SITE VARIATION OF TRACHEID FEATURES AND STATIC BENDING PROPERTIES IN *PINUS ELDARICA* WOOD

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Tracheid dimension (tracheid length, tracheid diameter, cell wall thickness, and lumen diameter), morphology properties (Runkel index, flexibility ratio, slenderness coefficient) and mechanical strength properties (modulus of rupture and modulus of elasticity) variations of *Pinus eldarica* wood (eldar pine) were determined on three sites with different soil fertility in Iran. Nine normal trees of pine wood were selected from three different sites in the western part of the Mazandaran region: Benafshde site (site 1), Kelardashat site (site 2) and Marzanabad site (site 3). Logs and discs were cut at breast height. Wood specimens were taken along radial direction from the pith to the bark (six distances from pith) to determine tracheid features and from mature wood to determine static bending properties. The analysis of variance indicated that site, radial direction and interactions between site and radial position had a significant effect on tracheid dimensions and morphology properties. In addition, the effect of site was significant on modulus of elasticity (MOE) and modulus of rupture (MOR) in mature wood. The highest of tracheid length, tracheid diameter, lumen diameter, flexibility coefficients, MOE and MOR were found on site 2, the highest of cell-wall thickness and Runkel were found on site 3, and the highest of slenderness coefficients were found on site 1. Variations of tracheid length, cell wall thickness, slenderness coefficients and Runkel coefficients increased along radial direction from the pith to the bark, while the flexibility coefficients decreased. A rapid increase of tracheid diameter and lumen diameter was observed from the pith to about 60% of radial direction, and it decreases up to the bark in eldar pine wood. Results based on the morphological properties analysis indicated that the fibers obtained from three different sites are suitable for paper production.

Keywords: *Pinus eldarica*, tracheid dimension, static bending strength

INTRODUCTION

Parks and Forestry officials have imported approximately 48 foreign fast-growing softwood species into Iran since 1956 and planted them in different ecological conditions.[1] *Pinus eldarica* Medw. was one of the softwood species planted in many parts of Iran, and it has shown good adaptation to environmental conditions.

The anatomical structure of secondary xylem is composed of different types of woody cells (vessel, fiber (tracheid) and radial and axial parenchyma), whose origins are in vascular cambium.[2] During their formation, these cells are affected by many factors, such as site, ecological conditions, management, genetics, and age for trees growing under plantation conditions.[3] The anatomical features are modified within trees during their growth in order to adjust to physiological and water stress.[4,5]

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 member, and MOE is an indication of stiffness. The prediction of MOR and MOE in bending with specific gravity is usually found for some species. For example, Zhang reports a linear equation ($y = a + bx$) for 16 hardwood and softwood species.[6]

There is plenty of information on physical,[7] chemical[8] and mechanical properties,[7] pulp and paper production,[8] the effect of air pollution on tree-ring width,[9] heavy metal levels in bark pine[10] and anatomical properties[11] of *Pinus eldarica* trees, while data on the relationship between site variation and wood properties are not available for the studied species. In line with the abovementioned studies, we investigated: (a) the influence of site variation on the tracheid features and strength properties, and (b) the relationship between the different properties of *Pinus eldarica* Medw. wood by linear regression.

EXPERIMENTAL

Materials

Sites

Pinus eldarica Medw. plantation trees located on three sites in the Western part of the Mazandaran province in the North of Iran were sampled: Benafeshde (site 1), Kelardashat (site 2) and Marzanabad (site 3). The environmental and ecological characteristics of the sites and plantation conditions are shown in Table 1. The soil conditions (natural soil) vary from site to site.

Sampled trees

Nine normal (3 trees per site) were randomly selected from each plantation. Logs and discs were cut down at breast height from each tree. Selected trees with straight trunks, normal branching and no disease or pest symptoms were felled. From each selected tree, a cross-section was extracted at a diameter at breast height (dbh) and a log from the tree base to dbh.

Methods

Tracheid features

Wood samples for testing were taken along the radial direction from the pith to the bark (six positions from pith at 15, 30, 45, 60, 75, 90%) in the northern part of the trees to determine tracheid features (3 sites x 3 trees x 6 positions in radial direction = 54 samples). Tracheid features comprise length, diameter, cell wall thickness, lumen diameter, flexibility coefficients, slenderness index, and Runkel ratio. Specimens for measuring tracheid dimensions were macerated in a mixture (1:1) of 30% hydrogen peroxide and glacial acid in a 64 °C oven for 24 hours.[12] After maceration, the samples were washed with distilled water. The tracheid dimensions were determined by Leica Image Analysis System. For this test, it was necessary to measure 20 tracheid dimensions per sub-samples. The calculations of Runkel ratio (2*cell wall thickness/lumen diameter × 100), coefficient of flexibility (lumen diameter/tracheid length × 100), and slenderness ratio (tracheid length/tracheid diameter) were carried out using the measured data.

Table 1
Ecological characteristics of sampled sites

Sites		Site 1	Site 2	Site 3
Altitude (m)		1300	1100	500
Temperature (°C)		10	10	14
Rainfall (mm)		350	500	500
Age (year)		33-35	35-36	36-38
Height (m)		11.5	15.6	13.4
Soil type		Clay-loam	Clay	Silty-clay-loam
Soil physical and chemical properties	pH	6.86	6.38	7.33
	Clay (%)	37	47	45
	Silt (%)	37	34	41
	Sand (%)	26	19	14
	Mn* (ppm)	16.36	19.85	13.7
	Fe (ppm)	18.36	29.03	6.09
	Zn (ppm)	1.46	1.45	3.18
	P (ppm)	7.53	5.8	1.4
	K (ppm)	275	300	640
	N (%)	0.292	0.224	0.374

*Soil nutrients, such as manganese (Mn), iron (Fe), zinc (Zn), phosphorus (P), potassium (K) and nitrogen (N)

Static bending

Only static bending (mechanical property) was determined and evaluated for mature wood only, as it is more stable than juvenile wood, as regards mechanical properties.[3] Previous research established that the age demarcation point between juvenile and mature wood is estimated at around 24 years.[13] 15 samples were extracted from the mature wood zone of each sampled tree for determining static bending (3 sites x 3 trees x 15 samples = 135 samples). Their dimensions were 2.5 × 2.5 × 45 cm, according to ASTM-D143 (second method). The mature wood zone of each tree was limited in thickness, therefore the radial variation of mechanical properties was not determined. The prepared samples were then conditioned in a room at a temperature of 20 °C and 65

± 5% relative humidity, until the specimens reached an equilibrium moisture content of about 12%. The load was applied in the tangential direction. The static bending strength properties were calculated using the following equations:

$$MOR = 3 \times Pmax \times l / 2 \times b \times h^2$$

$$MOE = P \times l^3 / 4 \times D \times b \times h^3$$

where P = load at the limit of proportionality (Kg); Pmax = maximum load (Kg), l = span of the test specimen (cm), b = width of the test specimen (cm), h = depth of the test specimen (cm) and D = deflection at the limit of proportionality (cm). Then strength values 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} = strength at 12% moisture content, δ_m = strength at moisture content deviated from 12%, α = constant value showing the relationship between strength and moisture content (α = 0.04, 0.02 for modulus of rupture and modulus of elasticity, respectively), M_2 = moisture content during test.

Statistical analysis

The total of the samples for measuring tracheid features was 52 (3 sites x 3 trees x 6 positions in radial direction) and for static bending – 45. The statistical significance of the differences in the wood properties among the sites and radial positions was determined by an analysis of variance by the statistical program SPSS 18. Where statistical differences occurred, the means were compared using Duncan's test. Linear regression analysis (y = xa + b + error) was used to determine the relationships between wood density at 12% in moisture content and static bending strength with tracheid features. The results for the tracheid dimensions (in 24-year old mature wood) were averaged for each tree and their average was correlated with the average for the mechanical properties of each tree.

RESULTS AND DISCUSSION

Tracheid length

The variation of tracheid length in pine wood in radial direction from the pith to the bark (six distances from pith) for the three different sites is shown in Table 2. The analysis of variance indicated that the site, radial direction and their interaction had a significant effect on tracheid length (Table 3). The highest and the lowest values of tracheid length were found on site 2 (2.89 mm) and site 1 (2.54 mm), respectively. The tracheid length values increased along the radial axis from the pith to the bark in pine wood.

Tracheid diameter

The variation of tracheid diameter in pine wood along radial direction from the pith to the bark (six distances from pith) for three different sites is shown in Table 4. The analysis of variance indicated that the site, radial direction and their interaction had a significant effect on tracheid diameter (Table 5). The highest and the lowest values of tracheid diameter were found on site 2 (46.76 µm) and site 1 (34.91 µm), respectively. A rapid increase of tracheid diameter was observed from the pith to about 60% of radial direction, and it decreased to the bark in eldar pine wood.

Table 2
Radial variation of tracheid length for three different sites

Radial direction (%)	Site 1	Site 2	Site 3	Mean
15	1.91 (0.209)	1.85 (0.491)	1.83 (0.469)	1.86 a
30	2.27 (0.199)	2.09 (0.477)	2.31 (0.295)	2.26 b
45	2.36 (0.140)	2.47 (0.517)	2.24 (0.361)	2.35 c
60	2.62 (0.208)	3.10 (0.480)	2.39 (0.293)	2.70 d
75	2.58 (0.195)	3.47 (0.613)	3.69 (0.196)	3.25 e
90	3.53 (0.673)	3.83 (0.529)	3.47 (0.567)	3.61 f
Mean	2.54 A	2.89 C	2.65 B	2.69

Capital letters show differences between sites and lowercase letters show differences in radial position

Cell wall thickness

The variation of cell wall thickness in pine wood along radial direction from the pith to the bark (six distances from pith) for three different sites is shown in Table 6. The analysis of variance indicated that the site, radial direction and their interaction had a significant effect on cell wall thickness (Table 7). The highest and the lowest values of cell wall thickness were found on site 3 (5.99 µm) and site 1 (4.605 µm), respectively. The cell wall thickness values increased along radial axis from the pith to the bark in pine wood.

Lumen diameter

The variation of lumen diameter in pine wood along radial direction from the pith to the bark (six distances from pith) for three different sites is shown in Table 8. The analysis of variance indicated that the site, radial direction and their interaction had a significant effect on lumen diameter (Table 9). The highest and the lowest values of lumen diameter were found on site 2 (35.93 µm) and site 3 (24.51 µm), respectively. A rapid increase of lumen diameter was observed from the pith to about 60% of radial direction, and it decreased to the bark in eldar pine wood.

Table 3
Analysis of variance for tracheid length in three sites

Source	Sum of squares	Df	Mean square	F
Site (A)	12.039	2	6.020	34.399*
Radial (B)	391.486	5	78.297	447.429*
A×B	53.833	10	5.383	30.763*
Error	185.843	1062	0.175	
Total	8351.220	1080		
Corrected total	643.201	1079		

R square = 0.711 (adjusted R square = 0.706), *significant at 99%

Table 4
Radial variation of tracheid diameter for three different sites

Radial direction (%)	Site 1	Site 2	Site 3	Mean
15	31.15 (8.61)	42.98 (9.70)	28.77 (7.90)	34.30 a
30	36.96 (9.73)	47.10 (9.68)	31.65 (5.01)	38.98 b
45	34.62 (4.89)	49.63 (11.82)	34.89 (5.66)	39.71 b
60	42.21 (11.86)	51.83 (9.87)	36.24 (4.40)	43.43 c
75	34.23 (10.26)	44.98 (12.50)	42.34 (12.17)	40.52 b
90	30.30 (8.12)	43.91 (8.70)	43.91 (10.45)	39.30 b
Mean	34.91 A	46.76 C	36.43 B	39.36

Capital letters show differences between sites and lowercase letters show differences in radial position

Table 5
Analysis of variance for tracheid diameter in three sites

Source	Sum of squares	Df	Mean square	F
Site (A)	29810.130	2	14905.065	170.847*
Radial (B)	7950.440	5	1590.088	18.226*
A×B	11526.482	10	1152.648	13.212*
Error	91517.004	1049	87.242	
Total	1795404.774	1067		
Corrected total	140623.070	1066		

R square = 0.349 (adjusted R square = 0.339), *significant at 99%

Table 6
Radial variation of cell wall thickness for three different sites

Radial direction (%)	Site 1	Site 2	Site 3	Mean
15	4.11 (1.485)	4.225 (1.355)	4.12 (1.495)	4.15 a
30	4.235 (1.07)	5.3 (1.575)	6.43 (2.065)	5.235 b
45	4.57 (2.05)	5.085 (1.71)	6.805 (3.44)	5.49 b
60	4.58 (1.74)	4.655 (2.49)	4.485 (2.46)	4.575 a
75	5.115 (0.945)	5.905 (2.68)	6.85 (2.805)	5.955 c
90	5.035 (2.185)	7.405 (3.305)	7.33 (2.65)	6.575 d
Mean	4.605 A	5.415 B	5.99 C	5.335

Capital letters show differences between sites and lowercase letters show differences in radial position

Table 7
Analysis of variance of cell wall thickness in three sites

Source	Sum of squares	df	Mean square	F
Site (A)	1392.105	2	696.053	35.950*
Radial (B)	2832.250	5	566.450	29.256*
A×B	1039.122	10	103.912	5.367*
Error	20252.285	1046	19.362	
Total	146375.528	1064		
Corrected total	25467.612	1063		

R square = 0.205 (adjusted R square = 0.192), *significant at 99%

Table 8
Radial variation of lumen diameter for three different sites

Radial direction (%)	Site 1	Site 2	Site 3	Mean
15	22.92 (7.41)	34.52 (10.26)	20.53 (7.81)	25.99 a
30	28.49 (8.41)	36.50 (10.33)	18.87 (4.45)	28.66 b
45	25.47 (7.40)	39.45 (12.53)	21.27 (6.25)	28.73 b
60	33.05 (12.66)	42.51 (10.86)	27.26 (6.03)	34.28 c
75	24.00 (10.79)	33.17 (11.79)	28.64 (11.94)	28.60 b
90	20.23 (6.99)	29.10 (10.94)	29.25 (9.80)	26.14 a
Mean	25.69A	35.93B	24.51A	28.71

Capital letters show differences between sites and lowercase letters show differences in radial position

Table 9
Analysis of variance for lumen diameter in three sites

Source	Sum of squares	df	Mean square	F
Site (A)	28275.501	2	14137.751	153.095*
Radial (B)	8117.217	5	1623.443	17.580*
A×B	10658.567	10	1065.857	11.542*
Error	96594.056	1046	92.346	
Total	1022538.508	1064		
Corrected total	143264.023	1063		

R square = 0.326 (adjusted R square = 0.315), *significant at 99%

Slenderness coefficients

The variation of slenderness coefficients in pine wood along radial direction from the pith to the bark (six distances from pith) for three different sites is shown in Table 10. The analysis of variance indicated that the site, radial direction and their interaction had a significant effect on slenderness coefficients (Table 11). The highest and the lowest values of slenderness coefficients were found on site 1 (78.55) and site 2 (64.02), respectively. The slenderness coefficients increased along radial axis from the pith to the bark in pine wood.

Flexibility coefficients

The variation of flexibility coefficients in pine wood along radial direction (six distances from pith) from the pith to the bark for three different sites is shown in Table 12. The analysis of variance indicated that the site, radial direction and their interaction had a significant effect on flexibility coefficients (Table 13). The highest and the lowest values of flexibility coefficients were found on site 2 (75.50%) and site 1 (66.75%), respectively. The tracheid length values decreased along radial axis from the pith to the bark in pine wood.

Runkel coefficients

Th variation of Runkel coefficients in pine wood along radial direction (six distances from pith) from the pith to the bark for three different sites is shown in Table 14. The analysis of variance indicated that the site, radial direction and interaction effects between site and radial position had significant on Runkel coefficients (Table 15). The highest and lowest values of Runkel coefficients were found on site 3 (57.79%) and site 2 (38.05%), respectively. The Runkel coefficients values increased along radial axis from the pith to the bark in pine wood.

Table 10
Radial variation of slenderness coefficients for three different sites

Radial direction (%)	Site 1	Site 2	Site 3	Mean
15	66.34 (19.91)	44.52 (13.39)	67.93 (25)	59.59 a
30	66.34 (20.62)	46.98 (17.35)	74.93 (18.62)	61.80 ab
45	69.79 (11.34)	53.56 (18.83)	65.70 (13.68)	63.02 ab
60	68.02 (23.07)	62.79 (18.13)	66.79 (10.53)	65.87 b
75	81.09 (20.48)	86.78 (23.14)	95.16 (28.76)	87.68 c
90	119.72 (21.71)	90.83 (18.38)	85.71 (33.81)	98.89 b
Mean	78.55 B	64.02 A	76.08 B	72.88

Capital letters show differences between sites and lowercase letters show differences in radial position

Table 11
Analysis of variance of slenderness coefficients in three sites

Source	Sum of squares	df	Mean square	F
Site (A)	41619.616	2	20809.808	41.998*
Radial (B)	232878.345	5	46575.669	93.999*
A×B	57751.640	10	5775.164	11.655*
Error	518282.728	1046	495.490	
Total	6505161.335	1064		
Corrected total	854744.322	1063		

R square = 0.394 (adjusted R square = 0.384), *significant at 99%

Table 12
Radial variation of flexibility coefficients for three different sites

Radial direction (%)	Site 1	Site 2	Site 3	Mean
15	73.00 (8.00)	79.15 (8.99)	70.30 (10.51)	74.15 d
30	76.62 (4.48)	76.12 (9.63)	59.60 (11.11)	71.65 c
45	72.51 (14.06)	78.00 (9.51)	61.71 (15.93)	70.74 bc
60	75.75 (14.41)	81.36 (10.25)	75.22 (13.32)	77.45 e
75	67.73 (9.14)	72.74 (12.03)	66.09 (12.29)	68.85 b
90	66.77 (12.05)	65.14 (16.20)	66.04 (11.62)	66.01 a
Mean	72.06 B	75.50 C	66.75 A	71.43

Capital letters show differences between sites and lowercase letters show differences in radial position

Table 13
Analysis of variance of flexibility coefficients in three sites

Source	Sum of squares	df	Mean square	F
Site (A)	14199.311	2	7099.655	52.292*
Radial (B)	14443.068	5	2888.614	21.276*
A×B	9586.597	10	958.660	7.061*
Error	142016.080	1046	135.771	
Total	5617448.772	1064		
Corrected total	179487.928	1063		

R square = 0.209 (adjusted R square = 0.196), *significant at 99%

Table 14
Radial variation of Runkel coefficients for three different sites

Radial direction (%)	Site 1	Site 2	Site 3	Mean
15	38.53 (14.97)	28.18 (12.45)	45.53 (22.78)	37.41 ab
30	30.95 (7.88)	33.88 (17.75)	74.35 (36.79)	44.22 bc
45	44.65 (36.18)	30.50 (16.75)	76.91 (35.23)	50.69 c
60	38.35 (10.23)	25.52 (14.32)	38.14 (30.31)	34.00 a
75	50.09 (18.68)	41.86 (27.78)	57.40 (35.00)	49.78 c
90	55.60 (28.34)	69.98 (73.03)	58.02 (41.47)	61.56 d
Mean	43.03 A	38.05 A	57.79 B	46.29

Capital letters show differences between sites and lowercase letters show differences in radial position

Table 15
Analysis of variance of Runkel coefficients on three sites

Source	Sum of squares	df	Mean square	F
Site (A)	76864.956	2	38432.478	32.97*
Radial (B)	86313.042	5	17262.608	14.810*
A × B	84540.425	10	8454.043	7.253*
Error	1219247.130	1046	1165.628	
Total	3731903.587	1064		
Corrected total	1462858.860	1063		

R square = 0.167 (adjusted R square = 0.153), *significant at 99%

Static bending strength

The average values and the coefficient of variation for static bending strength (MOE and MOE) and wood density at 12% moisture content are shown in Table 16. The analysis of variance indicated that the location had a significant effect on the static bending strength properties (MOR and MOE) and wood density at 12% moisture content. The values of modulus of elasticity and modulus of rupture on site 2 were higher than on other sites, however a statistical difference was found with site 1, where the lowest values of modulus of elasticity and modulus of rupture were found. There were no significant differences between site 2 and site 3 in MOR, MOE and wood density at 12% moisture content. According to these results, there is an increasing trend in the strength properties of wood with increasing wood density at 12% moisture content. The relationship between wood density and MOE is stronger than the relationship between wood density and MOR (Figure 1).

Relationship between tracheid dimensions and static bending

Although we studied only nine trees, a relationship was found between tracheid dimensions and static bending (MOR and MOE), its linear regression being shown in Figures 2 and 3. The results indicate that there are positive and strong relationships between tracheid features and static mechanical properties (MOR and MOE). The weakest and the strongest relationships between MOE and tracheid features were found with lumen diameter (R^2 = 0.547) and tracheid length (R^2 = 0.684), respectively. The strongest and the weakest relationships between MOR and tracheid features were found with tracheid diameter (R^2 = 0.80) and tracheid length (R^2 = 0.47), respectively.

Relationship between wood density and tracheid dimensions

Although we studied only nine trees, a relationship was found between wood density at 12% moisture content and tracheid dimensions, its linear regression being shown in Figure 4. The results indicate that there are positive relationships between wood density and tracheid properties. The weakest and strongest relationships between wood density and tracheid features were found with cell wall thickness (R^2 = 0.44) and lumen diameter (R^2 = 0.14), respectively. The correlation coefficients between wood density with tracheid length and tracheid diameter were determined as 0.39 and 0.28, respectively. Tracheid features represent one of the important indexes for paper production is. For pulp and paper production, species with higher lengths are preferred, resulting in a higher resistance of the paper. This feature was observed in the ring samples situated near the bark of trees, where there tended to be higher tracheid length compared to the ring samples situated near the tree pith. *P. eldarica* trees have more pronounced tracheid features as they get older.

Table 16
Average mechanical properties of *Pinus eldarica* wood growing in three sites

Mechanical properties	MOR (Kg cm^{-2})	MOE (Kg cm^{-2})	Wood density at 12%
Site 1	639^{A} (37)	48508^{A} (35)	0.49^{A} (7.5)
Site 2	836^{B} (28)	72142^{B} (26)	0.55^{B} (9.1)
Site 3	761^{B} (23)	67101^{B} (21)	0.57^{B} (13.2)
Mean	745 (31)	62480 (31)	0.54 (12.6)

The values in parenthesis represent the coefficient of variation and capital letters express statistical difference at 99%

This is a result of the many molecular and physiological changes that occur in the vascular cambium during the aging process.[2] The cells produced in the primary xylem divide less frequently, thus allowing more time for the fusiform initial section to elongate longitudinally and transversally.[14] This behavior is similar to the behavior described and observed by several authors, such as Zobel and van Buijtenen,[3] Kiaei,[15] Hashemi and Kord[16] and Ferreira *et al.*[17]
A study on the variations of the tracheid dimensions of pine wood (*Pinus eldarica* Medw.) from the Golestan-Iran plantation indicated that the tracheid length and cell wall thickness increased from the pith toward the bark.[11]
There is significant variation in tracheid dimensions in eldar pine wood depending on site conditions. In general, such differences might be attributed to ecological factors, such as growth conditions and soil properties, which can affect wood properties. A similar trend has been reported by Bektas *et al.*, Koizumi *et al.* and Raiskila *et al.* for different softwood species.[18,19,20] The tracheid length of eldar pine wood on site 2 was found higher than those for sites 1 and 3.

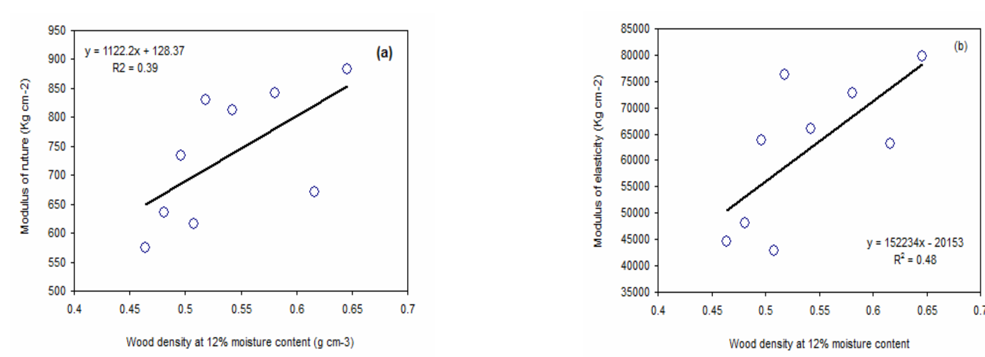
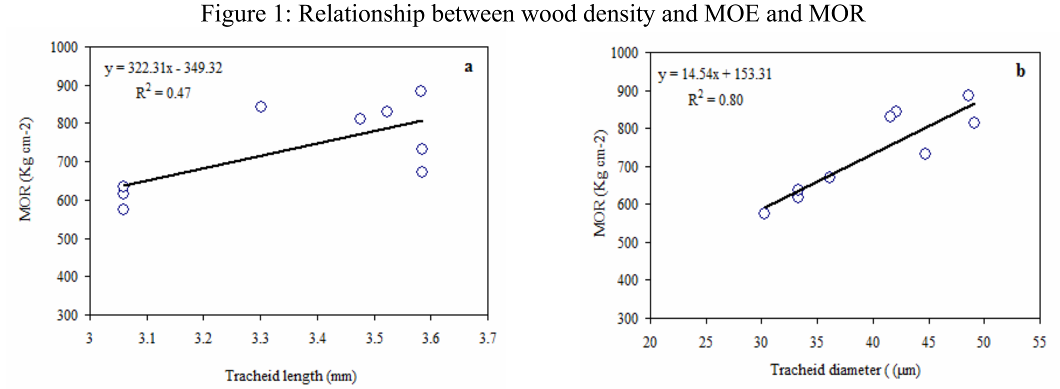


Figure 1: Relationship between wood density and MOE and MOR



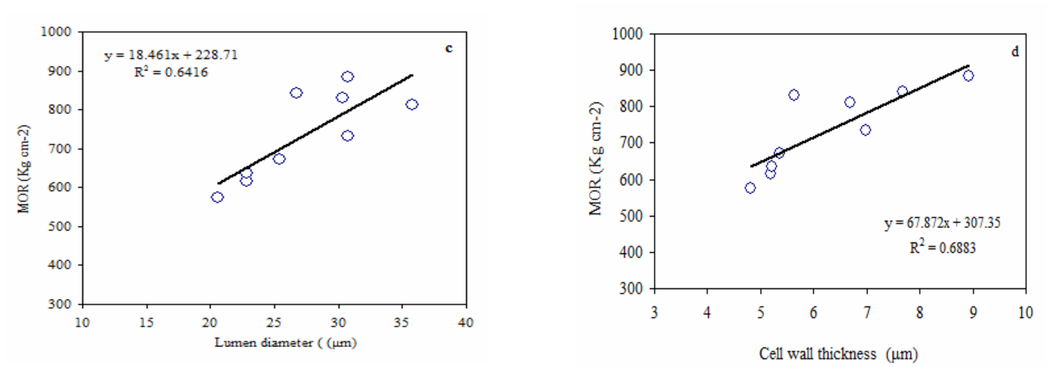


Figure 2: Relationship (linear regression) between MOR and tracheid features of *Pinus eldarica* wood

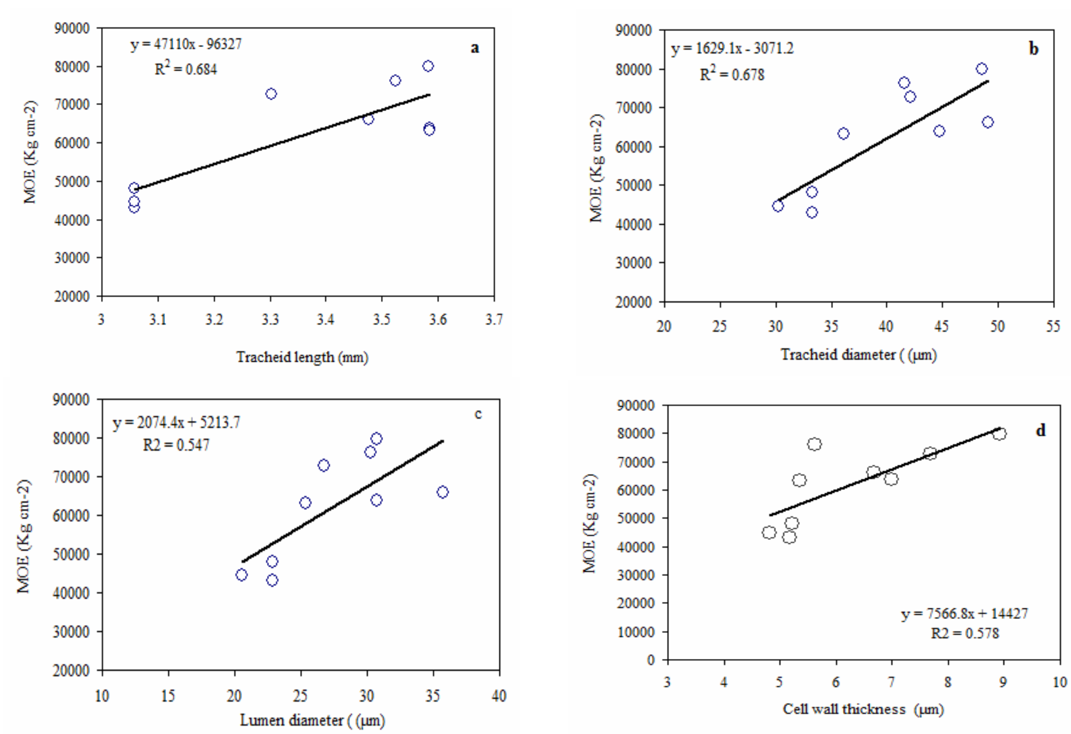


Figure 3: Relationship (linear regression) between MOE and tracheid features of *Pinus eldarica* wood

Actually, on site 2 the highest tracheid length was found, which makes the trees from this site more appropriate for paper production, compared to the trees from other sites.

Acceptable values for slenderness index and Runkel coefficients for paper production are those higher than 33 and lower than 1 (100%), respectively.[21] Such values were found in eldar pine from all the studied sites. Therefore, these sites are suitable paper production according to the results of morphological properties.

There are four groups according to the flexibility ratio:[22] 1) highly elastic (flexibility ratio greater than 75), 2) elastic (flexibility coefficient between 50-75), 3) rigid (flexibility ratio between 30-50), and 4) highly rigid (flexibility coefficient lower than 30). Thus, the observed tracheid length of the pine wood from all studied sites belongs to the elastic group, which makes it suitable for paper production.

The density of wood is a function of both cell wall thickness and lumen diameter and there exists a correlation between the strength and the density of wood. Thus density is the best predictor of wood strength.[23] In the present study, there are significant differences in the mechanical properties of eldar pine from site to site. Site 2 has the best wood quality, as to the results of strength properties. Therefore, it can be attributed to wood density, as there is a positive correlation between wood density and strength properties in eldar pine. Previously, research has shown that higher density species tend to have stronger timber than lower density species.[7,24]

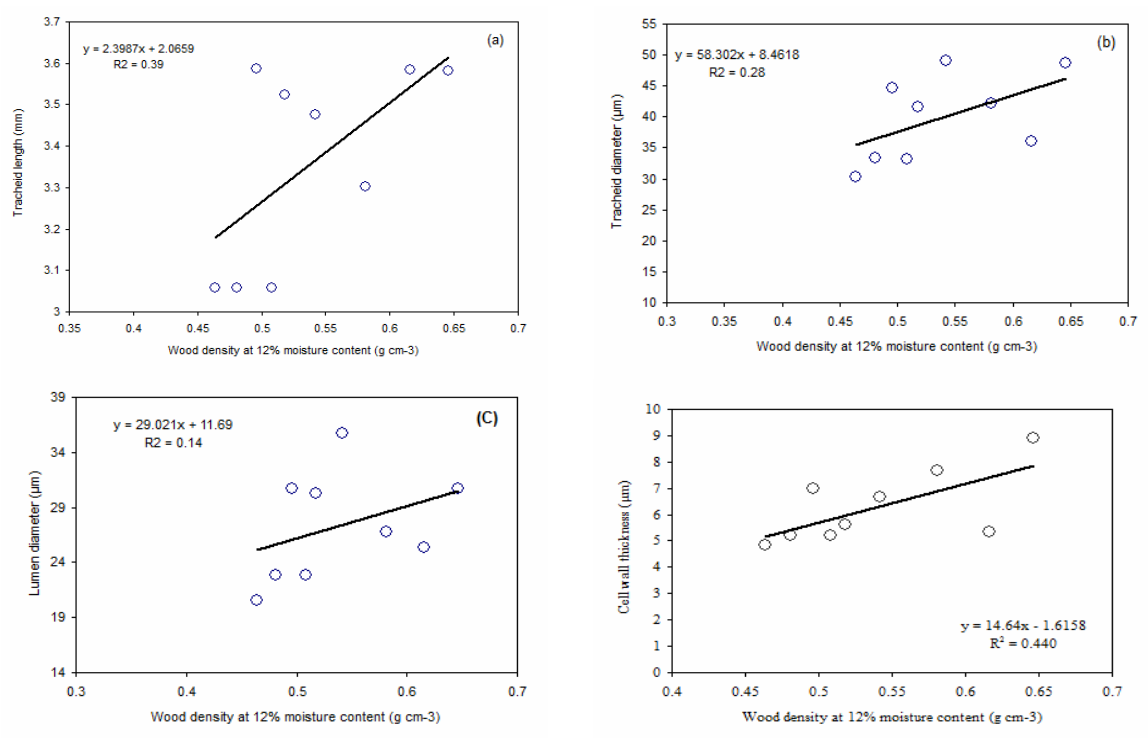


Figure 4: Relationship between wood density at 12% moisture content and tracheid diameter

The correlation coefficients between wood density and MOE are stronger than the relationships between wood density and modulus of rupture, which is not in agreement with the results of Zhang.[6] He showed that modulus of rupture and the maximum crushing strength in compression parallel to the grain are most closely and almost linearly related to wood density, whereas modulus of elasticity is poorly and least linearly related to wood density.

Finally, we admit that the results discussed in this study are of observational nature and consequently we recommend conducting an experimental study on a number of trees growing under different growing conditions (as only nine trees were sampled), which would permit to reach definite conclusions about the relationships between mechanical properties and tracheid features. Overall, the cell size and relative cell dimensions have an influence on the quality of pulp and paper products and on solid wood products.[25] The tracheid length and width, wall thickness, and lumen size have an effect on the bulk, burst, tear, fold, and tensile strengths of paper.[3] However, this study showed that cell dimensions have relationships with mechanical properties. The relationships between mechanical properties and cell dimensions are important for many pinus species. There is lack of references for *Pinus eldrica*. For example, a positive and strong relationship between MOR and tracheid length of pine wood (*Pinus taeda*) was found by Omidvar[26] and this result is in agreement with those obtained for *Pinus eldrica* growing in Iran.

CONCLUSION

- The site, radial direction and the interaction between site and radial position had a significant effect on the tracheid dimensions. The highest of tracheid length and cell wall thickness were found on site 2. The values of tracheid length and cell wall thickness increased along radial direction from the pith to the bark.
- Site variation had a significant effect on the

static bending (MOE and MOR). The modulus of elasticity and modulus of rupture on site 2 were higher than on other sites (site 1 and 3).

- There are positive relationships between wood tracheid features and static bending and between wood density and tracheid dimensions in elder pine.
- The pine growing on site 2 is the most suitable for structural applications, due to adequate tracheid length and good mechanical properties.
- The pine wood planted on three different sites is suitable for paper production due to the high tracheid length and good morphological properties.

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