69
Maximum	245.83	43.33	76.67
Minimum	92.06	23.33	56.67
Standard deviation	37.55	4.90	4.90

The values marked with different letters are significantly different, mean ± standard deviation



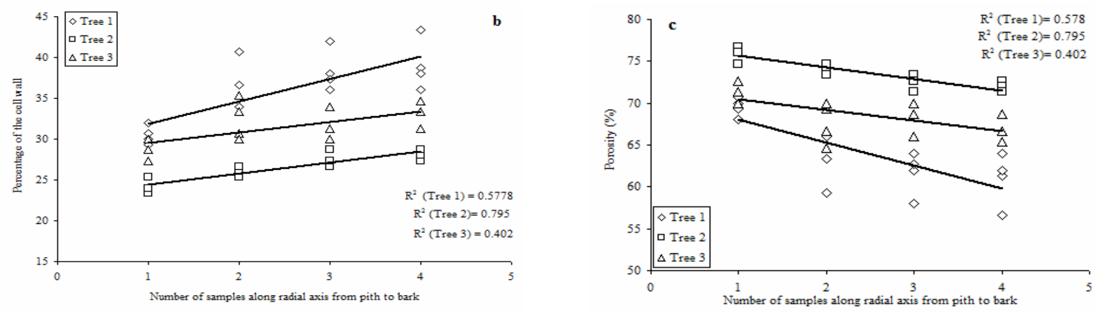


Figure 3: Moisture content (a), cell wall percentage (b) and porosity (c) variation from pith to bark

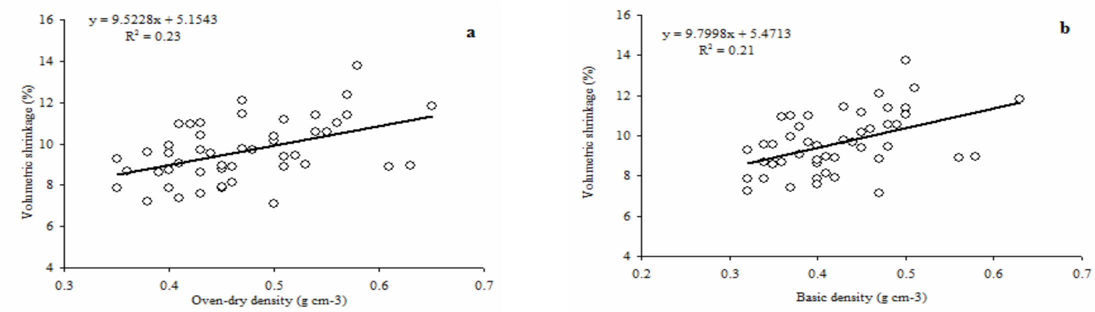


Figure 4: Relationship between wood density and volumetric shrinkage in eldar pine (a, b)

Table 8
Analysis of variance (ANOVA) for moisture content, cell wall and porosity along radial axis

Properties		Sum of squares	df	Mean square	F
Maximum moisture content (%)	Among groups	13215.203	3	4405.068	3.652*
	Within groups	53069.384	44	1206.122	
	Total	66284.587	47		
Cell wall (%)	Among groups	225.667	3	75.222	3.650*
	Within groups	906.741	44	20.608	
	Total	1132.407	47		
Porosity (%)	Among groups	225.667	3	75.222	3.650*
	Within groups	906.741	44	20.608	
	Total	1132.407	47		

*Significant at 0.05; df – degree of freedom

Table 9
Analysis of variance (ANOVA) for the relationship between wood density and volumetric shrinkage

Relationship		Sum of squares	df	Mean square	R^2	F
Oven-dry density and volumetric shrinkage	Regression	23.354	1	23.354	0.23	13.669*
	Residual	78.593	46	1.709		
	Total	101.947	47			
Relationship		Sum of squares	df	Mean square	R^2	F
Basic density and volumetric shrinkage	Regression	21.633	1	21.633	0.21	12.390*
	Residual	80.314	46	1.746		
	Total	101.947	47			

*Significant at 0.01; df – degree of freedom

The volumetric shrinkage and swelling properties are affected by several wood factors, such as the heartwood to sapwood ratio or the fibrillar angle on the S_2 layer.[31] However, the most important parameter affecting wood shrinkage is wood density.[32]

Relationship between ring width and wood density

Regression analysis showed that there is a negative relationship between ring width and oven-dry density (R^2 = 0.644) or basic density (R^2 = 0.632) in eldar pine wood (Figure 5, Table 10). In conifers, increased growth rate usually leads to a greater increase in earlywood (low density) than in latewood (high density). It is generally believed that a rapid growth rate results in low density and lower mechanical properties in softwood.[33,34]

Mechanical properties

The average mechanical properties of eldar pine wood are listed in Table 11. The average density of the test samples (at 12% moisture content) was of 578.35 kg m^{-3}, modulus of rupture – of 73.77 MPa, modulus of elasticity – of 6.73 GPa, and compression parallel to the grain – of 43.82 MPa in mature wood. The relationships between wood density at 12% moisture content and mechanical strength properties are shown in Figure 6 and Table 12. These results indicate that the wood density of the test sample presented a strong correlation with strength properties. Overall, MOE had a weaker correlation (R^2 = 0.367) with density than the modulus of rupture (R^2 = 0.575) and the compression parallel to the grain (R^2 = 0.467).

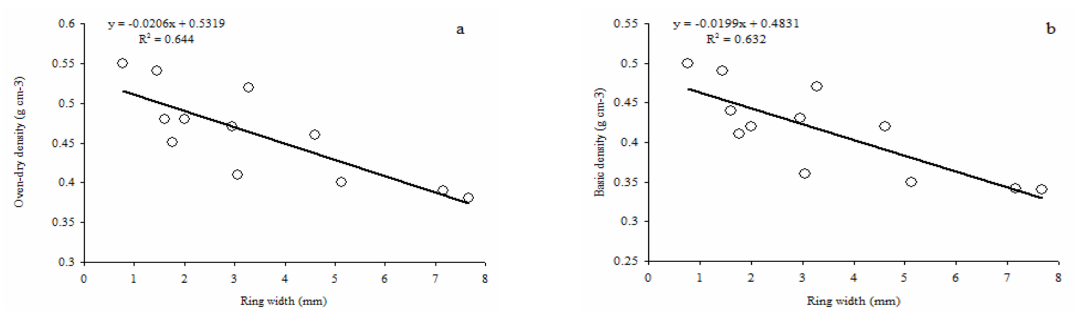


Figure 5: Relationship between ring width and oven-dry density (a), and between ring width and basic density (b) in eldar pine

Table 10
Analysis of variance (ANOVA) for the relationships between ring width and wood density in eldar pine

Relationship		Sum of squares	df	Mean square	R^2	F
Ring width and oven-dry density	Regression	0.024	1	0.024	0.644	18.092*
	Residual	0.013	10	0.001		
	Total	0.036	11			
Relationship		Sum of squares	df	Mean square	R^2	F
Ring width and wood basic density	Regression	0.022	1	0.022	0.632	17.190*
	Residual	0.013	10	0.001		
	Total	0.035	11			

*Significant at 0.01; df – degree of freedom

Table 11
Average and descriptive statistics of mechanical properties of eldar pine

Mechanical properties	Density at 12% moisture content (Kg m^{-3})	MOR (MPa)	MOE (GPa)	Compression strength parallel to grain (MPa)
Mean	578.35	73.77	6.73	43.82
Maximum	714.82	119	10	65.15
Minimum	437.44	36	4.60	23.19
Standard deviation	76.33	17.46	1.29	11.33

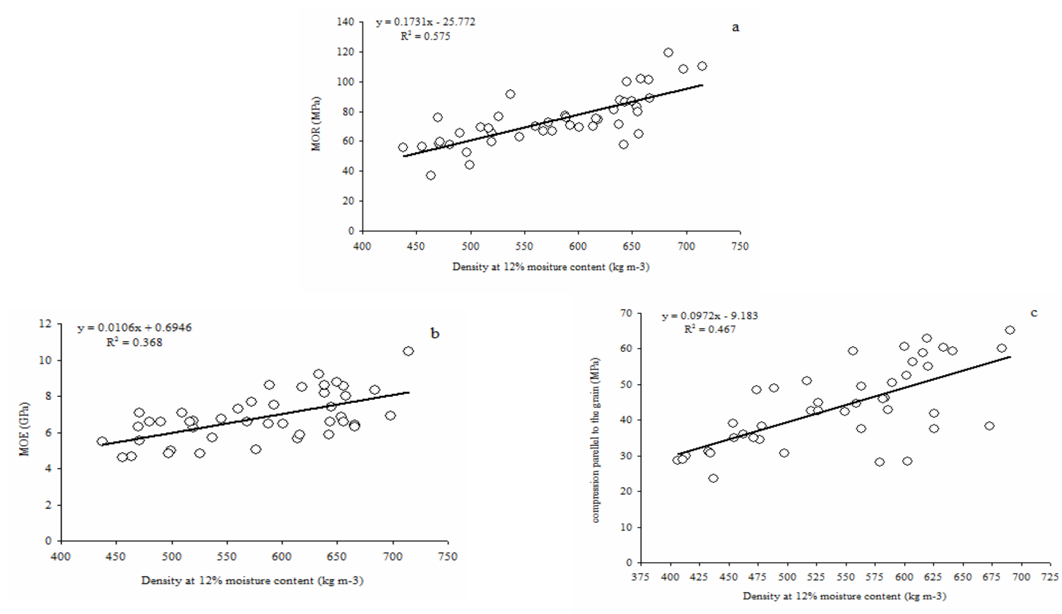


Figure 6: Relationship between density at 12% moisture content and modulus of rupture (a), modulus of elasticity (b), compression strength parallel to the grain (c) in eldar pine

Table 12
Analysis of variance (ANOVA) for the relationship between density at 12% moisture content and mechanical properties

Relationship		Sum of squares	df	Mean square	R^2	F
Density at 12% moisture content and MOR	Regression	7558.323	1	7558.323	0.575	57.184*
	Residual	5551.404	42	132.176		
	Total	13109.727	43			
Relationship		Sum of squares	df	Mean square	R^2	F
Density at 12% moisture content and MOE	Regression	26.335	1	26.335	0.368	24.340*
	Residual	45.444	42	1.082		
	Total	71.779	43			
Relationship		Sum of squares	df	Mean square	R^2	F
Density at 12% moisture content and compression strength parallel to the grain	Regression	2522.291	1	2522.291	0.467	35.994*
	Residual	2873.098	41	70.076		
	Total	5395.389	42			

*Significant at 0.01; df – degree of freedom

The modulus of rupture (MOR) and modulus of elasticity (MOE) are important properties for the use of wood as a structural material. MOR is an indication of the bending strength of a board or structural elements, and MOE is an indication of stiffness. The correlation of MOR and MOE with wood density or specific gravity is typically very strong, as reported by Shepard and Shottafer,[35] Shottafer *et al*.[36] for red pine, and by Wolcott[37] for red spruce. However, in some coniferous species, such as *Abies fabric* and *Picea asperata*, the relationship of MOE and specific gravity is weaker than the relationship between MOR and specific gravity.[38] This was also found to be true for fast-growing eldar pine (*Pinus eldarica*).

Softwoods, including eldar pine, can be classified according to static quality values (ratio of compression strength parallel to the grain and 100 × wood density at 12% moisture content) – below 8 is low quality, between 8 and 9.5 is fair quality, and above 9.5 is good quality.[39] The static quality value of the studied eldar pine (7.67) is lower than that obtained for the Kelardashat site (9.56).[14]

Generally, the **p** value (ratio of static bending strength and compression strength parallel to the grain) is accepted as 1.75.[39] The **p** value calculated for eldar pine is of 1.68, that is lower than 1.75. Therefore, eldar pine trees growing on this site do not present good quality wood, compared to the reference **p** value (1.75). Overall, the wood quality of eldar pine on the studied site ranges between very poor and low.

CONCLUSIONS

In this study, the ring width, physical and mechanical properties of eldar pine wood (*Pinus eldarica Medw*.) grown in the Marzanabad region were determined, leading to the following conclusions:

1) A significant difference in ring width, wood density and volumetric shrinkage is observed along the radial axis from pith to bark – wood density and volumetric shrinkage increase, while the value of ring width decreases. Significant positive relationships have been found between wood density and volumetric shrinkage in eldar pine.

2) Significant negative relationships have been found between wood density and ring width in eldar pine.

3) Strong positive relations have been observed between wood density at 12% moisture content and mechanical strength properties, while the relation between the density of the test samples and the modulus of elasticity (MOE) was weak.

4) The wood of eldar pine trees does not present a sufficiently high quality, as to the static index and **p** value, which makes it unsuitable for applications as structural elements.

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