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RESEARCH ARTICLE

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Effects of altitude on density and biometric properties of hornbeam wood (*Carpinus betulus*)

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Abstract

Aim of the study: This study aimed to investigate the effect of altitude difference on the wood dry density, fiber dimensions, and morphological properties of hornbeam wood (*Carpinus betulus* L.).

Area of study: The study area was located in the province of Mazandaran, north of Iran.

Material and method: 18 mature trees were randomly selected and harvested at six altitude levels (300, 500, 700, 900, 1100, and 1300 m) in the north of Iran. The clear test samples were prepared at diameter at breast height (DBH) to measure the wood dry density, fiber length, fiber diameter, cell wall thickness, Runkel coefficients, flexibility coefficients, and slenderness coefficients. Further analyses included the relationships between the wood properties and site conditions (temperature, precipitation, crown canopy, and understory herb layer) as well as tree's main dimensions (tree height and the DBH).

Main results: The results indicated significant effects of altitude variations on the studied properties. The pattern variations of wood properties were very regular at different levels of height. The average fiber length and fiber diameter decreased while the wood dry density and cell wall thickness increased with increasing the altitude levels. The average values of wood dry density, fiber length, fiber diameter, cell wall thickness, slenderness coefficients, flexibility coefficients, and Runkel coefficients of hornbeam wood were 698 kg/m^3, 1.42mm, 25.58 µm, 5.72µm, 55.55, 54.04%, and 0.93, respectively, in the above six altitudes. Pearson matrix correlation showed that there were significant relationships between temperature, crown canopy, tree height and DBH with the studied wood properties (except the slenderness coefficients).

Research highlights: The hornbeams grown at altitudes above 900-1300 m were not suitable for pulp and paper production due to relatively higher Runkel coefficients, the lower flexibility coefficients, as well as smaller fiber length than other altitude levels.

Additional keywords: *Carpinus betulus*; altitude variation; density; fiber dimensions; morphological properties.

Abbreviations used: WDD (wood dry density); FL (fiber length); FD (fiber diameter), CWT (cell wall thickness); FC (flexibility coefficient); RC (Runkel coefficients); SC (slenderness coefficient).

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Introduction

About 35 wood species of the genus *Carpinus* of the Betulaceae are widely distributed in Europe, eastern Asia, and North and Central America. In addition, the highest density of species diversity has been reported in China (Kiaei, 2011; Kiaei, 2012). Hornbeam is one of a native diffuse-porous hardwood species in Caspian forests. Besides, it grows in a mixture of oak and beech, as well as in some areas with *Parrotia persica* (Abdi *et al.*, 2009). It is classified as a medium-density hardwood, hence, it is considered as a wood of semi-hard to hard, high volumetric shrinkage, and with low cleavage strength properties (Moosavi *et al.*, 2017; Kiaei, 2012). Hornbeam, as one of the most important wood species in the paper-making industry, has a longer fiber length than other wooden species (Kiaei, 2011).

Physiographic factors (altitude, aspect, slope, and side slope), edaphic factors (soil characteristics), climatic factors (light intensity, temperature, air humidity, precipitation, and wind), and biotic factors (humans, animals, plants, and microorganisms) can affect different wood properties (Usta *et al.*, 2014; Kaygin *et al.*, 2016; Topaloglu *et al.*, 2016). There are various reports about the effects of ecological factors on wood properties mostly related to the relationship between altitude and wood properties. Many researchers, such as Noshiro *et al.* (1994) for *Alnus nepalensis*, Noshiro *et al.* (1995) for Rhododendron, and Yılmaz *et al.* (2008) for *Quercus pontica*, have reported that there are significant relationships between wood anatomical properties and ecological factors. On the other hand, there are reports indicating no significant relationships between the wood anatomical properties and altitude, including *Dodonae aviscosa* (Liu & Noshiro, 2003), the genus *Castanopsis* (Pande *et al.*, 2005), and *Buddleja cordata* (Aguilar-Rodriguez *et al.*, 2006).

Many studies have focused on understanding the relationship between wood density and altitude. Govorcin *et al.* (2003) stated that wood density of *Fagus sylvatica* L. decreased with increasing altitude. Barij *et al.*, (2007) for *Quercus pubescens* and Kiaei (2011, 2012) for *Carpinus betulus* reported that wood density increased by increasing the altitude. Hernandez & Restrepo (1995) stated that there was no change in the wood density of *Alnus acuminata* by increasing the altitude. Topaloglu *et al.*, (2016) reported that trees growing at altitudes of 400–600 m and 0–200 m had the highest and lowest density values, respectively. Besides, there are very few studies about the impact of altitude on the wood mechanical properties. Barij *et al.* (2007) found that the compression strength of *Quercus pubescens* increased by increasing the altitude. Kahveci (2012) reported that bending strength, modulus of elasticity, compressive strength parallel to grain, and dynamic bending strength of *Alnus glutinosa* decreased by increasing the altitude.

The main objectives of this study were (a) to investigate variations of wood dry density, fiber dimensions and morphological properties including the coefficients of Runkel, flexibility, and slenderness of hornbeam (*Carpinus betulus*) at six different altitudes, (b) to examine the relationship between wood properties and site condition.

Material and Methods

Eighteen mature and healthy trees (without reaction wood, decay, and insect damage or fungal infection) were clear-selected and harvested at six altitudes above sea levels (300, 500, 700, 900, 1100, and 1300m) in the northern forests of Iran (Nowshahr city, Mazandaran province). The main dimensions of the tree and site characteristics are listed in Table 1.

Disks were cut from the stem diameter at breast height (DBH = 1.30 m aboveground). Sampling was then performed after harvesting and removing pith and juvenile wood. The age demarcation point between juvenile and mature wood was estimated at about 19 years for all studied altitude levels (Kiaei, 2006). The physical and morphological properties were measured using the specified procedure of ISO 3131 standard (wood-determination of density for physical and mechanical tests-international standard, 1975) and Franklin method (1945), respectively. Site conditions at higher altitudes are very harsh for the growth of hornbeam trees due to the suppressed species. Therefore, the height and diameter of the trees are lower at higher than other altitudes.

Wood dry density (WDD)

After the preparation process, initial weights and dimensions of the test samples were measured using a digital balance and a vernier caliper, respectively. Afterward, small clear specimens were immersed in water (20 ± 2 °C) for 48 h under atmospheric pressure in a laboratory environment. Finally, the specimens were dried for in an oven (103 ± 2 °C, 24 h). The dimensions and weight of the specimens were measured when no changes were observed in the weights of dried specimens. The dry density was calculated according to the following equation:

Table 1. Site conditions and the trees traits at the six altitudes.

Altitude (m)	300	500	700	900	1100	1300
Temperature (°C)[a]	13.6	13.2	12.8	11.6	10.7	9.7
Precipitation (mm)[a]	1345	1340	1300	1300	1300	1300
Soil[b]	Alfisols	Alfisols	Alfisols	Alfisols	Alfisols	Alfisols
Crown canopy (%)[b]	67	68	70	72	72	75
Understory herb layer (%)[b]	58	66	75	71	70	65
Height (m)	21.6	20.2	19.8	18.5	17.7	17.1
Diameter (cm)[c]	34.6	33.2	31.4	29.7	28.7	28
Age (years)	37	35	36	37	38	40
Tree social status	Dominant	Dominant	Suppressed	Suppressed	Suppressed	Suppressed

[a]Both were reported by the region weather/ meteorological station (1978-2018); [b]Based on the initiative plan of forestry (Shafiee, 2004); [c]This factor is with bark.

$$WDD = \frac{M_{OD}}{V_{OD}} \quad (1)$$

where WDD is wood dry density (g/cm^3), M_{OD} is the weight after oven-drying (g), and V_{OD} is the oven-dry volume (cm^3).

Biometry properties

Fiber suspension was prepared using the Franklin method (1945). In this method, a mixture of hydrogen peroxide (H_2O_2) and acetic acid (CH_3COOH) is used in a ratio of 50:50. Additionally, an Image Analysis System was used to measure the fiber length (FL), fiber diameter (FD), cell wall thickness (CWT), lumen diameter (LD), Runkel coefficient (RC), flexibility coefficient (FC) and slenderness coefficient (SC). The total fibers were measured to achieve more accuracy in the studied properties. Morphological properties (fiber indices) were then calculated according to the following equations (Saikia *et al.*, 1997):

$$\text{Runkel coefficient (RC)} = \frac{2CWT}{LD} \quad (2)$$

$$\text{Flexibility coefficient (FC)} = \frac{100LD}{FD} \quad (3)$$

$$\text{Slenderness coefficient (SC)} = \frac{FL}{FD} \quad (4)$$

Statistical analysis

In the current study, the effect of altitude levels was studied on wood dry density and fiber morphology. Analysis of variance (ANOVA) and Duncan's test were applied to determine significant differences and for grouping means, respectively. Pearson correlation matrix was also applied to determine the relationships between the site conditions (temperature, precipitation, forest canopy, and understory herb layer) and tree main dimensions (tree height and DBH) with the wood properties (wood dry density, fiber length, fiber diameter and cell wall thickness). Forward stepwise regression classifies the most important factors affecting the wood properties as well.

Results

Wood dry density (WDD)

ANOVA revealed a highly significant effect of altitudes on the WDD ($P < 0.05$, Table 2). The lowest and highest WDD values were measured at altitudes of 300 m and 1300 m, respectively. Average values of WDD (698 kg/m^3) and CV (3.10%) were obtained for hornbeam wood (Table 3). The lowest variability

Table 2. Analysis of variance (ANOVA) of wood properties at different altitudes

Wood properties		Sum of squares	df	Mean square	F	Sig.
WDD	Between groups	0.091	5	0.018	6.653	0.000
	Within groups	0.297	109	0.003		
	Total	0.388	114			
FL	Between groups	22.278	5	4.456	100.294	0.000
	Within groups	17.637	385	0.044		
	Total	39.915	390			
FD	Between groups	7254.031	5	1450.806	186.308	0.000
	Within groups	2998.044	385	7.787		
	Total	10252.076	390			
CWT	Between groups	646.865	5	129.373	101.728	0.000
	Within groups	489.627	385	1.272		
	Total	1136.492	390			
SC	Between groups	7419.635	5	1483.927	23.206	0.000
	Within groups	24618.900	385	63.945		
	Total	32038.535	390			
RC	Between groups	150.320	5	30.064	129.649	0.000
	Within groups	89.277	385	0.232		
	Total	239.597	390			
FC	Between groups	49374.771	5	9874.954	103.148	0.000
	Within groups	37337.122	390	95.736		
	Total	86711.893	395			

WDD: Wood dry density; FL: Fiber length; FD: Fiber diameter; CWT: Cell wall thickness, SC: Slenderness coefficient; RC: Runkel coefficient; FC: Flexibility coefficient.

Table 3. Mean (± standard deviation) of physical and biometric properties in *C. betulus*.

Altitude (m)	WDD (Kg/m^3)	FL (mm)	FD (µm)	CWT (µm)
300	677±21 a	1.83±0.21 c	32.16±3.47 c	4.88±0.87 a
500	681±21 a	1.57±0.22 b	26.64±3.83 bc	4.89±0.85 a
700	690±24 ab	1.37±0.24 ab	25.12±2.40 b	5.05±0.78 ab
900	699±23 ab	1.34±0.13 ab	23.63±2.06 ab	6.09±0.84 b
1100	720±18 b	1.23±0.19 a	23.02±2.79 a	6.21±0.92 b
1300	723±23 b	1.21±0.21 a	22.92±2.10 a	7.22±0.97 c

Values with different letters per column have significant differences with Duncan's test.

(CV = 2.5%) and the highest variability (CV = 3.47%) of the WDD were measured at altitudes of 1100 m and 700 m, respectively.

Fiber length (FL)

ANOVA showed that in addition to FL regular variations at various altitude levels, the effect of altitude levels on FL was highly significant ($P < 0.05$, Table 2). In addition, the value of FL decreased with increasing altitudes (Table 3). The average values of FL and CV were 1.42 mm and 11.67%, respectively.

Fiber diameter (FD)

ANOVA results indicated significant differences in fiber diameter among the altitude levels ($P < 0.05$, Table 2). The average FD decreased with increasing altitude at a CV of 10.84% (Table 3). The mean of FD was 25.58 µm in the six altitudes.

Cell wall thickness (CWT)

According to ANOVA results, the altitude significantly affected the CWT ($P < 0.05$, Table 2), with the highest and lowest values measured at 1300 m and 300 m, respectively, and an average of 5.72 µm and a CV of 15.23% (Table 3).

Morphological coefficients

Slenderness coefficient (SC)

As shown by ANOVA results, significant effects of altitude levels were observed on the SC with an average of 55.55 and a CV of 13.14%. Additionally, the highest and lowest SC was measured at 500 m and 1300 m, respectively (Fig. 1).

Runkel coefficient (RC)

RC represents the paper's resistance to rupture, which is obtained from the thickness of two cell walls divided by the fiber diameter. ANOVA results illustrated significant effects of altitude levels on the RC with an average of 0.93, and a CV of 5.37%. The lowest and highest RC values were found at 300 m and 1300 m, respectively. Moreover, the values of RC increased with increasing altitudes (Fig. 2).

Flexibility coefficient (FC)

The results of ANOVA revealed significant effects of altitude levels on the FC, which is the ratio of the lumen diameter divided by the fiber diameter. FC averaged 54.04% with a CV of 12.43%. Furthermore, the value of FC decreased with increasing altitudes. The highest and lowest FC values were measured at 300m and 1300 m, respectively (Fig. 3).

Relationship among studied variables

The relationship between the studied wood properties (WDD, FL, FD, CWT, FC, RC, and SC) with site conditions (such as temperature, precipitation, crown canopy, and understory herb layer) and tree main dimensions (such as tree height, tree diameter at breast height, and tree age) were investigated by the Pearson matrix correlation (Table 4) and forward stepwise regression (Table 5).

Results of Pearson matrix correlation indicated that the temperature, crown canopy, tree height and DBH (diameter at breast height) had significant relationships with the studied wood properties (except SC). A correlation coefficient of above 80% was measured between the environmental variables and the studied wood properties (except SC).

A correlation coefficient of less than 72% was obtained between the understory herb layer and the studied wood properties (WDD, FL, FD, CWT, RC, FC, and SC), while a correlation of over 72% was found between temperature, crown canopy, and tree diameter and height with the studied wood properties. Therefore, it can be concluded that the relationship between the understory herb layer with the studied wood properties was lower than the other environmental variables.

The results illustrated that there was a significant relationship between fiber length and fiber diameter with precipitation rate. The precipitation effect on other wood properties was not significant. Furthermore,

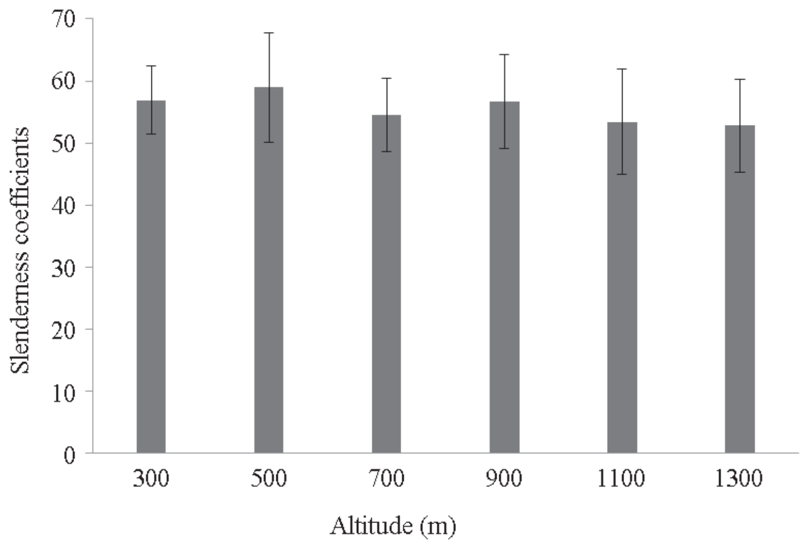

Figure 1. The effect of altitude on the slenderness coefficients of *Carpinus betulus*.

correlation coefficients between the fiber length and fiber diameter with precipitation rate were measured more than 87%, while the relationship between precipitation and the other wood properties was less than 79%.

There were significant relationships between tree's age and WDD, CWT, and RC. Besides, a correlation coefficient of more than 82% was measured between tree's age and the mentioned wood properties. The tree's age effect on the other wood properties was not significant.

The results indicated no significant differences between all site conditions/tree main dimensions with the SC, with a correlation coefficient of less than 79.6% between all environmental conditions and FC. As a result, in all of relationships, the lowest and highest of correlation coefficients were measured between the understory herb layer and CWT (less than 11%), as well as the temperature and Runkel coefficients (about 98.8%), respectively.

Multiple forward stepwise correlation analysis showed that the wood properties could be explained by the model: $Y= a + b*\beta_1 + c*\beta_2$, which presented a high correlation coefficient ($R > 0.96$) as well. The wood properties were affected by one environmental variable only (site conditions/tree main dimensions), except the FD that was corrected to two variables (Table 5). In addition, more than 96% of the variations in wood dry density, CWT, and RC depended on the ambient temperature. About 92% of fiber length variation was

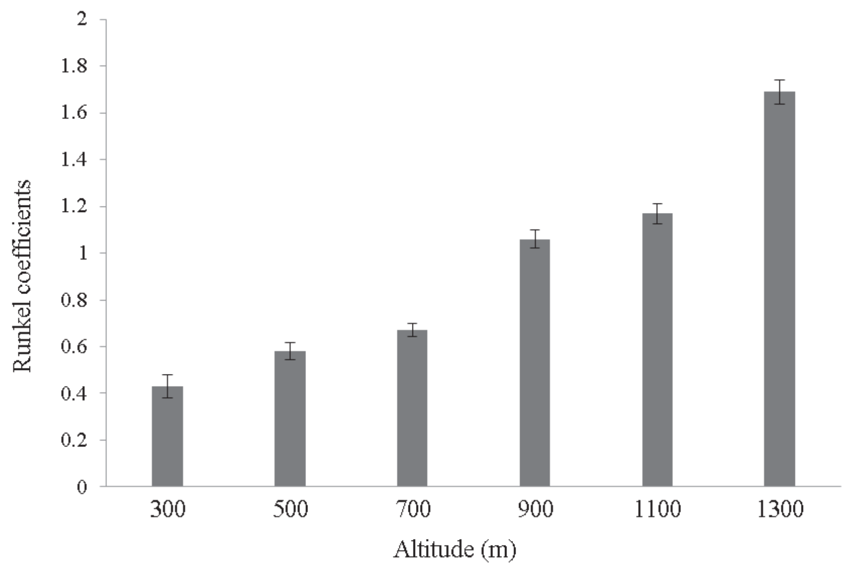

Figure 2. The effect of altitude on the Runkel coefficients of *Carpinus betulus*.

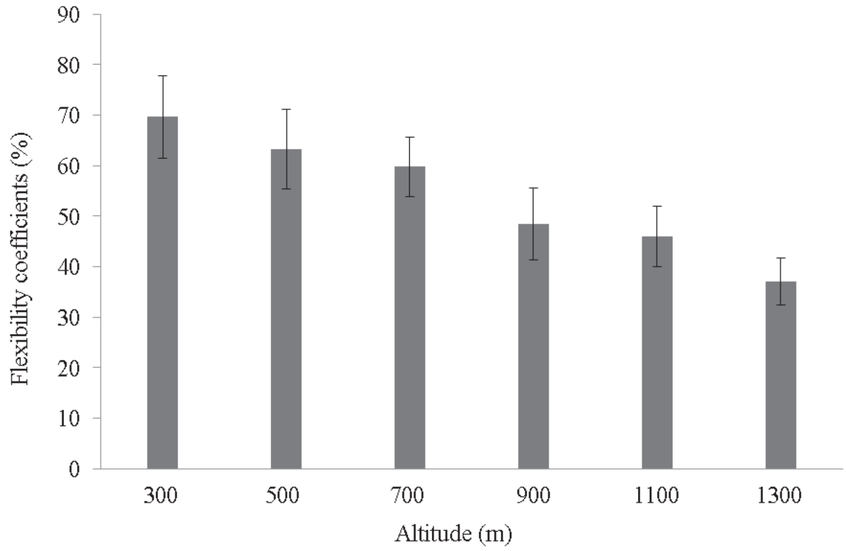

Figure 3. The effect of altitude on the flexibility coefficients of *Carpinus betulus*.

related to the tree DBH. The FD variations were corrected with tree diameter (84%) and tree age (13%). About 97% of FC variations were related to the crown canopy. As a result, there were no relationships between the site conditions/tree main dimensions with SC.

Discussion

Wood density is one of the most important wood qualities in softwood and hardwood species. It is affected by cell wall thickness, cell diameter, ratio of earlywood to latewood, and chemical content of the wood (Zobel & van Buijtenen, 1989). In the present study, we showed that the effect of altitude levels was significant on wood dry density of hornbeam wood. Also, the average of WDD was increased by altitude increasing. Similar results were previously reported by Barij *et al.*, (2007) for *Quercus pubescens*, Topaloglu *et al.*, (2016) for oriental beech, & Kiaei (2011, 2012) for *C. betulus*.

The average WDD of hornbeam wood at the studied altitudes (698 kg/m^3) was lower than that in Turkey (Gunduz *et al.*, 2009; 794 kg/m^3) and in the Guilan (732 kg/m^3, Golbabaei *et al.*, 2004) and Golestan (717 kg/m^3, Golbabaei *et al.*, 2004) sites (Iran), but it was higher than that of Mazandaran site (Iran) (688 kg/m^3, Golbabaei *et al.*, 2004).

The influences of wood fiber dimensions and their derived values (slenderness ratio, flexibility coefficient, and Runkel ratio) are well described on pulp and paper mechanical properties. Wood fibers are one of the most important factors in the production of pulp and paper, or the fiberboards. Kellogg & Thykeson (1975) and Matolcsy (1975) also reported the importance of fiber dimensions in predicting wood pulp mechanical properties. It has been reported that the morphological

Table 4. Relationships between site conditions and trees traits with the wood properties of *C. betulus*.

Wood properties	FL	FD	CWT	WDD	SC	RC	FC
Temperature	0.861*	0.802*	-0.981**	-0.981**	0.778	-0.988**	0.986**
Precipitation	0.924**	0.873*	-0.686	-0.770	0.757	-0.715	0.798
Crown canopy	-0.902*	-0.852*	0.962**	0.929**	-0.766	0.978**	-0.987**
Understory herb layer	-0.678	-0.714	0.108	0.280	-0.287	0.180	-0.323
Tree diameter	0.946**	0.920**	-0.926**	-0.961**	0.768	-0.932**	0.977**
Tree height	0.961**	0.921**	-0.912*	-0.956**	0.720	-0.951**	0.987**
Age	-0.528	-0.402	0.898*	0.825*	-0.796	0.864*	-0.791

(n=18 individual trees) *Statistically significant at 95%-confidence level ($p < 0.05$); **statistically significant at 99%- confidence level ($p < 0.01$); fiber length (FL), fiber diameter (FD); cell wall thickness (CWT), WDD (wood dry density), SC: Slenderness coefficients, RC: Runkel coefficients, FC: flexibility coefficient.

Table 5. Multistage regression analysis between the wood properties and site conditions at six altitudes.

Wood properties	Correlation parameters			
		β_1	β_2	Equation
WDD R=0.981	Variable	Temperature**	-	Y= 847.34 – 12.48*β_1
	R^2ap.	0.963	-	
	R^2mul.	0.963	-	
FL R=0.961	Variable	Tree diameter[a]**	-	Y= -1.27 + 0.087*β_1
	R^2ap.	0.924	-	
	R^2mul.	0.924	-	
FD R=0.991	Variable	Tree diameter[a]**	Tree age**	Y= -68.414+1.752*β_1+1.071*β_2
	R^2ap.	0.848	0.134	
	R^2mul.	0.848	0.982	
CWT R=0.980	Variable	Temperature**	-	Y=12.91 – 0.603*β_1
	R^2ap.	0.962	-	
	R^2mul.	0.962	-	
SC -	Variable	-	-	No variables were entered into the equations
	R^2ap.	-	-	
	R^2mul.	-	-	
RC R=0.988	Variable	Temperature**	-	Y=4526 – 0.301*β_1
	R^2ap.	0.978	-	
	R^2mul.	0.978	-	
FC R=0.987	Variable	Crown canopy**	-	Y=343.222 – 4.092*β_1
	R^2ap.	0.974	-	
	R^2mul.	0.974	-	

(n=18 individual trees). ** Statistically significant at 99% confidence level ($p < 0.01$); R^2ap: the parameter contributions to the determination coefficient; R^2mul: Multiple coefficients of determination, fiber length (FL), fiber diameter (FD); cell wall thickness (CWT), WDD (wood dry density), SC: Slenderness coefficients, RC: Runkel coefficients, FC: flexibility coefficient, a is tree DBH.

features of fiber are important because they determine the suitability of lignocellulosic materials prior to production (Ververis *et al.*, 2004; Ona *et al.*, 2001). The altitude levels affected significantly the FL, FD, and CWT of *C. betulus* wood. The average of FL and FD decreased while CWT increased with increasing altitude. Similar results were reported by many researchers for *Alnus nepalensis* (Noshiro *et al.*, 1994), *Rhododendron* (Noshiro *et al.*, 1995), and *Quercus pontica* (Yılmaz *et al.*, 2008).

The fibers were classified into three groups. The first group was considered as short fibers, such as some hardwood species (length > 0.9 mm). The second group had an average length of 0.9-1.9 mm. The third group consisted of fibers with a length of more than 1.9 mm (Salehi, 2001). Furthermore, the results showed that the average fiber length of the hornbeam wood was equal to 1.2-1.8 mm. therefore it is concluded that the fibers of current study are classified in the second group. Also, the average fiber length (1.42mm) at the studied altitudes was similar to that of Turkish hornbeam wood (1.49 mm; Tank, 1978).

The average fiber diameter of hornbeam wood in studied altitudes was about 25.58 µm which is located in the normal range compared with hardwood fibers (20-40 µm: Atchison, 1987; San *et al.*, 2016), and is also higher than that of Turkish hornbeam wood (21.93 µm: Tank, 1978).

The cell wall thickness (CWT) of the fiber affects the strength of individual fibers. It is known that the paper made from a pulp prepared by very thin cell wall fibers has a very low tear resistance. The fibers with very thick cell wall cause low resistance and high-volume papers because they do not properly flatten at the time of sheet formation (Seth & Page, 1988). Multiple reports indicated that there were positive relationships between wood density and CWT in many species. Our results showed that the lowest WDD and the thinnest CWT of the fibers, as well as the highest WDD and the thickest CWT of the fibers, were measured at 300 m and 1300 m, respectively. The decreased density at low altitudes may be related to both reduced CWT of the fibers and the cellulose content (Topaloglu *et al.*, 2016). Denne & Hale (1999) observed that trees with lower mean density had thinner fiber walls and wider vessel lumens than those with higher mean density. The average CWT at the studied altitudes was 5.72 µm, which is close to that of Turkish hornbeam wood (CWT: 5.85 µm).

Slenderness coefficient (SC) shows the quality of the paper, which is obtained from the fiber length divided by the fiber diameter. High value of this ratio provides better forming and a well-bonded paper (Ashori & Nourbakhsh, 2009). According to the physical properties of paper test, this feature as an important factor has a significant effect on strength, tear, burst, breaking off, and double folding resistance. In addition, it is usually between 70-90 for softwoods and 40-60 for hardwoods for papermaking (Akgul & Tozluoglu, 2009). The mean of SC had placed in hardwood range for all of studied altitudes. The acceptable value for a SC of the paper is more than 33 (Xu *et al.*, 2006; Kiaei *et al.*, 2014; Enayati *et al.*, 2009), as also measured for the Iranian hornbeam wood in the studied altitudes.

Runkel coefficient (RC) is usually used to determine the suitability of a fibrous material for the pulp and paper production. Wood species with a RC of more than 1 have a stiff fiber, less flexibility, and poor bonding ability. In addition, the fibers with ratios less than 1 produce good quality pulp and paper (Xu *et al.*, 2006; Jang & Seth, 1998). Therefore, according to the results of the RC, the fibers at altitudes of 300-700 m are suitable for paper production. Flexibility coefficient (FC) represents the paper resistance against rupture and burst, and also there is a direct relationship between the FC and the paper resistance (Enayati *et al.*, 2009; Ashori & Nourbakhsh, 2009). There are four groups of FC, namely highly elastic (> 75), elastic (50-75), rigid (35-50), and highly rigid (< 30) (Bektas *et al.*, 1999; Kiaei *et al.*, 2014). Hence, the measured characteristics of wood fibers at 300 m, 500 m, and 700 m belong to the elastic group being suitable for paper production. The fibers at altitudes of 900-1300 m are classified in the rigid group, which is not suitable for paper production due to inefficient elasticity. Therefore, they are mainly used in fiber plates, rigid cardboards, and cardboard production.

According to the forward matrix regression results, temperature, the DBH, crown canopy, and age of the trees were important factors in the wood variations compared to other factors. The temperature contributed significantly to the variations of WDD, cell wall thickness, and Runkel coefficients. This result of multiple stepwise correlation analysis are supported by those of Bakhshi *et al.* (2011) for maple wood. They found that fiber diameter dimensions were related to the precipitations in November (52.9%), August (19.6%), January's minimum temperature (5.6%), and November's maximum temperature (4.4%).

Conclusions

In this study, the wood dry density, fiber length, fiber diameter, cell wall thickness, and morphological properties of hornbeam wood were studied at six altitudes above sea level in Nowshahr site. The following is a summary of the most important findings:

- There are significant differences in WDD, FL, FD, CWT, SC, RC, and FC of hornbeam wood at various altitude levels.
- The average values of FL, FD, SC, and FC decreased by increasing the altitude to 51%, 40%, 7.7%, and 87%, respectively. However, the average values of WDD, CWT, and RC increased by increasing the altitude levels to 6%, 32%, and 74%, respectively.
- The temperature and tree DBH played an important role in the wood properties as shown by forward stepwise regression. The variations of WDD, CWT, and RC were related to the temperature. FL and FD were affected by the tree DBH.
- Hornbeam wood at low altitudes is suitable for paper and pulp production due to longer fiber length, favorable flexibility coefficients, lower Runkel coefficients, and more desirable slenderness coefficients.

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