https://doi.org/10.22320/s0718221x/2024.30

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Anatomy-based papermaking potential of some woody plants under different ecological conditions

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Abstract:
The increasing use of wood in the forest industry and reduction of forest resources have prompted the paper industry to look for new materials. To this end, this study examined the biometric coefficients of the seven woody stems grown in different regions and investigated suitability for papermaking as an alternative to the use of wood. Wood samples of each species were collected from two different regions in Türkiye: the Kozan region, which has a Mediterranean climate, and the Yuvacık region, which has a mostly oceanic climate. The species included in the study were *Phillyrea latifolia* (mock privet), *Arbutus andrachne* (greek strawberry tree), *Erica arborea* (tree heath), *Spartium junceum* (spanish broom), *Laurus nobilis* (bay tree), *Pistacia turpentine* (cyprus turpentine tree), and *Rhus coriaria* (elm-leaved sumac). All fibers were classified as short. The longest fiber was observed for *Spartium junceum* (spanish broom) in Kozan. The fiber diameter was highest for *Arbutus andrachne* (greek strawberry tree) from Kozan, followed by *Rhus coriaria* (elm-leaved sumac) from Yuvacık and *Laurus nobilis* (bay tree) from Kozan. The fiber dimensions and the relationship between them were statistically analyzed. These included the slenderness ratio, flexibility coefficient, Runkel ratio, rigidity coefficient, Luce's shape factor, F-factor, and Muhlsteph ratio. Although differences in fiber properties were detected between the two regions, it was determined that these were not enough to affect the desired properties for paper production. It was concluded that the fibers could be used in pulp, paperboard, and corrugated board production when mixed with long fibers.

Keywords: Biometric coefficient, fiber length, fiber morphology, papermaking, woody plants.

Received: 24.06.2022
Accepted: 24.01.2024

Introduction

The global production of paper and paperboard reached 401 million metric tons in 2020 (FAO 2022) and in this sector, the most used raw material is wood. Worldwide paper production is expected to increase in the future by 2050 (Bajpai 2016). The increasing use of wood in the forest products industry and the reduction in forest resources have led the paper industry to search for new and different raw materials such as woody plants, bamboo, recycled fibers, bagasse, wheat straw, rice husk, etc. Woody plants are being considered among such alternative materials because of the similarity of their structure to wood. Studies have been carried out on the suitability of fibers of woody plants for papermaking and are still being carried out (Yaman and Gencer 2005, Yiğit *et al*. 2021, Maiti *et al.* 2016, Kalyoncu and Ondaral 2021, Sadiku *et al.* 2016, Hızal and Koçer 2023) .

Türkiye is one of the richest areas for flora in the world; it is one of the richest countries in terms of biodiversity. This status is related to the geographical location of the country at the junction of different floristic regions and to its different topographic and climatic features (Yaltırık and Efe 1989, Ekim and Güner 2000, Çolak *et al*. 2010, Özhatay *et al*. 2013). The most important feature that distinguishes Türkiye from other regions in the temperate zone is its plant diversity. The flora of Türkiye can be distinguished according to three floristic regions: Europe-Siberia, Mediterranean, and Iran-Turan. These are divided according to climate types, geomorphological features, diversity, the presence of different wetland types, different ecosystem types, and the presence of the Anatolian diagonal connecting North Anatolia to South Anatolia (Avcı 1993). This diversity also affects the plant structure. Many studies have revealed that environmental factors may cause differentiation in the anatomical features of wood and consequently, the fibers. The properties of wood fiber (fiber morphology) vary greatly according to the age, type, ecological conditions, site, and genetics of the tree (Zobel and Van Buijtenen 1989, Kırcı 2000). However, information on wood anatomical characters depending on different ecological conditions is insufficient, especially for wood fibers.

Investigation of the fiber is an important factor in estimating the pulp quality of any fiber material (Ogunsanwo 2000, Pirralho *et al* 2014, Anupam *et al.* 2016, Rodriguez *et al.* 2016). The morphology of the fiber and its derived indices correlates with most of the strength properties of pulp (Oluwadare and Ashimiyu 2007, Dutt and Tyagi 2011, Yahya *et al*. 2020). For example, paper from long fibers is higher in strength. Fibers with thinner cell walls are more flexible and thus, the paper will have higher tensile strength, compression strength, burst strength, and elasticity (Tofanica *et al.* 2011, Boadu *et al.* 2020). Paper made from fibers with large lumens and thin walls has good strength properties because of the bondability between fibers (Dutt and Tyagi 2011, Anupam *et al*. 2016).

Due to the increase in wood and fiber demand and the decrease in wood supply, the pulp and paper industry has started to search for alternative raw materials. Hence there is a need to investigate the new raw materials for the pulp and paper industry. The objectives of the present study were to examine the effects of different ecological factors on the fiber characteristics of seven wood species of the Mediterranean maquis, namely greek strawberry tree (*Arbutus andrachne* L.), tree heath (*Erica arborea* L.), mock privet (*Phillyrea latifolia* L.), bay tree (*Laurus nobilis* L.), cyprus turpentine tree (*Pistacia terebinthus* L.), elm-leaved sumac (*Rhus coriaria* L.), and spanish broom (*Spartium junceum* L.), estimate their suitability for paper production using various biometric coefficients and asses their potential as raw materials for paper production by comparing their examined properties with those of some woods. Thus, it will be revealed whether the species growing in different regions examined in the study can be an alternative raw material for the paper industry, which is experiencing a shortage of wood raw materials.

Materials and methods

Materials

Wood *s*amples were obtained from the district of Kozan (Adana) and Yuvacık (Kocaeli) in Türkiye, where the species grow in natural forests. Kozan is located at 37° 14′ - 37° 38′ N, 35° 40′- 35° 55′ E and Yuvacık at 40° 32′ - 40° 41 ′ N, 29° 29′ - 30° 08′ E. The altitude at which the species grow ranges between 650 m (for Kozan) and 843 m (for Yuvacık). The mean annual precipitation and temperature (January/July) values of the study areas are 725 mm and 6,4 ºC/26,8 ºC for Kozan and 771 mm and 6 ºC/23 ºC for Yuvacık.

The Mediterranean climate prevails in the Adana (Kozan) region, which has all the characteristics of this climate and is distinguished by hot summers and dry winters. The south-facing parts are warm and rainy. The natural vegetation consists of Turkish pine, which has a high light demand and is resistant to drought. In places where these have been degraded, evergreen maquis can be found (Adana Forest Regional Directorate 2014). According to the Thornthwaite water balance assessment, the Kocaeli (Yuvacık) basin has a medium temperature, no water deficit, and a humid climate type that includes conditions close to those of an oceanic climate (Zengin *et al.* 2005) (Figure 1).

Figure 1: Yuvacık basin and Kozan district (Google Earth 2022).

This study investigated seven different species belonging to the *Ericaceae*, *Oleaceae*, *Lauraceae*, *Anacardiacaea*, and *Fabaceae* families. Bay tree (*Laurus nobilis* L.) is a small tree and all of the others are shrubs. A list of the species used in the study with their common names is provided in Table 1.

Table 1: Wood samples used; their botanical name, family, common and local names.

Species	Family	Common name	Height (m)	Diameter (cm)	Age (years)
Arbutus andrachne L.	*Ericaceae*	Greek strawberry tree	3-6	3,6-3,7	9-13
Erica arborea L.	*Ericaceae*	Tree heather	1,2-2	2,5-2,8	16-18
Phillyrea latifolia L.	*Oleacea*	Mock privet	1,8-3	2,8-4,8	42-44
Laurus nobilis L.	*Lauraceae*	Bay tree	4,2-7	6,8-8,1	19-20
Pistacia terebinthus L.	*Anacardiacaea*	Cyprus turpentine tree	2,1-2,5	3,5-4,2	15-16
Rhus coriaria L.	*Anacardiacaea*	Elm-leaved sumac	2-3,6	3,9-4,4	10-11
Spartium junceum L.	*Fabaceae*	Spanish broom	2-2,5	2,4-5	10-12

Healthy-looking plants with straight stems of each species were selected. Stems of all species were cut into pieces and utilized as fiber sample sources. Since both climate types prevail at different altitudes, sampling from the same altitude was not possible. However, sampling was conducted in areas where the effects of both climate types are clearly seen, and an attempt was made to select samples having similar morphological characteristics (maturity status, diameter, height, etc.). Wood samples of each species with a thickness of 5 cm were at a height of 30 cm above the ground. The wood pieces were then taken to the Wood Anatomy Laboratory at the Faculty of Forestry in Düzce University, Düzce, Türkiye.

Methods

Wood samples were cut into approximately the size of a matchstick. Maceration was carried out according to Schultz's method as adopted by Merev (1998). The matchstick samples were placed in test tubes to which was added potassium chlorate ($KClO_3$) and nitric acid (HNO_3) (1:1) and these were then heated at 60 °C. The setup was allowed to react in a fume cupboard until the chips were softened and bleached. Distilled water was then poured into each tube and the bleached and softened sticks were washed several times until the distilled water became clear. The washed fibers were filtered and then rinsed with alcohol. The liquid samples were stored in bottles with added glycerin and stained with safranin.

The morphological parameters of the unbroken fibers, i.e., fiber length (FL), fiber diameter (FD), fiber cell wall thickness (FCWT), and fiber lumen diameter (FLD) were measured using an Olympus BX51 light microscope (Olympus, Japan) connected to an Olympus DP71 camera with 50 fiber measurements performed for each species according to the International Association of Wood Anatomists (IAWA 1989) standard, and the average measurement was taken. These values were used to calculate the slenderness (felting) ratio (SR), flexibility (elasticity) coefficient (FC), Runkel ratio (RUNK), rigidity coefficient (RIGID), Luce's shape factor (LSF), F-factor (FF), and Muhlsteph ratio (MUHT) of the samples. The equations used are shown below (Casey 1961, Saikia *et al.* 1997, Ogbonnaya *et al.* 1997, Ohshima *et al.* 2005, Sadiku *et al.* 2016) (Equation 1, Equation 2, Equation 3, Equation 4, Equation 5, Equation 6, Equation 7):

$$Slenderness\ (felting)\ ratio = \frac{Fiber\ length\ (FL)}{Fiber\ diameter\ (FD)} \quad (1)$$

$$Flexibility\ coeficient = \left(\frac{Lumen\ diameter}{Fiber\ diameter}\right) x\ 100 \quad (2)$$

$$Runkel\ diameter = \frac{2\ x\ Cell\ Wall\ thickness}{Lumen\ diameter} \quad (3)$$

$$Rigidity\ coefficient = \frac{2\ x\ Cell\ Wall\ thickness}{Fiber\ diameter} \quad (4)$$

$$Luce's\ Shape\ Factor = \frac{Fiber\ diameter^2 - Lumen\ diameter^2}{Fiber\ diameter^2} \quad (5)$$

$$F-\ factor = \left(\frac{Fiber\ length}{Cell\ wall\ thickness}\right) x\ 100 \quad (6)$$

$$Muhlstep\ ratio = \left(\frac{Cell\ wall\ thickness\ area}{Fiber\ cross\ -sectional\ area}\right) x\ 100 \quad (7)$$

The data collected in this study were subjected to a one-way analysis of variance (ANOVA) using the SPSS 21 software package program to test for significant differences between regions. Homogeneous groups were formed by applying Duncan's test if there was a significant difference at the level of p <0,05, and the results were interpreted.

Results and discussion

Fiber morphology

The mean and the standard deviation of fiber length (FL), fiber diameter (FD), fiber lumen diameter (FLD), and cell wall thickness (FCWT), and the differences between the two regions and between species are shown in Table 2. There was a significant difference between regions in fiber length for mock privet (*Phillyrea latifolia* L.), greek strawberry tree (*Arbutus andrachne* L.), tree heath (*Erica arborea* L.), spanish broom (*Spartium junceum* L.), and bay tree (*Laurus nobilis* L.). The fiber of mock privet (*Phillyrea latifolia* L.), spanish broom (*Spartium junceum* L.), and bay tree (*Laurus nobilis* L.) in Kozan were significantly longer compared to the Yuvacık samples. Accordingly, the maximum fiber length was 0,63 mm for spanish broom (*Spartium junceum* L.), and the minimum was 0,32 mm for tree heath (*Erica arborea* L.) in Kozan. However, in Yuvacık, the maximum FL values were 0,47 mm for spanish broom (*Spartium junceum* L.), 0,50 mm for bay tree (*Laurus nobilis* L.), and 0,48 mm for cyprus turpentine tree (*Pistacia terebinthus* L.). It was determined that the FL values of mock privet (*Phillyrea latifolia* L.), spanish broom (*Spartium junceum* L.), and bay tree (*Laurus nobilis* L.)

grown in Kozan were longer than those grown in Yuvacık, while the FL values of greek strawberry tree (*Arbutus andrachne* L.) and tree heath (*Erica arborea* L.) grown in Yuvacık were longer than those grown in Kozan. There was no difference beween the two regions for FL values of cyprus turpentine tree (*Pistacia terebinthus* L.) and elm-leaved sumac (*Rhus coriaria* L.). According to Atchison (1987) and Kırcı (2000), the fiber length of hardwoods is 0,7 - 1,6 mm, whereas the fiber length of softwoods is 3 - 5 mm.

Table 2: Variation in the fiber characteristics of wood/woody species.

Species	Regions	Mean fiber dimensions							
		FL (mm)	*p* <0,05	FD (µm)	*p* <0,05	FLD (µm)	*p* <0,05	FCWT (µm)	*p* <0,05
Phillyrea latifolia L	Kozan Yuvacık	0,45 ±0,07^{c} 0,41 ±0,01^{1}	*	9,99±1,20^{a} 10,12±1,27^{2}	ns	3,62 ±0,9^{a} 3,97 ±0,8^{1}	*	3,19 ±0,39^{bc} 3,08 ±0,45^{2}	ns
Arbutus andrachne L	Kozan Yuvacık	0,38 ±0,05^{b} 0,41 ±0,06^{1}	*	14,01±2,20^{d} 9,65±1,45^{12}	*	6,86±1,64^{d} 4,59±1,13^{1}	*	3,58 ±0,62^{d} 2,53 ±0,47^{1}	*
Erica arborea L.	Kozan Yuvacık	0,32±0,06^{a} 0,39 ±0,06^{1}	*	9,95 ±1,42^{a} 11,8±1,77^{3}	*	3,63 ±1,06^{a} 5,60±1,73^{3}	*	3,16±0,46^{bc} 3,10±0,57^{2}	ns
Spartium junceum L.	Kozan Yuvacık	0,63 ±0,10^{f} 0,47 ±0,09^{2}	*	11,32±1,75^{c} 9,52±1,08^{12}	*	5,38 ±1,6^{c} 3,52±0,89^{1}	*	3,00±0,4^{b} 3,00±0,5^{2}	ns
Laurus nobilis L.	Kozan Yuvacık	0,56±0,07^{e} 0,50 ±0,08^{2}	*	13,64±2,29^{d} 13,45±2,11^{4}	ns	6,99±1,91^{d} 7,52±1,88^{4}	ns	3,33±0,84^{c} 2,97±0,62^{2}	*
Pistacia terebinthus L.	Kozan Yuvacık	0,49 ±0,12^{d} 0,48 ±0,12^{2}	ns	10,48±1,42^{ab} 9,2±1,17^{1}	*	4,39±0,94^{b} 3,91±0,87^{1}	*	3,04±0,46^{b} 2,64±0,36^{1}	*
Rhus coriaria L.	Kozan Yuvacık	0,42±0,08^{c} 0,41±0,07^{1}	ns	10,81±1,55^{bc} 13,71±1,36^{4}	*	5,62±1,46^{c} 5,77±1,39^{3}	ns	2,59 ±0,4^{a} 3,97±0,49^{3}	*

Alphabetic characters indicate the species in Kozan; numeric characters indicate the species in Yuvacık,
[*] Significant at 0,05 level and ns Non-significant level. (FL: Fiber length, FD: Fiber diameter, FLD: Fiber lümen diameter, FCWT: Fiber cell Wall thickness).

According to Metcalfe and Chalk (1983), fibers below 1,60 mm in length, and according to IAWA (1989), fibers below 0,9 mm were classified as short. According to this classification, the mean fiber length of all species was less than 0,6 mm except spanish broom (*Spartium junceum* L.) (0,63 mm) and thus, the fibers of all species were short, as presented in Table 3. Long-fiber pulps have been reported to affect the strength properties of paper positively (Kırcı 2000, Eroğlu and Usta 2004), but may cause formation defects such as flocculation which leads to a more open and less uniform sheet structure (Karlsson 2007). Short fiber lengths are less suitable for paper making than longer fibers (Sadiku and Abdukareem 2019; Okoegwale *et al*. 2020) and paper produced from short fibers is likely to have low tear strength (Ashori and Nourbakhsh 2009, Ekhuemelo *et al*. 2020). When short fibers are mixed with long-fiber pulp, opacity, printability, and stiffness properties are improved (Sadiku and Abdukareem 2019). Previously, it was thought that fiber length alone was effective on paper properties. However, according to recent studies, it has been determined that fiber width, lumen width, and fiber cell wall thickness are also effective on paper properties (Panshin and de Zeeuw 1980, Tutuş and Çiçekler 2016).

There was a significant difference between regions in fiber diameter (FD) for greek strawberry tree (*Arbutus andrachne* L.), tree heath (*Erica arborea* L.), spanish broom (*Spartium junceum* L.), cyprus turpentine tree (*Pistacia terebinthus* L.), and elm-leaved sumac (*Rhus coriaria* L.). The FD of greek strawberry tree (*Arbutus andrachne* L.), spanish broom (*Spartium junceum* L.), cyprus turpentine tree (*Pistacia terebinthus* L.), and elm-leaved sumac (*Rhus coriaria* L.) in Kozan was significantly higher than in Yuvacık. Accordingly, the maximum FD values were found to be 14,01 µm for greek strawberry tree (*Arbutus andrachne* L.) and 13,64 for bay tree (*Laurus nobilis* L.), and the minimum values to be 9,95 µm for tree heath (*Erica arborea* L.) and 9,99 µm for mock privet (*Phillyrea latifolia* L.) in Kozan. However, in Yuvacık, the highest FD was 13,71 µm for elm-leaved sumac (*Rhus coriaria* L.) and the minimum 9,2 µm for cyprus turpentine tree (*Pistacia terebinthus* L.). There was no difference between regions in FD for mock privet (*Phillyrea latifolia* L.) and bay tree (*Laurus nobilis* L.) and in FLD for bay tree (*Laurus nobilis* L.) and elm-leaved sumac (*Rhus coriaria* L.).

There was a significant difference between regions in fiber lumen diameter (FLD) for greek strawberry tree (*Arbutus andrachne* L.), tree heath (*Erica arborea* L.), spanish broom (*Spartium junceum* L.), and cyprus turpentine tree (*Pistacia terebinthus* L.). The maximum FLD values were found to be 6,99 µm for bay tree (*Laurus nobilis* L.) and 6,86 µm for greek strawberry tree (*Arbutus andrachne* L.) in Kozan and as 7,52 µm for bay tree (*Laurus nobilis* L.) in Yuvacık. The minimum FLD values were 3,62 µm for mock privet (*Phillyrea latifolia* L.) and 3,63 µm for tree heath (*Erica arborea* L.) in Kozan and 4,59 µm for greek strawberry tree (*Arbutus andrachne* L.) in Yuvacık. A large and broad lumen diameter ensures better collapsibility and provides sufficient bonding surface during paper production (Ogunkunle 2010). According to this, from both regions, bay tree (*Laurus nobilis* L.) would provide better inter-bonding, whereas cyprus turpentine tree (*Pistacia terebinthus* L.) would provide the poorest.

The ANOVA revealed significant differences between regions in cell wall thickness (FCWT) for greek strawberry tree (*Arbutus andrachne* L.), bay tree (*Laurus nobilis* L.), cyprus turpentine tree (*Pistacia terebinthus* L.), and elm-leaved sumac (*Rhus coriaria* L.). The FCWT of greek strawberry tree (*Arbutus andrachne* L.), bay tree (*Laurus nobilis* L.), and cyprus turpentine tree (*Pistacia terebinthus* L.) in Kozan was significantly higher than in Yuvacık. The maximum FCWT (3,58 µm) was found for greek strawberry tree (*Arbutus andrachne* L.) in Kozan, and the minimum (2,53 µm) for greek strawberry tree (*Arbutus andrachne* L.), in Yuvacık. A thinner cell wall is better for papermaking because it collapses easily and provides an effective bonding surface (Palmer 1973). However, the tearing strength of paper made from very thin-walled fibers is quite low. Extremely thick-walled fibers exhibit low strength and bulk due to insufficient flattening (Kırcı 2000). The fibers of all the selected species from both regions are thin-walled with narrow lumens.

Table 3: Fiber dimension values of all species in the literature.

Species	Regions	FL (mm)	FD (µm)	FLD (µm)	FCWT (µm)	Literature
Phillyrea latifolia L	Kozan	0,45	9,99	3,62	3,19	Current
	Yuvacık	0,41	10,12	3,97	3,08	
Phillyrea latifolia L		0,81	15,56	4,73	5,41	Merev 1998
Phillyrea latifolia L		0,82	-	-	-	Voulgaridis 1990
Phillyrea latifolia L		0,79 (0,47-1,24)	15,27	6,61	4,30	Erşen Bak 2006
Arbutus andrachne L	Kozan	0,38	14,01	6,86	3,58	Current
	Yuvacık	0,41	9,65	4,59	2,53	
Arbutus andrachne L		1,35	18,24	9,70	4,86	Merev 1998
Arbutus andrachne L		0,56	-	-	-	Voulgaridis 1990
Erica arborea L.	Kozan	0,32	9,95	3,63	3,16	Current
	Yuvacık	0,39	11,8	5,60	3,10	
Erica arborea L.		0,67	-	-	-	Voulgaridis 1990
Spartium junceum L.	Kozan	0,63	11,32	5,38	3,00	Current
	Yuvacık	0,47	9,52	3,52	3,00	
Spartium junceum L.		0,7 - 1,35	-	-	-	Merev 2003
Laurus nobilis L.	Kozan	0,56	13,64	6,99	3,33	Current
	Yuvacık	0,50	13,45	7,52	2,97	
Laurus nobilis L.		0,85	23,27	17,50	2,92	Merev 1998
Laurus nobilis L.		0,45 - 0,6	15	-	-	Heo 1998
Laurus nobilis L.		0,47 - 1,27	-	-	-	Merev 2003
Pistacia terebinthus L.	Kozan	0,49	10,48	4,39	3,04	Current
	Yuvacık	0,48	9,2	3,91	2,64	
Pistacia terebinthus L.		0,67	16,09	8,11	3,98	Merev 1998
Pistacia terebinthus L.		0,64	-	-	-	Voulgaridis 1990
Rhus coriaria L.	Kozan	0,42	10,81	5,62	2,59	Current
	Yuvacık	0,41	13,71	5,77	3,97	
Rhus coriaria L.		0,58	15,48	10,82	2,34	Merev 1998
Alnus glutinosa L. Gaertner		1,20	26,46	17,32	4,57	Hızal Tırak and Erdin 2016
Alnus glutinosa		1,34	31,43	-	6,87	Kiaei *et al*. 2016
Populus tremula		1,41	24,8	18	3,4	Atik 1995
Pinus nigra		1,25	27,2	17,2	5	Alkan *et al*. 2003
Fraxinus angustifolia L.		1,20	23,62	18,74	4,88	Hızal Tırak and Erdin 2020
Quercus robur		1,35	18,60	7,40	5,60	Gülsoy *et al.* 2005
Eucalyptus globulus		0,93	21,4	9,1	6,1	Gominho *et al*. 2014
Fagus orientalis		0,67	17,9	-	4,6	Akgül and Tozluoğlu 2009
Salix alba		0,92	20,8	-	5,0	Eroğlu and Usta 2004
Acer platanoides		0,26	21,4	-	3,5	Durmaz and Ateş 2016
Beema bamboo		1,89 - 2,18	26 - 30	16 - 17	5 - 6	Boadu *et al.* 2020
Oxythenantera abyssinica		2,03 - 2,39	25 - 30	14 - 19	5 - 6	Boadu *et al.* 2020

FL: Fiber length, FD: Fiber diameter, FLD: Fiber lümen diameter, FCWT: Fiber cell Wall thickness.

The results in Table 3 indicate that the fiber length (FL) values of all species were lower than those in the literature (Voulgaridis 1990, Merev 1998, Heo 1998, Merev 2003). The FD, FLD, and FCWT values of mock privet (*Phillyrea latifolia* L.), greek strawberry tree (*Arbutus andrachne* L.), and cyprus turpentine tree (*Pistacia terebinthus* L.) were lower than those in the study by Merev (1998). The FL values of the species were lower than the FL values of aspen (*Populus tremula* L.) (Atik 1995), black pine (*Pinus nigra* J.F. Arnold) (Alkan *et al*. 2003), white willow (*Salix alba* L.) (Eroğlu and Usta 2004), english oak (*Quercus robur* L.) (Gülsoy *et al.* 2005), oriental beech (*Fagus orientalis* Lipsky) (Akgül and Tozluoğlu 2009), bluegum eucalyptus (*Eucalyptus globulus* Labill.) (Gominho *et al.* 2014), black alder (*Alnus glutinosa* (L.) Gaertn) (Hızal Tırak and Erdin 2016), and narrow-leaved ash (*Fraxinus angustifolia* Vahl.) (Hızal Tırak and Erdin 2020). In various parts of the world, bamboo fibers are valued as good alternative pulping materials (Musau 2016). Fibers are as long as 2,18 mm for golden bamboo (*Beema bamboo* Roxb.) and 2,39 mm for *Oxythenantera abyssinica* (Boadu *et al.* 2020).

Biometric coefficients

Searching for a relationship between fiber sizes and paper properties is not considered to be a very accurate approach. However, a more objective approach to evaluate paper properties would be one considering the felting ratio, elasticity coefficient, rigidity coefficient, Muhlsteph ratio, and F-factor derived from the fiber sizes (Kırcı 2000).

The derived values obtained from the species in this study are shown in Table 4. The slenderness ratio (SR) of the species was significantly different between Kozan and Yuvacık except for tree heath (*Erica arborea* L.). spanish broom (*Spartium junceum* L.) had the maximum SR (56,67) and greek strawberry tree (*Arbutus andrachne* L.) the minimum SR (27,36) in Kozan. For Yuvacık, the maximum values were 53,31 for cyprus turpentine tree (*Pistacia terebinthus* L.) and 50,41 for spanish broom (*Spartium junceum* L.) and the minimum values 30,45 for elm-leaved sumac (*Rhus coriaria* L.) and 33,37 for tree heath (*Erica arborea* L.). The SR is related to the tearing strength and folding endurance of paper and paper products (Yahya *et al*. 2010). A high SR indicates well-formed and well-bonded paper (Ashori and Nourbakhsh 2009). The most suitable SR value for papermaking is 33 and above. The SR affects the flexibility and resistance to rupture of fibers and paper products (Xu *et al.* 2006). All selected species had high SR except greek strawberry tree (*Arbutus andrachne* L.) (27,36) from Kozan and elm-leaved sumac (*Rhus coriaria* L.) (30,45) from Yuvacık. In the literature, the SR values were 32,98 for black willow (*Salix nigra* Marsh.) (Gülsoy *et al*. 2021), 57,7 for red gum (*Eucalyptus camaldulensis* Dehnh.) (Huş *et al.* 1975), 57 for aspen (*Populus tremula* L.) (Atik 1995), 35,8 for *Punica granatum* (Gülsoy *et al.* 2015), 37,2 for oriental beech (*Fagus orientalis* Lipsky) (Akgül and Tozluoğlu 2009), 39 for red gum (*Eucalyptus camaldulensis* Dehnh.) (Pirralho *et al.* 2014), 12,1 for norway maple (*Acer platanoides* L.) (Durmaz and Ateş 2016), 27,77 for *Rosmarinus officinalis* (Serin *et al.* 2017), 52,84 for *Cornus australis* (Gençer and Aksoy 2017), 55,09 for *Prunus armeniaca* (Gençer *et al.* 2018), and 44,76 for *Olea europea* (Topaloğlu *et al.* 2019).

Table 4: Variation in the biometric coefficients of the wood/woody species.

Species	Regions	SR	p	FC	p	RUNK	p	RIGID	p	LSF	p	FF	p	MUHT	p
Phillyrea latifolia L	Kozan	45,46±9,04 ^{de}	*	0,36±0,07^{a}	*	1,87±0,52 ^{d}	*	32,04±3,22 ^{d}	*	0,87±0,05 ^{d}	*	142,48 ±27,07 ^{b}	ns	86,68^{d} ±4,76	*
	Yuvacık	41,04±9,56^{23}		0,39±0,06$^{1\,2}$		1,61±0,37^{3}		30,45±2,72$^{3\,4}$		0,84±0,04$^{3\,4}$		135,6 ±32,57^{2}		84,42$^{3\,4}$ ±4,34	
Arbutus andrachne L	Kozan	27,36±5,32^{a}	*	0,49±0,07^{cd}	ns	1,11±0,35 ^{ab}	*	25,70±3,51 ^{ab}	ns	0,76±0,07 ^{b}	ns	107,71 ±23,51 ^{a}	*	75,89^{b} ±6,65	ns
	Yuvacık	43,43±9,36^{3}		0,47±0,08^{3}		1,18±0,42^{2}		26,34±3,86^{2}		0,77±0,07^{2}		167,51 ±38,69^{3}		77,02^{2} ±7,28	
Erica arborea L.	Kozan	33,04±7,05 ^{b}	ns	0,36±0,07 ^{a}	*	1,87±0,56 ^{d}	*	31,85±3,69^{d}	*	0,86±0,01^{d}	*	103,67 ±20,55 ^{a}	*	86,43^{d} ±5,48	ns
	Yuvacık	33,37±7,51^{1}		0,47±0,1^{3}		1,23±0,46^{2}		26,59±4,78^{2}		0,77±0,09^{2}		128,92 ±34,28^{2}		77,18^{2} ±9,27	
Spartium junceum L.	Kozan	56,67±11,69^{f}	*	0,47±0,08 ^{c}	*	1,21±0,46^{b}	*	26,60±4,13 ^{b}	*	0,77±0,08 ^{b}	*	216,32 ±47,67 ^{d}	*	77,43^{b} ±7,63	*
	Yuvacık	50,41±11,59^{4}		0,37±0,08^{1}		1,86±0,72^{4}		31,54±4,20^{4}		0,86±0,07^{4}		162,51 ±42,36^{3}		61,68^{4} ±14,75	
Laurus nobilis L.	Kozan	41,88±9,09 ^{cd}	*	0,51±0,1^{cd}	*	1,05±0,51^{ab}	*	24,48±4,85 ^{a}	*	0,73±0,10 ^{a}	*	176,73 ±48,88 ^{c}	ns	73,04^{a} ±9,46	*
	Yuvacık	37,75±8,35^{2}		0,55±0,09^{4}		0,85±0,32^{1}		22,29±4,25^{1}		0,69±0,09^{1}		173,73 ±42,88^{34}		68,58^{1} ±9,35	
Pistacia terebinthus L.	Kozan	47,42±11,64 ^{e}	*	0,42±0,06 ^{b}	ns	1,45±0,36 ^{c}	ns	29,13±2,99 ^{c}	ns	0,82±0,05 ^{c}	ns	163,71 ±39,15 ^{c}	*	82,23^{c} ±5,07	ns
	Yuvacık	53,31±16,29^{4}		0,42±0,06^{2}		1,43±0,43^{3}		28,86±3,09^{3}		0,82±0,05^{3}		186,23 ±59,47^{4}		81,75^{3} ±4,94	
Rhus coriaria L.	Kozan	39,28±8,96 ^{c}	*	0,52±0,08 ^{d}	*	0,99±0,33 ^{a}	*	24,26±4,01 ^{a}	*	0,73±0,08 ^{a}	*	165,38 ±42,91 ^{c}	*	72,86^{a} ±8,26	*
	Yuvacık	30,45±6,33^{1}		0,42±0,08^{2}		1,50±0,61^{3}		29,11±3,81^{3}		0,82±0,06^{3}		105,8 ±23,00^{1}		121,3^{3} ±21,08	

Slenderness ratio (SR), Flexibility coefficient (FC), Runkel ratio (RUNK), Rigidity coefficient (RIGID), Luce's shape factor (LSF), F-factor (FF), Muhlsteph ratio (MUHT), * Significant at 0,05 level and ns Non-significant level.

There was no significant difference between regions for the flexibility coefficient (FC) for values of greek strawberry tree (*Arbutus andrachne* L.) and cyprus turpentine tree (*Pistacia terebinthus* L.). The maximum FC value was 0,55 for bay tree (*Laurus nobilis* L.) in Yuvacık and the minimum was 0,36 for mock privet (*Phillyrea latifolia* L.) and tree heath (*Erica arborea* L.) in Kozan. For Yuvacık, the maximum FC was 0,55 for bay tree (*Laurus nobilis* L.) and the minimum 0,37 for spanish broom (*Spartium junceum* L.). The FC is one of the most important derived indices in determining the strength properties of paper. It also determines the degree of fiber bonding in paper sheet (Smook 1997). Fibers with a high elasticity coefficient (greater than 0,75) and an FC value of 0,50 - 0,75 are considered as elastic fibers. The flexibility of rigid fibers is less than 0,30 - 0,50, and less than 0,30 for highly rigid fibers (Bektaş *et al*. 1999). An increase in the rigidity of fibers results in a decrease in fiber bonding. Thus, this type of fiber is undesirable in paper production. Since such fibers have thick walls, and narrow lumens, and very few show flattening (collapse), the fiber surface contact area is smaller. Therefore, the bonds between the fibers are weak. All FC values for all species were between 0,30 and 0,50 except for bay tree (*Laurus nobilis* L.) (0,51) and elm-leaved sumac (*Rhus coriaria* L.) (0,52) from Kozan and bay tree (*Laurus nobilis* L.) (0,55) from Yuvacık, and these values were in the 2nd group in FC classification, that is they were elastic fibers. These fibers result in better ability and softness compared to the other fibers (Assis *et al*. 2018). Fibers of the other species belonged to the 3rd group in FC classification. They had rigid fibers and these fibers in this category should not be used for writing paper production but may be suitable for manufacturing fiberboard, rigid cardboard, cardboard or packaging paper (Kırcı 2000, Dutt and Tyagi 2011, Kiaei *et al.* 2011). The FC values of 0,51 and 0,55 for bay tree (*Laurus nobilis* L.) in both regions, and 0,52 for elm-leaved sumac (*Rhus coriaria* L.) in Kozan were close to those of *Fagus orientalis* (48,3 %) (Akgül and Tozluoğlu 2009) and red gum (*Eucalyptus camaldulensis* Dehnh.) (53,8 %) (Huş *et al.* 1975). All FC values were lower than those of aspen (*Populus tremula* L.) (72,5 %) (Atik 1995), norway maple (*Acer platanoides* L.) (71,9 %) (Durmaz and Ateş 2016), and 64/12 clones of *S. excelsa* (64,4 %) (Elmas *et al*. 2018).

There was a significant difference in Runkel ratios between regions except for cyprus turpentine tree (*Pistacia terebinthus* L.). In Kozan, the maximum Runkel ratio (RUNK) value was 1,87 for mock privet (*Phillyrea latifolia* L.) and tree heath (*Erica arborea* L.) and the minimum was 0,99 for elm-leaved sumac (*Rhus coriaria* L.). The highest RUNK value was 1,86 for spanish broom (*Spartium junceum* L.) and the lowest value was 0,85 for bay tree (*Laurus nobilis* L.) in Yuvacık. In other studies, the RUNK value was reported as 0,86 for red gum (*Eucalyptus camaldulensis* Dehnh.) (Huş *et al*. 1975), 0,4 for aspen (*Populus tremula* L.) (Atik 1995), 1,1 for oriental beech (*Fagus orientalis* Lipsky) (Akgül and Tozluoğlu 2009), 1,8 for bluegum eucalyptus (*Eucalyptus globulus* Labill.), 0,5 for manna gum (*Eucalyptus viminalis* Labill.) (Pirralho *et al.* 2014), 0,8 for norway maple (*Acer platanoides* L.) (Durmaz and Ateş 2016), 1,16 for *Cornus australis* (Gençer and Aksoy 2017), 0,99 for *Prunus armeniaca* (Gençer *et al.* 2018), 0,78 for *Olea europea* (Topaloğlu *et al.* 2019), and 0,70 for *Eucalyptus* sp. (Rahmanto *et al.* 2021). The RUNK is the most important and primary parameter used to determine the suitability of fibers for papermaking. The most suitable RUNK value for paper production is less than 1 (Kpikpi 1992), and when the RUNK is greater than 1, the fibers are assessed as having thick walls, and the cellulose obtained from this type of fiber is the least suitable (Eroğlu 1980) and of poor quality for papermaking (Sadiku and Abdukareem 2019). In addition, Bektaş *et al.* (1999) stated that a higher RUNK lowers paper strength properties, especially the burst, tear, and tensile indices. Consequently, bay tree (*Laurus nobilis* L.) from Yuvacık (0,85) and elm-leaved sumac (*Rhus coriaria* L.) from Kozan (0,99) might be expected to produce good paper.

The magnitude of the rigidity coefficient (RIGID) and the physical strength of the paper, especially the bursting, rupture (Bostancı 1987), and bending resistance (Takeuchi *et al*. 2016), have a negative effect on folding resistance (Tofanica *et al*. 2011). A RIGID value of ≤50 is normally seen to produce good pulp wood. This increases the collapsibility of the fibers to make a flexible and strong paper sheet (Tamolang and Wangaard 1961). As seen in Table 4, the RIGID value varied between 22,29 and 32,04. The maximum RIGID values were 32,04 for mock privet (*Phillyrea latifolia* L.) and 31,85 for tree heath (*Erica arborea* L.) in Kozan and 31,54 for spanish broom (*Spartium junceum* L.) in Yuvacık, whereas the minimum values were found to be 24,26 for elm-leaved sumac (*Rhus coriaria* L.) and 24,48 for bay tree (*Laurus nobilis* L.) in Kozan and 22,29 for bay tree (*Laurus nobilis* L.) in Yuvacık. There was significant variance between regions for mock privet (*Phillyrea latifolia* L.), tree heath (*Erica arborea* L.), spanish broom (*Spartium junceum* L.), bay tree (*Laurus nobilis* L.), and elm-leaved sumac (*Rhus coriaria* L.). According to these results, paper made from all seven species from the two regions would have high rigidity and thus, would have less tensile, tear, burst, and double-fold resistance, making them suitable raw material for pulp and papermaking. In the literature, the RIGID values in some broad-leaved trees have been reported, e.g., 27,80 for plane (Bektaş *et al*. 1999), 27,66 for *Eucalyptus* sp. (Hus *et al.* 1975), 42,0 for oriental hornbeam (*Carpinus orientalis* Mill.) (Tank 1978), and 15,28 for *Robinia* sp. (Liao *et al.* 1981). The RIGID values for softwoods have been found as 19,97 for scots pine (*Pinus sylvestris* L.) (Akkayan 1983), 20,0 for turkish pine (*Pinus brutia* Ten.), 17,82 for maritime pine (*Pinus pinaster* Ait.) (Bektaş *et al.* 1999), and 16,24 for oriental spruce (*Picea orientalis* (L.) Peterm.) (Bostancı 1976). According to these values, the rigidity coefficient of all the woody species fibers was higher compared to softwoods and close to that of other hardwoods.

For Luce's shape factor (LSF), there was significant variance between the regions for mock privet (*Phillyrea latifolia* L.), tree heath (*Erica arborea* L.), spanish broom (*Spartium junceum* L.), bay tree (*Laurus nobilis* L.), and elm-leaved sumac (*Rhus coriaria* L.). The LSF values obtained from the species were 0,73 - 0,87 in Kozan and 0,69 - 0,84 in Yuvacık. The maximum LSF values were 0,86 for tree heath (*Erica arborea* L.) and 0,87 mock privet (*Phillyrea latifolia* L.) in Kozan and 0,86 for spanish broom (*Spartium junceum* L.) and 0,84 for mock privet (*Phillyrea latifolia* L.) in Yuvacık. The minimum LSF values were 0,73 for bay tree (*Laurus nobilis* L.) and elm-leaved sumac (*Rhus coriaria* L.) in Kozan and 0,69 for bay tree (*Laurus nobilis* L.) in Yuvacık. The LSF is related to paper sheet density (Kaur and Dutt 2013) and a low LSF value could be significantly correlated to the breaking length of paper (Ona *et al.*

2001). A low LSF value has been reported to indicate decreased resistance to beating in paper production (Luce 1970).

The F-factor (FF) is one of the important parameters for the papermaking industry and indicates the filexibility of fibers and more filexible fibers have more inter-fiber contact (Sadiku and Abdukareem 2019). Increasing FF values yield usable fibers (Tunçtaner *et al.* 2003, İstek *et al.* 2009). There was no significant difference between regions for mock privet (*Phillyrea latifolia* L.) and bay tree (*Laurus nobilis* L.). The maximum FF value was 216,32 for spanish broom (*Spartium junceum* L.) in Kozan, and 186,23 for cyprus turpentine tree (*Pistacia terebinthus* L.) in Yuvacık, and the minimum FF values were calculated as 103,67 for tree heath (*Erica arborea* L.) and 107,71 for greek strawberry tree (*Arbutus andrachne* L.) in Kozan and 105,8 for elm-leaved sumac (*Rhus coriaria* L.) in Yuvacık. All species from both regions except spanish broom (*Spartium junceum* L.) in Kozan had lower F-factor values than hardwood and softwood, e.g., 235,92 for hybrid black poplar (*Populus euroamericana* Moench), 206,78 for aspen (*Populus tremula* L.) (Kar 2005), 231,4 for willow (*Salix excelsa* S.G.Gmel.) (Elmas *et al.* 2018), 249,1 for red gum (*Eucalyptus camaldulensis* Dehnh.) (Huş *et al.* 1975), 606,66 for turkish pine (*Pinus brutia* Ten.), and 410,34 for cedar of lebanon (*Cedrus libani* A.Rich.) (Erdin 1983). The F-factor values obtained from spanish broom (*Spartium junceum* L.) (Kozan) indicated that this species could be recommended for papermaking.

For the Muhlsteph ratio (MUHT), there was a significant difference between regions for mock privet (*Phillyrea latifolia* L.), spanish broom (*Spartium junceum* L.), bay tree (*Laurus nobilis* L.), and elm-leaved sumac (*Rhus coriaria* L.). The maximum MUHT values were 86,68 for mock privet (*Phillyrea latifolia* L.) and 86,43 for tree heath (*Erica arborea* L.) in Kozan and 121,3 for elm-leaved sumac (*Rhus coriaria* L.) in Yuvacık. The minimum values were 72,86 for elm-leaved sumac (*Rhus coriaria* L.) and 73,04 for bay tree (*Laurus nobilis* L.) in Kozan and 68,58 for bay tree (*Laurus nobilis* L.) in Yuvacık. The MUHT values reported in other studies were found to be 47,4 for aspen (*Populus tremula* L.) (Atik 1995), 48,4 for norway maple (*Acer platanoides* L.) (Durmaz and Ateş 2016), 58,4 for 64/12 willow (*Salix excelsa* S.G. Gmel.) clones (Elmas *et al*. 2018), 76,7 for oriental beech (*Fagus orientalis* Lipsky) (Akgül and Tozluoğlu 2009), and 70,45 for russian olive (*Elaeagnus angustifolia* L.) (Akgül and Akça 2020). Moreover, the MUHT values of the species in the study were similar to those of hybrid poplar and oriental beech (*Fagus orientalis* Lipsky) and higher than the values of aspen (*Populus tremula* L.), norway maple (*Acer platanoides* L.), and 64/12 willow clones. The MUHT affects tearing, tensile, and strength properties of paper. A low MUHT will result in low pulp sheet density with low pulp strength (Przybysz *et al*. 2018). A higher MUHT ratio indicates that the material would be more suitable to produce paperboard and corrugated board rather than paper (Elmas *et al.* 2018).

Conclusions

Fiber length and fiber wall thickness are two important parameters considered for pulp and papermaking. Fibers from all seven studied species were classified as short. All species were determined to have small fiber diameters and thin lumens. The fiber wall thickness did not show significant variation between the regions for *Phillyrea latifolia*, *Erica arborea*, and *Spartium junceum*. FCWT of *Arbutus andrachne*, *Laurus nobilis,* and *Pistacia terebinthus* grown in Kozan were thicker than those grown in Yuvacık. FCWT of *Rhus coriaria* grown in Yuvacık was thicker than those grow in Kozan. Since *Arbutus andrachne* had a slenderness ratio of 27,36, it was found to be unsuitable for papermaking, whereas *Spartium junceum* (slenderness value = 56,67) from Kozan was suitable in this regard. The Runkel ratio for all species was higher than 1, which is not an acceptable value for papermaking, except *Laurus nobilis* (0,85) from Yuvacık and *Rhus coriaria* (0,99) from Kozan. The flexibility coefficient of *Laurus nobilis* from Kozan and Yuvacık and *Rhus coriaria* from Kozan surpassed FC >0,5, as the acceptable value for papermaking, indicating that these fibers were elastic. However, the flexibility coefficient of the other species was less than 50. The rigidity of the fibers was higher than in softwood fiber and therefore, would exhibit less tensile, burst, and double-fold resistance, making them suitable for pulp and papermaking. According to its F-factor value, *Spartium junceum* from Kozan could be recommended for papermaking. The Muhlstep ratio was high for *Rhus coriaria* from Yuvacık, and this value renders it unsuitable for papermaking. The other species had Muhlsteph ratios similar to those of hardwoods and softwoods.

This study investigated the fibers of species taken from different regions, and when each evaluation criterion was examined, interregional differences were observed in terms of fiber values but these differences did not lead to different classifications in terms of suitability for papermaking. Use of the fiber from the species might be suitable in paperboard and corrugated board production. Paper could be produced from fibers of these species by mixing them with long-fiber pulps or recycled paper pulps. Our research on these fibers is important in terms of creating a reference for other academicians studying their utilization.

Authorship contrıbutions

K.T.H.: Writing – original draft, writing - review & editing, methodology, investigation, conceptualization, supervision, visualization, formal analysis T.B.: Conceptualization, resources.

All authors have read and agreed to the published version of the manuscript.

Acknowledgements

The authors thank Esra Baltacı Gürler, who helped us by supplying of some of the wood samples.

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