

Article

Geographic Variations of the Wood Density and Fiber Dimensions of the Persian Oak Wood

Noorollah Nazari ¹, Mohsen Bahmani ^{1,*}, Saleh Kahyani ¹, Miha Humar ²  and Gerald Koch ³

¹ Department of Natural Resources and Earth Science, Shahrekord University, Shahrekord 64165478, Iran; nazarinorolah71@gmail.com (N.N.); skahyani@sku.ac.ir (S.K.)

² Department of Wood Science, Biotechnical Faculty, University of Ljubljana, 1501 Ljubljana, Slovenia; miha.humar@bf.uni-lj.si

³ Thünen Institute of Wood Research Hamburg, Leuschnerstraße 91, 21031 Hamburg-Bergedorf, Germany; gerald.koch@thuenen.de

* Correspondence: mohsen.bahmani@sku.ac.ir; Tel.: +98-383-2324-401

Received: 27 July 2020; Accepted: 12 September 2020; Published: 17 September 2020



Abstract: Persian oak (*Quercus brantii* Lindl.) is a valuable native species in Iranian forests with very limited availability of data on its wood properties. The objective of the current study was to determine the influence of altitude and slope on physical properties and fiber dimensions of Persian oak wood. In addition, the relationship among wood properties, site conditions (temperature and rainfall) and growth traits of trees (tree height, DBH, basal area, age, crown diameter, crown basal area, volume and annual diameter increment) were studied by principal component analysis (PCA). Three altitude levels (1730, 1980 and 2250 m) and three slope classes (<30%, 30–45% and >45%) were considered in the current study. It was determined that trees growing in the intermediate altitude (1980 m) showed the highest oven-dry density values, and those in the lowest altitude (1730 m) revealed the lowest ones. The results also indicate significant statistical differences between altitude levels and slope classes on the fiber length, fiber diameter and volumetric swelling at the 99% confidence interval while no significant differences were found between average values of oven-dry density among different altitudes and slopes. PCA analysis indicated that altitude and temperature are the most important factors affecting the wood properties. Knowledge of the relationship between wood properties and environmental factors are essential in terms of both forestry management and wood applications.

Keywords: *Quercus*; biometry; Zagros forests; oven-dry density; PCA

1. Introduction

Quercus spp. represent essential members of the family Fagaceae including more than 500 species of oaks which are distributed in the whole northern hemisphere [1]. There are eight species of *Quercus* naturally occurring in Iran. Oak tree species are widely spread in Arasbaran, Hyrcanian and Zagros forests in Iran. The highest species diversity of oak is documented for the Zagros forests [2]. The Zagros forests with an area of five million hectares cover approximately 40% of Iranian forests and are the widest forest areas of the country [3]. The three main oak species are *Quercus brantii*, *Q. infectoria* and *Q. libani* [4]. Persian oak (*Quercus brantii* Lindl.), which represents the dominant tree species, covers more than 50% of the Zagros forests [3]. It forms mixed stands together with the three wood species: *Crataegus azarolus*, *Acer monspessulanum* and *Pistacia atlantica*. Persian oak is a ring-porous species [5] and its wood can be easily recognized by large rays and solitary vessels.

Climate, biotic and edaphic conditions together with the topography of the area, altitude, aspect and slope are interacting factors, affecting wood quality [6–8]. There are several studies on the relationships between environmental factors and wood characteristics, especially in terms of wood

density [9–13]. Wood density is considered as the most important index of the physical and mechanical properties of wood and is an indicator of tree growth rate in both conifers and hardwoods [14,15]. Govorcin et al. [16] indicated that wood density of *Fagus sylvatica* decreased with increasing altitude. Kiaei et al. [11] and Barij et al. [17] stated that there are significant associations between wood density and environmental factors for *Quercus pubescens* and *Carpinus betulus*. Noshiro et al. (1994) [18], Noshiro et al. (1995) [18] and Yilmaz et al. [19] reported that there is a significant relationship between wood anatomical properties and ecological factors for *Alnus nepalensis*, *Rhododendron* species (*R. anthopogon*, *R. lepidotum*, *R. campanulatum* and *R. arboretum*) and *Quercus pontica*. On the other hand, Liu and Noshiro [20], Pande et al. [21] and Hernandez and Restrepo [22] reported no significant relationship between wood oven-dry density and altitude difference for *Dodonaea viscosa*, *Alnus acuminata* and the genus *Castanopsis*. Topaloglu et al. [10] determined some changing anatomical properties for *Fagus orientalis* at different altitudes (0–200, 200–400, 400–600, 600–800 and 800–1000 m) and aspects (north and south) in Turkey. In detail, the results of the wood anatomical studies show that, with increasing altitude, vessel diameters narrowed, vessel numbers increased and vessel and fiber length decreased. Kaygin et al. [23] reported a significant relationship between wood oven-dry density and altitude difference for Scots pine (*Pinus sylvestris*). It worth mentioning that most studies mainly concentrated solely on wood properties on its own and ignored the relationship between wood properties and environmental growth traits. Berges et al. [24] studied the effects of ecological factors on radial growth and wood density of sessile oak (*Quercus petraea* Liebl.) in Northern France. They reported that there is a direct control of wood density by ecological factors. Bahmani et al. [25] inspected the influence of tree diameter classes on the wood properties of Persian oak such as basic and oven-dry density, fiber morphology and chemical compounds in Lorgedan forests, Iran. However, the relationship between wood properties and environmental growth traits was not investigated. To the best of our knowledge, there is no study on the influence of environmental conditions on the physical and fiber characteristics of Persian oak. Considering the importance of environmental factors on the wood properties and valuable position of *Q. brantii* for Iranian forests, the objectives of this study were to identify the changes of oven-dry density, fiber length, fiber diameter and cell wall thickness of Persian oak wood, depending on different altitude levels and slope classes as well as to explore the relationship between wood characteristics and environmental factors.

2. Material and Methods

2.1. Study Area and Sampling

The research area is located between 49°59'43" N and 50°15'28" N and between 32°07'42" E and 32°22'25" E in the Bazoft region of Chaharmahal Va Bakhtiari, Iran (Figure 1). Persian oak forests in this study area are spread between 1500 and 2300 m in altitude. The mean annual precipitation and temperature of the study area are 330 mm and 14 °C, respectively. This study was performed on trees collected from nine ecosites (three forest sample stands along an altitudinal gradient (1730, 1980 and 2250 m a.s.l.) × three terrain slope classes (less than 30%, 30–45% and more than 45%) in the Persian oak forests of Bazoft, creating three replicates in each ecosite (3 × 3 × 3 = 27 sampling plots, one sampled tree in each plot = 27 healthy dominant trees in total) (Figure 1). Due to their remote location and the absence of evidence of human impact, it is assumed that all stands have been developed under the influence of natural impacts and disturbances. In each ecosite, three plots were implemented. In total, 27 healthy dominant trees (3 trees × 3 altitudes × 3 slopes) were selected.

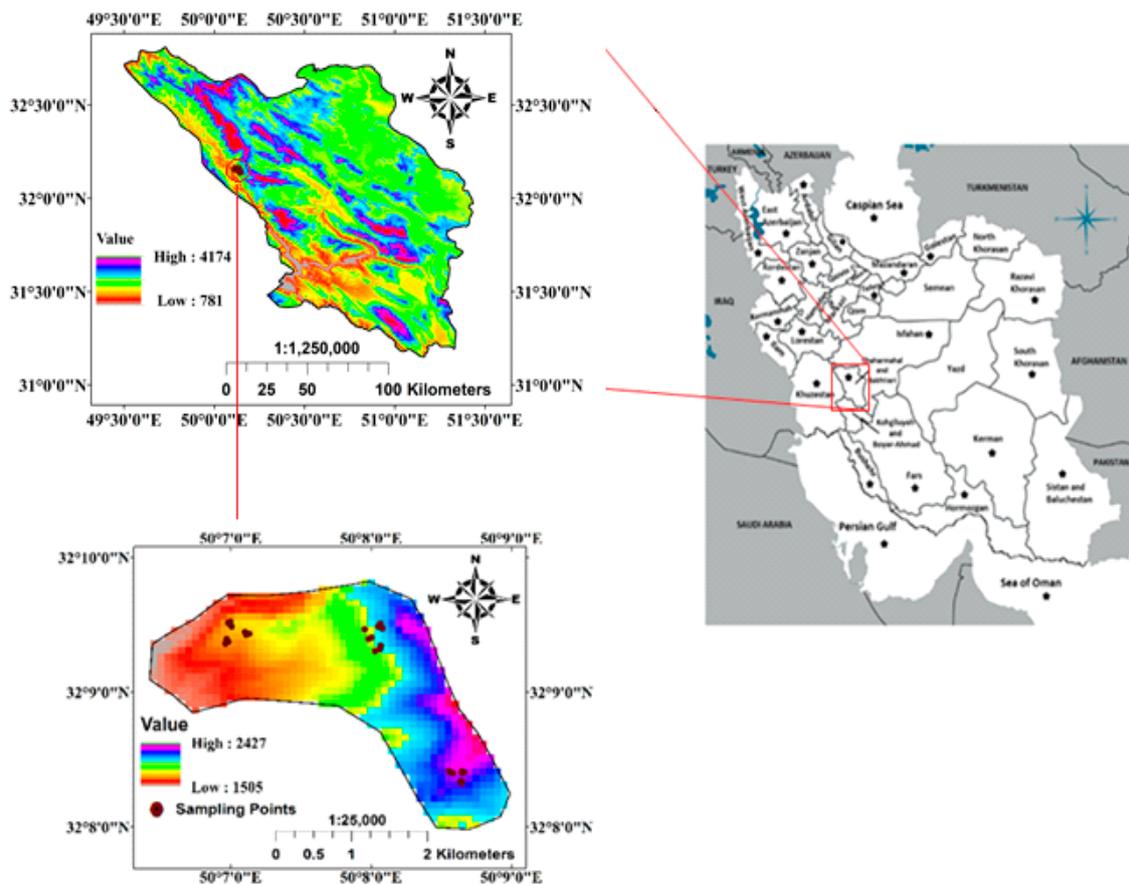


Figure 1. Location of the study area, the three forest stands and 27 sampling plots at nine study ecosites in the Bazoft region forest of Chaharmahal Va Bakhtiari, Iran.

In each circular plot, all living trees of at least 7.5 cm diameter at breast height (DBH, 1.30 m above the ground) were identified, and their diameter at breast height, height, crown length and perpendicular diameters were recorded within 0.1 ha area. The caliper, vertex and diameter tape were used to measure tree diameters, height and crown diameter, respectively. Then, in each plot, one healthy dominant tree with the largest diameters at breast height (DBH) without any defects and reaction wood was sampled and one disk was taken from the tree trunk at DBH for the determination of wood properties. Then, the tree age at breast height (ABH) was obtained by counting the annual rings of the sampled disks. Finally, the mean annual diameter increment (MADI) was obtained by dividing DBH by the number of annual rings. Stand-level traits such as stand basal area, stand density and stand quadratic mean diameter (QMD) and tree-level traits such as stem basal area, stem volume, tree crown diameters and tree crown basal area in each ecosite were calculated based on 27 circular 0.1 ha sample plots data. The tree crown diameter was measured as the average crown spread is the average of the lengths of longest spread from edge to edge across the crown and the longest spread perpendicular to the first cross-section through the central mass of the crown. Tree crown basal area as tree crown area projection was calculated based on the crown area as a circle using average crown spread as its diameter. The annual records of total precipitation and mean annual temperature, the main climatic factors affecting the wood properties and growth of Brant oaks in the region, were obtained from the Koohrang Synoptic Meteorological Station (32.46° N, 50.13° E; 2365 m a.s.l.) [26].

2.2. Preparation of Samples

For determination of physical properties and fiber dimensions, 5-cm-thick disks were taken at 1.30 m in height. Tree sampling and specimen preparation for physical properties and fiber dimensions are shown in Figure 2.

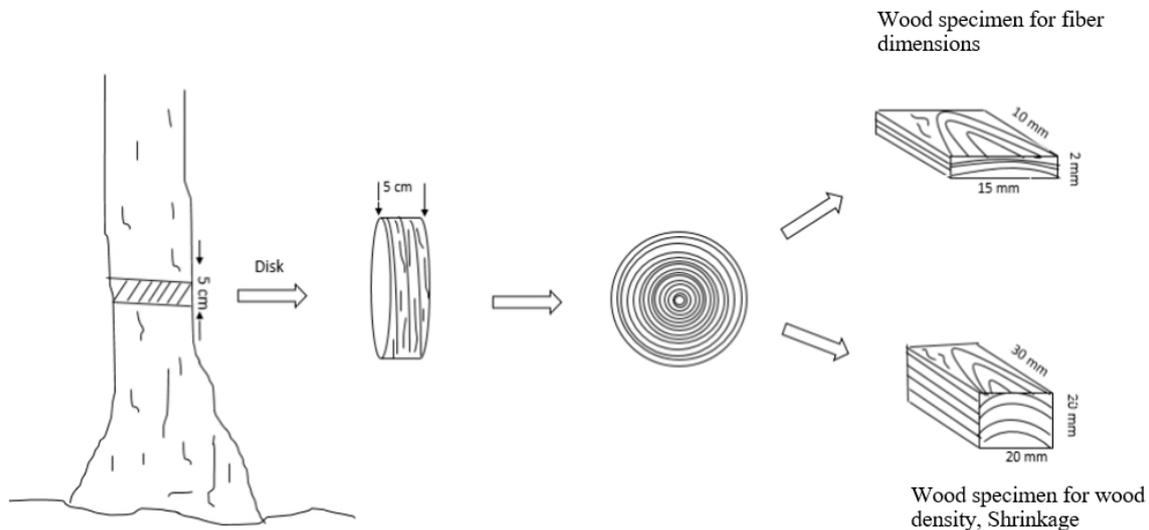


Figure 2. Diagram of specimen preparation from a disk of *Q. brantii* to measure the physical properties and fiber dimensions.

2.3. Physical Properties

After the preparation process, specimens with dimensions of 3 cm × 2 cm × 2 cm were prepared in accordance with ISO 13061-14 [27] for the investigation of oven-dry density and volumetric swelling. In total, 270 specimens from different parts of disks (10 specimens per each disk) were prepared.

Sample dimensions were measured in green (saturated) and oven-dry condition with a slide caliper; oven-dry mass was determined with an electric balance to an accuracy of 0.01 g. Swelling was calculated using the dimensional change from the green to oven-dry condition. The physical properties were calculated according to the following equations:

$$D_0 = \frac{P_0}{V_0} \quad (1)$$

$$\alpha_V = \frac{V_S - V_0}{V_0} \quad (2)$$

where: D_0 is the oven dry density ($\text{g}\cdot\text{cm}^{-3}$), α_v is the volumetric swelling (%), v_s is the volume in state of saturate (cm^3), V_0 is the volume in state of oven-dry (cm^3) and P_0 is the mass in state of oven dry (g).

2.4. Wood Fiber Properties

Separation of individual wood fiber was performed using Franklin method [28]. From each disk, wood specimens with the dimension of 15 mm × 10 mm × 2 mm were saturated in a mixture (1:1) of acetic acid and oxygenized water in test tubes. Afterwards, the specimens were kept in the oven at 65 ± 3 °C for 48 h. After maceration, the specimens were washed (2–3 times) in distilled water and then they were immersed with distilled water, shacked and the fiber dimensions (fiber length, fiber diameter and cell wall thickness) were measured with the use of microscope. From each disk, at least 50 fibers were used for the measurements.

2.5. Statistical Analysis

Normal distribution of data is one of the preconditions of the multivariate analysis of variance (MANOVA). Therefore, datasets were tested for normal distribution using the Shapiro–Wilk test of normality, and then data transformation was applied for those that were not normally distributed. Levene’s test was employed to examine the homogeneity of variances. MANOVA was conducted to evaluate significant differences between mean values of studied wood properties at altitude levels and slope classes using SPSS 23 (IBM, Armonk, NY, USA). This method generated a multivariate dataset that was interpreted by using principal component analysis (PCA). The patterns of variation of the measured traits were selected and used for performing PCA based on the method of alternating least squares (PRINQUAL procedure in SAS). A Kruskal secondary least-squares monotonic transformation was applied to all variables, with the restriction that ties were preserved. The results are presented by a PCA biplot that shows the transformed variables (e.g., the measured traits) projected onto the two-dimensional plane of the analysis described by the two principal components. PCA allowed the multivariate dataset to be reduced by minimizing multicollinearity and associating the correlated traits in two principal axes [13]. This approach improved data exploration and simplified the interpretation of the results.

3. Results

Descriptive statistics for the Persian oak sample trees, studied traits and forest stands in the study area are presented in Table 1.

Data normality was checked by the Shapiro–Wilk test (the data was normal; $\text{sig} > 0.05$), while the homogeneity of variances was tested using the Levene’s test (the variances were homogeneous; $\text{sig} > 0.05$).

Table 1. Descriptive statistics for the sample population of Persian oak representing nine different ecosites collected in the Bazoft region forest of Chaharmahal Va Bakhtiari, Iran.

Ecosites		E1S1	E1S2	E1S3	E2S1	E2S2	E2S3	E3S1	E3S2	E3S3
Latitude (N) m		3,558,132	3,558,227	3,558,354	3,558,250	3,558,120	3,558,137	3,556,272	3,556,280	3,556,299
Longitude (W) m		416,662	416,867	416,680	418,209	418,248	418,284	419,180	419,165	419,138
Altitude (m a.s.l)		1717	1726	1742	1980	1987	1968	2280	2244	2232
Mean annual precipitation (mm)		331	330	329	330	329	328	329	330	330
Mean annual temperature (°C)		15.3	15.2	15.3	14.5	13.9	13.0	12.8	12.9	12.9
Tree-Level variables	Height (m)	11.34 (2.15)	10.14 (0.06)	8.28 (0.60)	6.63 (0.68)	8.89 (0.24)	6.91 (1.04)	11.28 (0.11)	7.98 (3.20)	6.44 (2.74)
	¹ DBH (cm)	105.00 (8.00)	73.00 (7.00)	75.00 (1.00)	65.67 (2.52)	108.00 (16.00)	83.00 (9.54)	157.33 (2.52)	119.00 (41.00)	82.67 (20.65)
	² ABH (year)	1164 (148)	767 (30)	649 (17)	755 (15)	1089 (80)	847 (177)	1417 (4)	1146 (386)	813 (257)
	Stem basal area (m ²)	0.87 (0.13)	0.42 (0.08)	0.44 (0.01)	0.34 (0.03)	0.93 (0.28)	0.55 (0.12)	1.95 (0.06)	1.20 (0.77)	0.56 (0.25)
	Stem volume (m ³)	5.02 (1.68)	2.13 (0.40)	1.83 (0.09)	1.12 (0.20)	4.15 (1.32)	1.86 (0.36)	10.99 (0.25)	5.60 (5.14)	2.03 (1.38)
	Crown basal area (m ²)	22.22 (10.07)	19.71 (3.14)	27.24 (7.31)	20.38 (0.36)	13.04 (0.48)	24.03 (6.60)	14.89 (0.31)	13.71 (1.48)	21.73 (14.79)
	³ Crown diameter (m)	5.23 (1.23)	5.00 (0.40)	5.86 (0.80)	5.10 (0.05)	4.08 (0.08)	5.50 (0.74)	4.36 (0.05)	4.18 (0.23)	5.07 (1.73)
	⁴ MADI (mm)	0.91 (0.05)	0.95 (0.06)	1.16 (0.02)	0.87 (0.02)	0.99 (0.08)	1.01 (0.21)	1.11 (0.02)	1.04 (0.01)	1.04 (0.10)
	Basal Area (m ²)	109.89	72.23	57.70	89.24	103.34	109.95	110.66	69.52	113.23
Stand-Level variables	Stand Density (N/ha)	160	120	120	90	115	77	150	105	123
	⁵ QMD (cm)	93.54	87.57	78.26	112.39	106.99	135.17	96.94	91.84	108.14

Notes: ¹ DBH, diameter at breast height; ² ABH, age at breast height. ³ Crown width in m measured from below the tree in the field. ⁴ MADI, mean annual diameter increment; ⁵ QMD, quadratic mean diameter. Standard deviations are displayed in parentheses.

3.1. Oven-Dry Density

The average values of oven-dry density determined for Persian oak wood in three different altitude levels and slope classes are presented in Table 2. Multivariate analysis of variance (MANOVA) results revealed no significant differences between mean values of oven-dry density at altitude levels and slope classes (Table 3). The highest (0.83 g/cm³) and lowest (0.73 g/cm³) values of oven-dry density were identified in the intermediate altitude step on the slope of 30–45% and in the lowest altitude on the slope of <30%, respectively. Overall, a mean value of oven-dry density of 0.78 g/cm³ and a coefficient of variation of 7.84% was achieved for Persian oak wood.

Table 2. The average (standard deviation) of physical properties in three different altitudes and slope classes of Persian oak in the Bazoft region forest of Chaharmahal Va Bakhtiari, Iran.

Wood Properties	Altitude (m)								
	1730 m (Low)			1980 m (Intermediate)			2250 m (High)		
	Slope <30%	Slope 30–45%	Slope >45%	Slope <30%	Slope 30–45%	Slope >45%	Slope <30%	Slope 30–45%	Slope >45%
Oven-dry density (g/cm ³)	0.73 (0.05)	0.80 (0.01)	0.78 (0.02)	0.78 (0.01)	0.83 (0.16)	0.78 (0.09)	0.81 (0.01)	0.78 (0.05)	0.74 (0.03)
Volumetric swelling (%)	12.53 (0.69)	12.58 (1.23)	10.92 (1.50)	19.91 (0.07)	21.74 (0.39)	20.01 (1.91)	19.33 (1.12)	19.13 (2.07)	19.91 (2.67)

Standard deviations are displayed in parentheses.

Table 3. Multivariate analysis of Variance (MANOVA) results of wood properties.

Source of Variation	Wood Properties	Sum of Squares	DF	Mean Square	F	Sig.
Altitude	Oven-dry density	0.003	2	0.001	0.332	0.722 ^{ns}
	Volumetric swelling	388.719	2	194.360	84.531	0.000 ^{**}
	Fiber length	0.136	2	0.068	168.064	0.000 ^{**}
	Fiber diameter	18.025	2	9.012	23.417	0.000 ^{**}
	Cell wall thickness	0.021	2	0.010	0.216	0.808 ^{ns}
	MADI	0.052	2	0.026	3.684	0.046 [*]
Slope	Oven-dry density	0.007	2	0.003	0.828	0.453 ^{ns}
	Volumetric swelling	3.490	2	1.745	0.759	0.483 ^{ns}
	Fiber length	0.014	2	0.007	17.239	0.000 ^{**}
	Fiber diameter	6.778	2	3.389	8.805	0.002 ^{**}
	Cell wall thickness	0.225	2	0.112	2.320	0.127 ^{ns}
	MADI	0.052	2	0.026	3.645	0.047 [*]

DF: Degree of Freedom, F: F-test, * Significant (Sig.) at the 0.05 significance level, ** significant at the 0.01 significance level, ^{ns} not significant. Mean annual diameter increment (MADI).

3.2. Volumetric Swelling

Table 2 shows the mean values of volumetric swelling for Persian oak. From the MANOVA, it can be derived that the effects of altitude levels and slope classes on volumetric swelling are significant at the 0.01 significance level (Table 3). The highest (21.74%) and lowest (10.92%) values of volumetric swelling were found in the intermediate altitude level on the slope of 30–45% and in the lowest altitude step on the slope of >45%, respectively. Overall, a mean value of volumetric swelling of 17.34% and a coefficient of variation of 23.80% were determined.

3.3. Fiber Length

The highest (0.96 mm) and lowest (0.70 mm) values of fiber length were found in the lowest altitude step on the slope of 30–45% and in the high altitude on the slope of >45%, respectively (Table 4). Average values of fiber length (0.87 mm) and coefficient of variation (2.05%) were achieved in total. According to the results of MANOVA, altitude and slope have a significant statistical effect on the fiber length at the 99% confidence interval (Table 3).

Table 4. The average values of fiber dimensions in three different altitudes and slope of Persian oak in the Bazoft region forest of Chaharmahal Va Bakhtiari, Iran.

Wood Properties	Altitude (m)								
	1730 m (Low)			1980 m (Intermediate)			2250 m (High)		
	Slope <30%	Slope 30–45%	Slope >45%	Slope <30%	Slope 30–45%	Slope >45%	Slope <30%	Slope 30–45%	Slope >45%
Fiber length (mm)	0.94 (0.02)	0.96 (0.03)	0.92 (0.01)	0.87 (0.01)	0.92 (0.01)	0.91 (0.02)	0.81 (0.02)	0.82 (0.02)	0.70 (0.04)
Fiber diameter (µm)	21.54 (1.71)	23.30 (0.40)	20.09 (0.10)	19.70 (0.01)	20.09 (0.19)	19.82 (0.26)	20.06 (0.06)	20.00 (0.12)	19.81 (0.52)
Cell wall thickness (µm)	6.02 (0.03)	5.55 (0.15)	5.71 (0.05)	5.84 (0.02)	5.95 (0.06)	5.82 (0.63)	5.78 (0.03)	5.83 (0.02)	5.83 (0.08)

Standard deviations are displayed in parentheses.

3.4. Fiber Diameter

A maximum value of 23.30 µm and a minimum value of 19.70 µm for fiber diameter were determined in the lowest altitude level on the slope of 30–45% and in the highest altitude level on the slope of <30%, respectively (Table 4). Overall, average values of fiber diameter of 20.49 µm and coefficient of variation of 9.42% were determined. MANOVA test results indicate significant differences between average values of fiber diameter between three altitude and slope groups at the 99% confidence interval (Table 3).

3.5. Cell Wall Thickness

The maximum value of the parameter cell wall thickness (6.02 µm) as well as the minimum (5.55 µm) were determined for the selected oak trees in the lowest altitude level on the slope of <30% and in the lowest altitude level on the slope of 30–45%, respectively (Table 4). In total, average values of cell wall thickness of 5.77 µm and coefficient of variation of 3.95% were achieved. MANOVA results in Table 3 reveal that both altitude and slope have no effect on the parameter cell wall thickness.

3.6. Principal Component Analysis

The results of Kaiser–Meyer–Olkin (KMO = 0.57) and Bartlett’s test of sphericity ($p < 0.01$) confirmed the adequacy of dataset for PCA. The transformed parameters of the measured traits were projected onto two dimensional planes generated by the first two canonical axes (Figure 3). Graph of study parameter and biplot of sample plots as well as study parameter based on first and second components are presented in Figures 3 and 4. Canonical Axis 1 represented 33.62% of the variability, while the variance accounted for by Canonical Axes 2 and 3 represented 23.52% and 12.33% of the variability, respectively (Figure 3 and Table 5). The analysis of the PCA shows that three components explain 69.47% of the total variance (Table 5). Similar directions with respect to the origin revealed high correlations between the parameter of the measured traits. This is related to the volumetric swelling, fiber diameter and fiber length. Total variance explained by five principal components is 85.68% (Table 5).

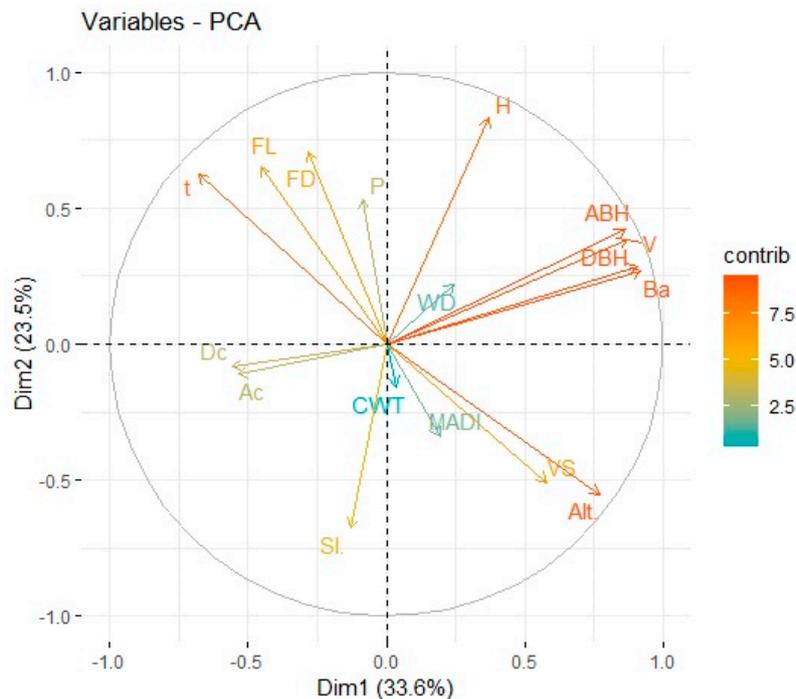


Figure 3. Graph of study variables based on first and second components. Notes: ¹ Dc, crown diameter, crown width in m measured from below the tree in the field; ² population level mean of tree-level mean fiber length weighted by Basal Area; ³ population level mean of tree-level standard deviation of fiber length calculated from a weighted variance function; ⁴ population level mean of tree-level coefficient of variation ((St. Dev/Mean) × 100) calculated from a weighted variance function; ⁵ H, tree height (m); ⁶ DBH, tree diameter at breast height (cm); ⁷ ABH, tree age at breast height (year); ⁸ MADI, mean annual diameter increment (mm); ⁹ Ba, stem basal area (m²); ¹⁰ V, stem volume (m³); ¹¹ Ac, crown basal area (m²); ¹² Alt., altitude (m a.s.l.); ¹³ Sl., slope (%); ¹⁴ P, mean annual precipitation (mm); ¹⁵ t, mean annual temperature (°C); ¹⁶ WD, wood oven-dry density (g/cm³); ¹⁷ VS, volumetric swelling (%); ¹⁸ FD, fiber diameter (μm); ¹⁹ FL, fiber length (mm); ²⁰ CWT, cell wall thickness (μm); ²¹ Dim1, first component; ²² Dim2, second component; ²³ contrib, variance explained by traits on first and second components; ²⁴ PCA, principal component analysis.

The first component explains 33.62% of the total variance and is most highly correlated with the following study variables: tree volume, DBH, tree basal area, tree age and tree height. These traits are not particularly correlated with the other principal components. The second component describes 23.52% of the variance mainly influenced by the volumetric swelling, altitude, temperature, fiber diameter and fiber length. The third component explains 12.33% of the total variance relating to the tree crown diameter and tree crown basal area. The fourth component describes 9.64% of the variance influenced by the tree annual diameter increment, slope and precipitation. The fifth component explains 6.57% of the variance influenced by the settings cell wall thickness and oven-dry wood density (Tables 5 and 6).

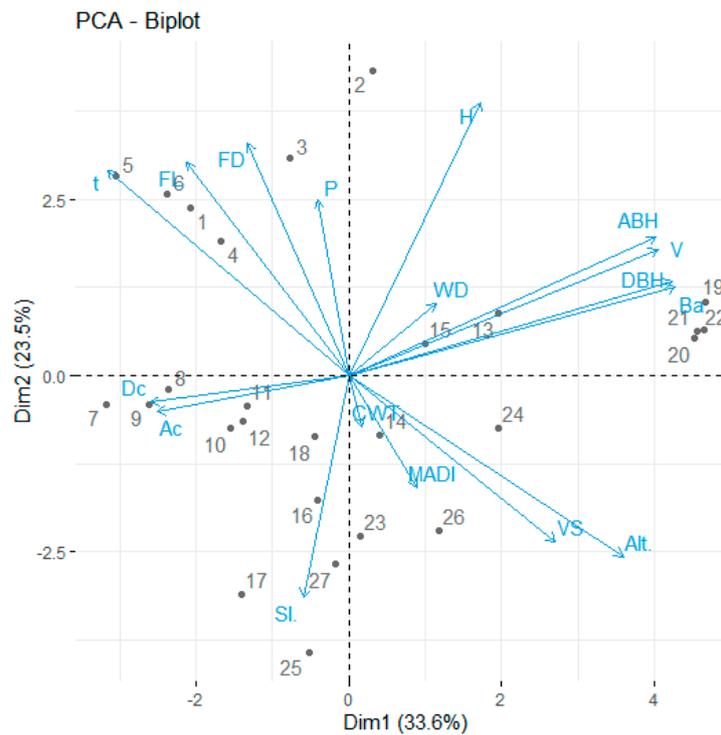


Figure 4. Biplot of sample plots and study variables based on first and second components. Notes: Dc, crown diameter; H, tree height (m); DBH, tree diameter at breast height (cm); ABH, tree age at breast height (year); MADI, mean annual diameter increment (mm); Ba, stem basal area (m²); V, stem volume (m³); Ac, crown basal area (m²); Alt., altitude (m a.s.l); Sl., slope (%); P, mean annual precipitation (mm); t, mean annual temperature (°C); WD, wood oven-dry density (g/cm³); VS, volumetric swelling (%); FD, fiber diameter (µm); FL, fiber length (mm); CWT, cell wall thickness (µm).

Table 5. Total variance explained and calculated eigenvalues for the principal components.

Component	Total Variance Explained		
	Total	Percent of Variance	Cumulative Percent
1	5.715	33.615	33.615
2	3.999	23.522	57.136
3	2.096	12.330	69.466
4	1.639	9.639	79.105
5	1.117	6.570	85.675
6	0.916	5.390	91.065
7	0.661	3.891	94.956
8	0.358	2.104	97.060
9	0.228	1.340	98.400
10	0.121	0.712	99.112
11	0.087	0.514	99.626
12	0.029	0.170	99.796
13	0.021	0.125	99.921
14	0.010	0.062	99.983
15	0.002	0.014	99.996
16	0.001	0.003	99.999
17	9.669 × 10 ⁻⁵	0.001	100.000

Table 6. Factor load traits in each of the principal components.

	Component				
	1	2	3	4	5
Precipitation	0.130	0.282	0.022	−0.628 *	−0.192
Temperature	−0.201	0.820 *	0.266	−0.267	0.066
Altitude	0.297	−0.859 *	−0.282	0.152	−0.067
Slope	−0.321	−0.246	0.134	0.772 *	0.175
DBH	0.963 *	−0.212	−0.120	0.046	0.019
Tree Height	0.788 *	0.469	0.010	−0.214	0.119
Tree crown diameter	−0.197	0.159	0.943 *	0.082	−0.073
Tree basal area	0.958 *	−0.225	−0.137	0.067	0.025
Tree crown basal area	−0.190	0.134	0.941 *	0.105	−0.097
Tree Volume	0.975 *	−0.106	−0.144	0.017	0.007
Tree Age	0.915 *	−0.184	−0.168	−0.219	0.081
Tree annual diameter increment	0.244	−0.031	0.124	0.840 *	−0.268
Oven-dry Density	0.288	−0.019	0.079	0.013	0.827 *
Fiber length	−0.040	0.739 *	0.136	−0.216	0.269
Fiber diameter	0.045	0.784 *	−0.266	−0.195	0.024
Cell wall thickness	0.120	−0.164	0.303	−0.075	−0.833 *
Volumetric swelling	0.120	−0.869 *	−0.109	−0.092	0.181

* Features that contributed most for Axes 1–5. Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. a. Rotation converged in 5 iterations.

4. Discussion

Denser woods are characterized by higher mechanical properties and are more resistant to (mechanical) failures. Wood density is generally a complex variable and is related to many factors such as anatomical characteristics, e.g., vessel and fiber morphology, ecological site, moisture content and chemical constituents [29,30]. In the present study, the density of *Q. brantii* is higher than that of *Q. robur* [31], *Q. cerris* [32] and *Q. rubra* L. [33]. However, oven-dry density values of *Q. brantii* evaluated for the Lordegan site in Iran (1.01 g/cm³, [25]) are significantly higher as compared to values of the Bazoft region in this study. This difference could be related to the site effects and stand age. Regarding the impact of site factors, there are no significant differences for average values of oven-dry density between altitudes and slope groups. This agrees well with findings by Guilley et al. [34] for *Q. petraea*. Overall, the highest average value of oven-dry density was found in the intermediate altitude. These findings are in line with previous findings of Sopushynskyy et al. [35] for *F. sylvatica* L and Kaygin et al. [17] for *P. sylvestris* L. However, Berges et al. [24] indicated that wood density decreased with increasing altitude for sessile oak.

Furthermore, the volumetric swelling is mainly affected by wood density (Guler et al. [36]). In the current study, the high altitude corresponds to the higher volumetric swelling, while the lowest altitude level had the lowest volumetric swelling. As is well known, the relationship between wood density and volumetric swelling is positive [29]. A similar finding was reported by Kiaei [37] for *Carpinus betulus*.

Fiber morphology and orientation are the primary elements responsible for the strength of wood and play an important role in determining the qualitative and quantitative wood properties and specific utilization of lignocellulosic materials [38,39]. The statistical evaluation of the wood fiber dimensions show that the altitude affects fiber length and fiber diameter of Persian oak but it is not influencing cell wall thickness. The average value of fiber length and fiber diameter declined while cell wall thickness increased with increasing altitude. Similar observations were previously reported by Kiaei et al. [11] for *Carpinus betulus*, Noshiro et al. [18] for *Alnus nepalensis* and Yılmaz et al. [19] for *Quercus pontica*.

According to Wheeler et al. [40], fibers are classified into three groups: (1) short fibers with a length less than 0.90 mm; (2) fibers of medium length between 0.90 and 1.90 mm, including Persian oak with an average fiber length of 0.95 mm; and (3) fibers longer than 1.90 mm.

The measured average fiber length of Persian oak is lower than that reported, e.g., for Cork oak [41] and most hardwoods [42].

Fiber diameter and cell wall thickness depend on exogenous growth conditions and annual ring width [30]. The average value of fiber diameter of Persian oak wood at different altitude and slopes amounts to 20.49 μm , which is in agreement with those values reported for other hardwood fibers [43]. Plomion et al. [44] reported that the variations in the fiber diameter depend on molecular and physiological changes occurring in the vascular cambium as well as in the wood cell walls throughout the tree growth.

Cell wall thickness plays a key role in wood quality and its strength properties. Basically, this important anatomical parameter is variable among species and sites, between and within trees, and it is as well highly correlated with wood density. A positive correlation between wood density and cell wall thickness is described by many researchers (e.g., [10,45]). According to the results of the present study, the highest average values of wood density and cell wall thickness were obtained at the altitude of 1800–2000 m. The increased density at the representative altitudes can be explained with higher fiber cell wall thickness and content of cellulose, lignin and extractives [11]. For comparable oak species of *Q. acutissima*, *Q. dealbata*, *Q. fenestrata*, *Q. lanceofolia* and *Q. semiserrata*, cell wall thicknesses of fibers in the range of 7.49–18.26, 5.30–19.86, 6.49–17.05, 7.52–27.42 and 6.37–14.92 μm were described, respectively, by Sharma et al. [46]. The values of these oak species are slightly higher as compared to the results of our own measurements for *Q. brantii*, which can be explained by individual genetic, physiological and silvicultural impacts.

By using PCA, not only the number of comparisons between treatment means is reduced, but also the meaningfulness of these comparisons is enhanced. In the present study, multivariate analysis was used to identify obvious differences in wood properties and the selected traits. The results show that the first axis has the highest correlation with tree-level traits and the second axis has the highest correlation with the traits wood properties, altitude and temperature. Comparable results were reported by Kiaei et al. [11], Noshiro et al. [18], Yilmaz et al. [19] and Kaygin et al. [23].

As mentioned above, the location of the traits wood properties, tree characteristics and forest stand in different regions of PCA axes is based on correlation coefficients between the traits. Therefore, the location of the traits in the diagram (Figure 3) is significant and important. For example, the traits forest stands and wood properties that occupied a specific region and are close to each other have several similar characteristics between each other and consequently the correlation coefficient between those characteristics occupying opposites places in the diagram (Figure 3); for example, opposite directions of an axis show distinct variations. According to the PCA results, altitude and temperature are the most important traits affecting the wood properties. Rossi et al. (2015) [13] and Van Der Maaten-Theunissen et al. (2013) [47] pointed that variations in the wood properties are anticipated, especially in terms of latitude and altitude, which are inherently related to temperature and rainfall. Summarizing, PCA shows noticeable variations of wood properties in the study area across altitude and slope gradient. Since this method is of high accuracy and has different abilities, it could be used for a habitat analysis and determination of effective ecological factors. Analyzing ecological data using ordination methods provides a simpler understanding of the complex relationship among growth traits, wood properties and environmental gradients. In addition, this method is impaired by the existence of ineffective factors and the data complexity of ecological methods. Further work is needed to investigate the anatomical properties (fibers proportions, rays, vessels and parenchyma), ring width and cambial age changes with geographic variations.

5. Conclusions

In the present study, physical and wood fiber properties of Persian oak wood were investigated at different altitudes above the sea level and slopes. The results indicate that there is a significant statistical effect of altitude and slope on the fiber length, fiber diameter and volumetric swelling of Persian oak wood. In contrast, no significant differences were found between average values of oven-dry density. The results also show that altitude and temperature are the most important factors affecting the wood properties, as shown by PCA analysis. Respective study can be used for predication of wood quality

due to climate change. The properties of the wood from higher altitude will become similar to the wood from lower altitudes.

Author Contributions: N.N., data curation; M.B., designing and performing experiments and writing the original paper; S.K., analyzing data and editing; M.H., review and editing; and G.K., review and editing. All authors have read and agreed to the published version of the manuscript

Funding: This research received no external funding.

Acknowledgments: We thank Shahrekord University and Gesellschaft der Förderer und Freunde des Zentrums Holzwirtschaft der Universität Hamburg for financial support.

Conflicts of Interest: The authors declare no conflict of interest.

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