Anatomical Characterization, Physical, and Chemical Properties of Wood of *Quercus macdougallii* Martínez, Endemic Species of the Sierra Juárez of Oaxaca, Mexico

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The anatomical characteristics and the physical and chemical properties of wood of *Quercus macdougallii* Martínez are presented for the first time. *Q. macdougallii* Martínez is an endemic species of the Sierra Juarez of Oaxaca. The microscopic characteristics were described in preparations of typical cuts and dissociated material. The physical properties were evaluated according to the ASTM D 143-94 standard in sapwood and heartwood specimens. The measurable elements and physical properties were classified according to the mean. With the measurable elements, the paper pulp quality index was determined. In sapwood and heartwood, the basic chemical composition was determined. The wood of *Q. macdougallii* presented a pronounced grain, a thick texture, and a straight thread. Fibers, fibrotracheids, uniseriate, multiseriate, and aggregate rays were found. Basic density 0.55 g cm^{-3} in sapwood and 0.61 g cm^{-3} in heartwood is classified as moderately heavy and heavy, respectively. The saturation point of the fiber is classified as high. Based on its physical properties, *Q. macdougallii* wood can be used in the manufacture of furniture, veneer, floors, tool handles, and construction. Based on the pulp quality indices and chemical composition, this wood could be used to obtain cellulose pulp for paper.

Keywords: Sapwood; Wood basic density; Pulp quality indexes; Wood chemistry

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INTRODUCTION

Oaks belong to the genus *Quercus* in the family Fagaceae, which comprises 8 to 10 genera and more than 900 species (Kremer *et al*. 2012). The genus *Quercus* is distributed throughout Mexico with 161 registered species. The states with the highest number of species are Oaxaca (48), Nuevo León (47), Jalisco (45), Chihuahua (40), and Veracruz (38) (Valencia and Nixon 2004).

The Sierra Norte in the state of Oaxaca has the highest species diversity with 23 of the total registered. *Quercus macdougallii* Martínez, the endemic species of the Sierra de Juárez in Oaxaca, is distributed in this region due to its reduced geographical and altitudinal distribution (Valencia and Nixon 2004).

Quercus macdougallii is a monoecious evergreen tree that can grow up to 40 m high, and the stem diameter can reach 4 m as an adult. Additionally, its flowering period is from May to July and it bears fruit from November to January (Clark-Tapia *et al*. 2018). It is distributed within the mountainous system called Sierra Madre de Oaxaca, specifically in the municipalities of San Pedro Yólox and Santiago Comaltepec. The area includes a mountain range with different elevations from 2648 to 3274 m above sea level (Anacleto-Carmona 2015).

Studies related to *Q. macdougallii* have been limited to tree structure and diversity (Anacleto-Carmona 2015), acorns sexual reproduction (Clark-Tapia *et al.* 2018), the effect of magnetite nanoparticles on the germination, early growth of *Q. macdougallii* (Pariona *et al.* 2017), and the delimitation of the climatic intervals where the maximum abundance of the species occurs (Antúnez *et al.* 2018).

The distribution of *Q. macdougallii* is restricted, with low abundance. Clark-Tapia *et al.* (2018) found sites with 150 trees per hectare, while Antúnez *et al.* (2018), report the presence of the species in 33 sites of 1000 m^2. However, information related to the characteristics of its wood was lacking. Therefore, the aim of this study was to perform the macroscopic and microscopic anatomical description of the wood. Additionally, the study evaluated the physical properties at different heights of the stem, and the chemical composition, as a contribution to the technological knowledge of the wood in this species.

EXPERIMENTAL

Materials

Study area

The study area was in the forests of the community of Santiago Comaltepec in the Sierra Norte of Oaxaca, at coordinates 17°33' 50" LN and 96° 32' 52" LO with altitude levels ranging from 450 to 3,000 m (INEGI 2016). The climate in this zone is temperate with low temperatures from November to February (minimum average 4.7 °C) and high temperatures from March to May (maximum average 13.4 °C) (Robson 2008; Antúnez *et al*. 2018). The average rainfall is 767 mm (Clark-Tapia *et al.* 2016). The collection site is located at coordinates 07°64'129" LN and 19°45'810" LO at an altitude of 2936 m.

Tree selection

A *Q. macdougallii* tree was studied that was knocked down by the wind. The tree showed straightness of stem and was free of pests or diseases. The tree had a diameter of 28 cm at breast height and a total height of 13 m. Dimensioning was done according to the methodology of Ramos and Diaz (1981). Logs of 40 cm in length were cut at different heights above ground level (0.30 m, 1.30 m, 3 m, and 6 m). A botanical sample was collected and identified in the herbarium of the University of Sierra Juarez. Based on the availability of the study material, it was only possible to describe the wood with one individual (De la Paz Pérez and Quintanar 1994; Bárcenas *et al.* 2005; De la Paz Pérez and Dávalos-Sotelo 2008). However, the values obtained for some physical properties should be considered with some caution.

Methods

Macroscopic and microscopic anatomical characterization

For the macroscopic description, a 30-cm thick slice obtained at 1.30 m above ground level was used. From the slice, sapwood and heartwood tablets were obtained and oriented in the three planes: radial, tangential, and transversal (De la Paz-Pérez and Dávalos-Sotelo 2008). The color was described using Munsell tables (1975). Texture, thread, grain, luster, and smell were classified according to Tortorelli (1956). The color, gloss, and smell were organoleptically tested.

For microscopic characterization, 4 slices of samples at 5 cm thickness obtained at different heights (0.30 m, 1.30 m, 3 m, and 6 m) were used. 2 by 2 cm cubes oriented in the transverse, tangential, and radial planes were cut (De la Paz-Pérez and Quintanar 1994), and the samples were labeled with the corresponding height data.

To make the histological cuts, the cubes were softened by boiling with distilled water for 8 h (De la Paz Pérez *et al.* 2015). The cuts were made with a Leica SMR2010 microtome (Leica, Buffalo Grove, IL, USA), and 15 μm thick lamellae were obtained in the following planes: transversal, tangential, and radial for sapwood and heartwood (De la Paz Pérez *et al.* 2006). Samples were stained by mixing distilled water, 96% alcohol, and safranin (García *et al.* 2003) dehydrated in a series of alcohols. The samples were finally rinsed in xylol for 2 min (Ruiz-Aquino *et al.* 2016). 50 permanent preparations were made by height for sapwood and heartwood (Navarro-Martínez *et al.* 2005).

For the preparation of the dissociation, small chips were cut from the material used for the histological cuts (Pineda *et al.* 2012). The small chips were placed in glass flasks. Glacial acetic acid and hydrogen peroxide at 30% were added (1 to 1 v per v) and were placed in the oven at 60 °C ± 5 °C for 24 h (Interián-Ku *et al.* 2011).

Measurements

The measurements were made on digital images from the Motic BA310LED optical microscope with an integrated camera and transferred to the Motic Images Plus ML Version 2.0 software (Motic, British Columbia, CA). The measurable elements (vessel elements, fibers, and rays) were classified based on the average according to Chattaway (1932) and the IAWA Committee (1937, 1939, 1989). 50 measurements were made per type of constituent element at each height and per type of wood. The length of the multiserial rays was only measured 25 times (Valencia and Barajas 1995; Aguilar and Castro 2006; Chávez *et al.* 2010).

The vessel elements were classified in wide diameter (greater than 150 μm) and narrow diameter (less than or equal to 150 μm) (Chávez *et al.* 2010). The diameter and number of vessels per mm^2 were measured on the cross-section of the histological sections and the length of the vessel elements in the dissociated material.

The length, overall diameter, lumen diameter, and cell wall thickness in the dissociated material were measured for the wood fibers. The number, cell number, and length of the uniseriate rays in the tangential section of the histological sections were recorded. The length of the multiseriate rays was measured with a Mitutoyo vernier (Mitutoyo, Aurora IL, USA) on the cross section of the wooden slats. The width and series number of the multiseriate rays were measured on the histological slices.

Pulp quality indexes for paper

Pulp quality indexes were calculated based on the following relationships given by Dadswell *et al*. (1959) and cited by Villaseñor-Araiza and Rutiaga-Quiñones (2000): stiffness coefficient (2 times the cell wall thickness per fiber diameter), flexibility coefficient (lumen diameter per fiber diameter), slenderness index (fiber length per fiber diameter), and Runkel index (2 times the cell wall thickness per lumen diameter). The classification of the pulp quality indexes for paper was based on the Runkel classification presented previously (Petroff and Nordman 1965; Porres and Valladares 1979) and cited by Villaseñor-Araiza and Rutiaga-Quiñones (2000). Group I (up to 0.25) was classified as excellent, Group II (from 0.25 to 0.50) was very good, Group III (from 0.50 to 1.00) was good, Group IV (from 1.00 to 2.00) was regular, and Group V (above 2.00) was unsatisfactory.

Physical properties

From each of the logs, 5 cm thick slices were cut at different heights (0.30 m, 1.30 m, 3 m, and 6 m). In each slice, sapwood and heartwood specimens were obtained according to the ASTM D 143-94 standard (2007). The physical properties determined were basic density, normal density (12% M. C.), green density, anhydrous density, volumetric, radial, tangential, and longitudinal shrinkage. The fiber saturation point (FSP) was calculated from Fuentes-Salinas (2000) equation as shown in Eq. 1,

$$FSP = VS \times (0.9 \times \text{basic density})^{-1} \quad (1)$$

where FSP represents the fiber saturation point, and *VS* represents volumetric shrinkage.

The anisotropy ratio (*RA*) was calculated according to Eq. 2,

$$RA = St \times (Sr)^{-1} \quad (2)$$

where *RA* represents the anisotropy ratio, *St* represents tangential shrinkage, and *Sr* represents radial shrinkage.

Chemical analysis

To determine the basic chemical composition of the wood of *Q. macdougallii*, wood samples were taken at different heights above ground level as mentioned earlier. From each slice, sapwood and heartwood were separated. This material was milled and sieved using the 40-mesh fraction. The chemical analysis included the determination of pH (Sandermann and Rothkamm 1959), the content of inorganic substances using the technique T 211 om-93 (TAPPI 2000), the solubility against organic solvents, the amount of lignin (Runkel and Wilke 1951), and the amount of holocellulose (Wise *et al*. 1946). For solvent solubility, a successive extraction in Soxhlet equipment was applied using cyclohexane, acetone, methanol, and finally hot water under reflux (Mejía-Díaz and Rutiaga-Quiñones 2008). In each case, the extraction lasted 6 h. Chemical analyses were performed in triplicate.

The inorganic elements in the ash were identified and quantified using an X-ray spectrometer connected to a Jeol JSM - 6400 scanning electron microscope (JEOL, Dearborn, MI, USA). The operating conditions were the same as reported by Téllez-Sánchez *et al*. (2010), 20 kV and 8.5 s.

Statistical analysis

A completely randomized experimental design was performed in which the four heights per type of wood (sapwood-heartwood) were compared. The parameters to be evaluated were the measurable anatomical elements (vessels, fibers, uniseriate, and multiseriate rays), pulp quality indexes, and physical properties (moisture content, basic density, anhydrous density, green density, normal density, volumetric shrinkage, fiber saturation point, linear shrinkage, and anisotropy ratio). For the anatomical elements, 50 repetitions per height were performed, and for the physical parameters, 18 repetitions per height. When significant differences in the parameters were found, a comparison of means was made using Tukey's HSD test ($\alpha = 0.05$). Statistical analysis was performed with the SAS® statistical package Version 9.0 (SAS Institute Inc., Cary, NC, USA).

RESULTS AND DISCUSSION

Macroscopic Anatomical

The wood of *Q. macdougallii* presented a very pale brown color (10YR8/2) in contrast to the heartwood, which is reddish yellow (5YR6/6). It has no characteristic smell, and the taste is bitter, a distinctive feature of the *Quercus* genus. This coincides with what has been reported for *Q. magnoliifolia*, *Q. obtusata*, and *Q. crassifolia* (Honorato 2002). The color, smell, and taste of the wood is given by the presence of extracts such as tannins and polyphenols that are deposited in the lumens and cell walls (De la Paz Perez 2000).

The brightness of the wood was medium (Fig. 1), a characteristic that occurs when the wood has annular porosity. The wood grain was pronounced, a feature that is determined by the vessels and the axial or longitudinal parenchyma. The wide multiseriate rays that make the grain more attractive also contribute to pronounced wood grain (Moglia *et al.* 2014).

The wood of *Q. macdougallii* presented a thick texture, a characteristic of the oaks *Quercus castanea* Née and *Quercus acutifolia* Née (De la Paz Pérez and Dávalos-Sotelo 2008). The thread of *Q. macdougallii* is straight and the woods with this characteristic present less shrinkage in contrast to woods that present inclined, spiral, or interlocked thread (León and Espinoza 2001). In addition, it facilitates the manufacture of turned and carved products.

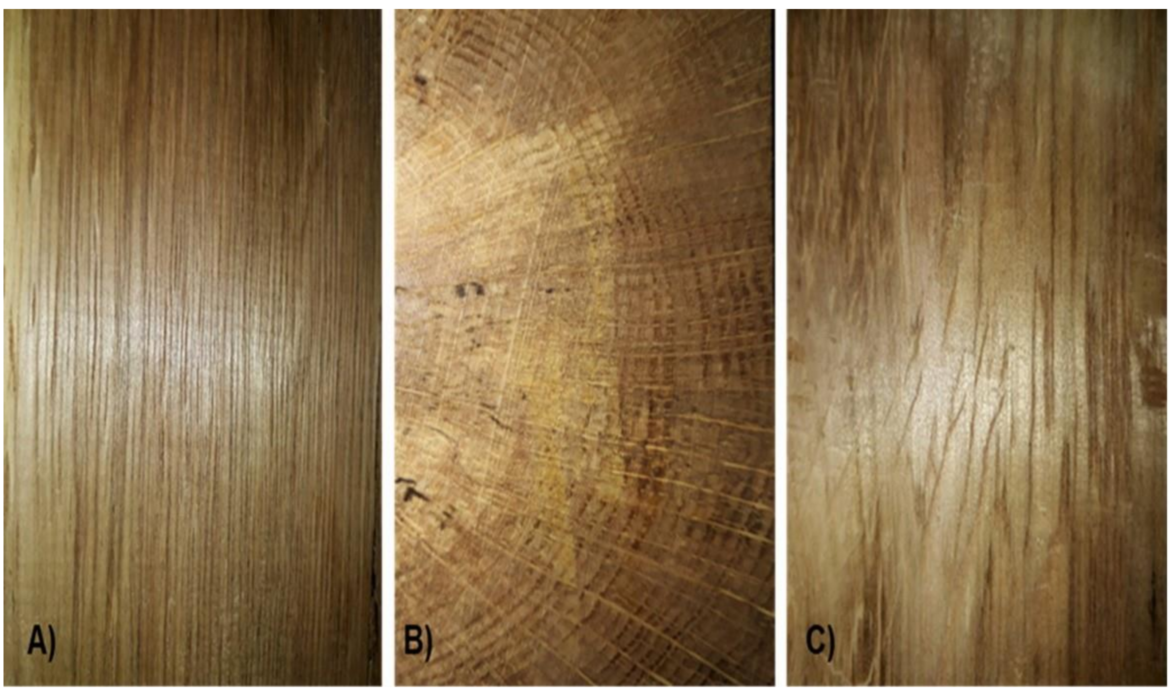

Fig. 1. Macroscopic characteristics of *Q. macdougallii* wood: A) tangential section, B) cross section, C) radial section

Microscopic Anatomical Characteristics

Vessels

The wood of *Q. macdougallii* presented annular porosity, which is associated with medium or high densities, and are the most recommended in the manufacture of hand tools handles (hammers, axes, picks, shovels, among others). This is where the wood is subjected to impact stress. The force received perpendicular to the thread is dispersed mainly in the lumens of the larger vessels (Rodríguez *et al.* 2007).

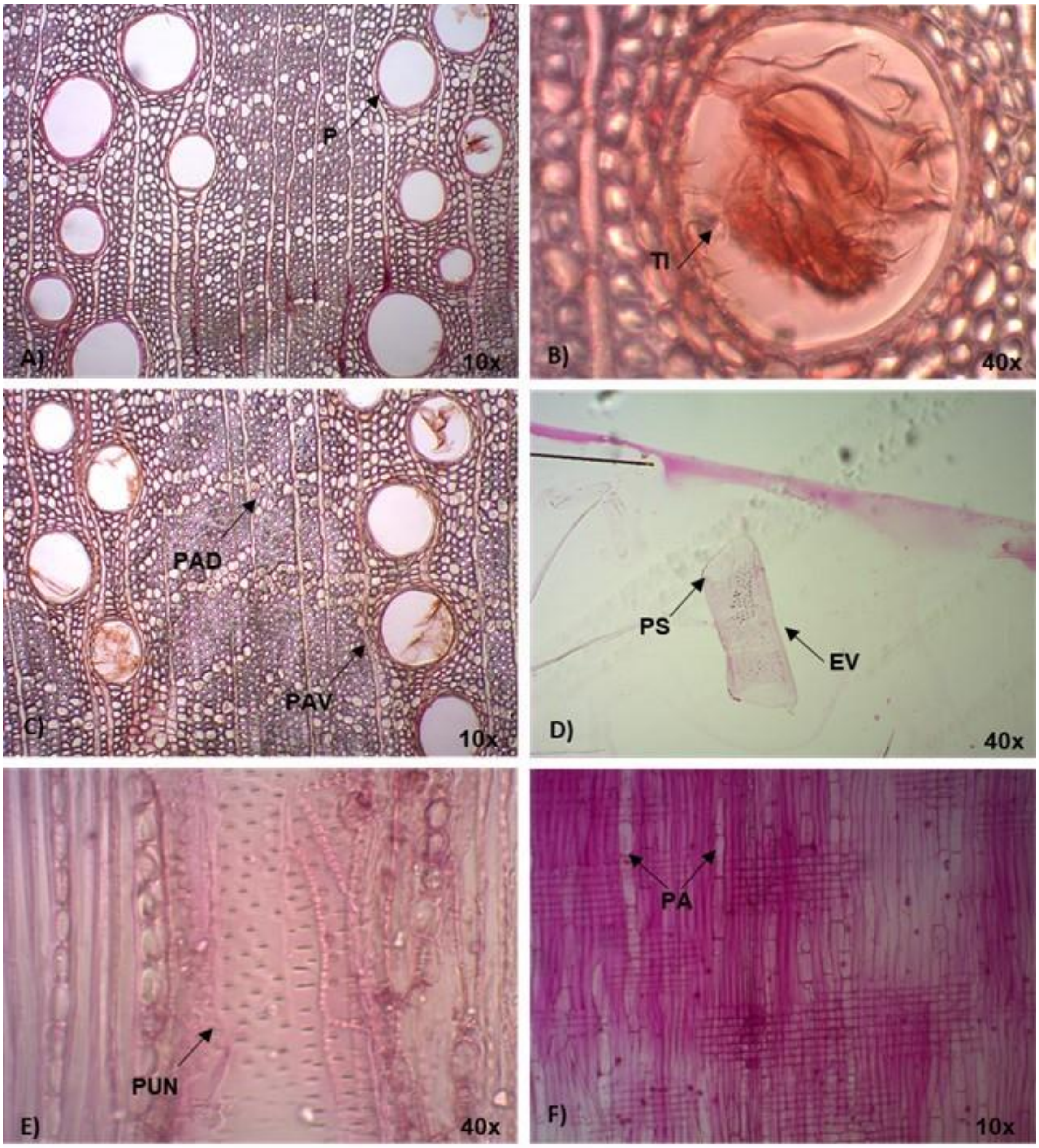

Fig. 2. Elements of vessels of *Q. macdougallii*: A) annular porosity: P: pore (10x); B) TI: pore with presence of tyloses (40x); C) cross section: PAD: diffuse apotracheal parenchyma, PAV: vasicentric paratracheal parenchyma (10x); D) EV: vessel element, PS: simple perforation plate (40x); E) tangential section: PUN: bordered pits with oval contour (40x); F) radial section: PA: parenchyma (10x)

The pores are solitary, have an oval contour, are arranged in radial rows, some present tyloses, and the axial parenchyma is apotracheal diffuse and paratracheal vasicentric. These results correspond with what has been reported for *Quercus glaucoides* Mart and Gal (Honorato 2002) and *Q. obtusata* (Chávez *et al.* 2010). The vessel elements presented simple perforation plates and alternate areolated pits of an oval shape (Fig. 2).

In the cross section, the vessels have medium pores (IAWA 1939). The pores per mm^2 in sapwood are few and moderately few in heartwood (Chattaway 1932). With respect to length, they are classified as medium for both sapwood and heartwood (Chattaway 1932). These are characteristics like those reported by Ruiz-Aquino *et al*. (2016) for *Q. laurina*, and *Q. crassifolia*.

The diameter and number of pores favor the penetration of liquids, while the vessels without obstructions favor the preservation process (Honorato 2002). However, the presence of tyloses makes the entrance of fungal hyphae and the circulation of water and oxygen difficult. Tyloses serves as a physical barrier for the entrance of pathogens and make the wood impenetrable (Moglia *et al.* 2014).

In the statistical analysis of sapwood by height, significant differences were found in the number of vessels per mm^2 ($p = 0.0001$), where heights 1 and 2 are different at height 4 (Table 1). The number of pores per mm^2 increased from the base to the crown, which was the case for *Quercus garryana* Dougl. (Lei *et al.* 1996). The structure of the wood varies by species, within each species, between trees, and even in the specimens. They can vary from the pith towards the exterior or from the base of the trunk to the crown (Zobel and Talbert 1994; Quintanar *et al.* 2012).

Table 1. Elements of the Wooden Vessels of *Q. macdougallii* by Height

Dimensions	Type	Height (m)				Mean
		0.30	1.30	3.00	6.00	
D > 150 µm	Sapwood	189.94 (40.02)a, A	191.94 (28.10)a, A	191.04 (25.48),a A	185.47 (24.67),a A	189.59 (30.70) A
	Heartwood	182.64 (22.49)b, A	177.18 (26.44)ab, B	167.68 (13.67)a, B	171.26 (26.54)a, B	174.69 (20.79) B
D ≤ 150 µm	Sapwood	119.99 (21.43)a, A	114.42 (23.24)a, B	114.22 (22.12)a, A	119.40 (21.08)a, A	117.01 (21.98) A
	Heartwood	115.75 (27.42)b, A	99.67 (27.87)a, A	120.05 (19.04)b, B	116.31 (22.64)b, A	112.94 (25.57) A
Length (µm)	Sapwood	505.8 (99.32)a, B	522.28 (124.53)a, B	485.24 (101.76)a B	481.51 (97.17)a, B	496.96 (106.11) B
	Heartwood	476.82 (123.65)a, A	505.27 (114.76)a, A	443.92 (84.65)a, A	468.86 (97.32)a, A	476.27 (106.66) A
Number (mm^{-2})	Sapwood	5 (1.38) a, A	5 (1.71) a, A	6 (2.02) ab, A	7 (2.36) b, A	6 (2.01) A
	Heartwood	5 (1.69) a, A	9 (5.34) b, B	9 (2.35) b, B	10 (3.85) b, B	8 (4.07) B

*Note: D is the vessel diameter, equal lowercase letters in the direction of the rows indicate statistical equality ($p < 0.05$), and equal uppercase letters in the direction of the columns indicate statistical equality by type of wood ($p < 0.05$). The values in parenthesis represent the standard deviation.

Vessels with diameters greater than 150 µm were significantly larger in sapwood with respect to heartwood ($p = 0.0001$). This can be attributed to sapwood being made up of cells whose function is to conduct water and nutrients (Wilson and White 1986). The diameters and lengths of the vessels of the species studied increase from the pith to the bark, which was also reported by Phelps and Workman (1994), Sousa *et al*. (2014), and Leal *et al*. (2011) for the wood of *Quercus alba*, *Q. faginea*, and *Q. suber*, respectively.

The size of the vessels is related to density. Woods that have a higher frequency of vessels and larger vessels will have lower density than those with small vessels (Panshin and Dezeeuw 1980). Additionally, the longer the vessels, the more likely the wood will present cracks (Savilla 1986).

Fibers

In sapwood and heartwood, libriform fibers and fibrotracheids were identified (Fig. 3). Based on the mean, the fiber diameter was classified as fine (Tortorelli 1956), the fiber wall thickness as medium (IAWA 1939), and the length as medium (IAWA 1937). These were similar characteristics to those reported for *Quercus hintonii* and *Q. affinis* by De la Paz Pérez *et al*. (2006). With *Quercus castanefolia*, they coincide in lumen diameter (Kiaei and Samariha 2011). Also, similarity in fiber diameter was found in the wood of *Quercus polymorpha* (González *et al.* 2016) and similar values in fiber length were found in those reported for *Q. obtusata* (Chávez *et al.* 2010) and *Q. sideroxyla* (De la Paz Pérez and Corral 1980).

The dimensions of the fibers intervene in the physical and mechanical behavior of the wood, where the total volume and the thickness of the cell wall directly influence the density. Species with thick walls have high density (González *et al.* 2016). The length, diameter, and thickness of the fiber wall influence the properties of the pulp and the paper that is made from it. The resistance to tearing of the paper is related to the length. Therefore, the greater the length the greater the resistance (Dinwoodie 1965). Pulps obtained from thin-walled fibers with large diameters are characterized by high tensile and breaking strength (Honorato 2002). The length of the fibers plays a predominant role when efforts are applied in a direction parallel to the grain (León and Espinoza 2001).

Statistically there were significant differences in the parameters analyzed between heights (Table 2). The total diameter of the fibers and the diameter of the lumen increase from the pith to the bark. This behavior also was exhibited in the wood of *Quercus castaneifolia* (Bakhshi *et al.* 2012) and *Q. faginea* (Sousa *et al.* 2014).

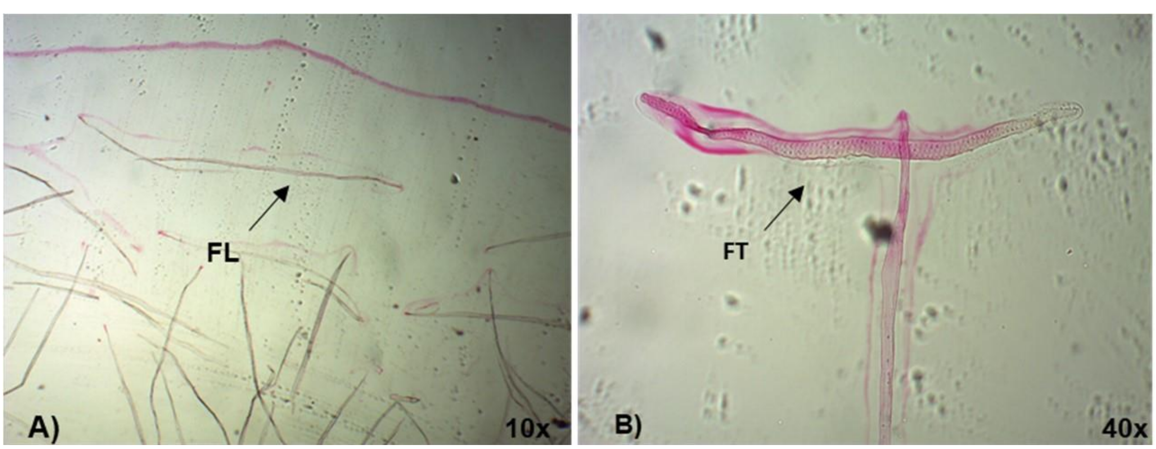

Fig. 3. Cellular elements of *Q. macdougallii* wood (fibers): A) FL: libriform fiber (10x); B) FT: fibrotracheids (40x)

Table 2. Wood Fibers of *Q. macdougallii* by Height

Dimensions	Type	Height (m)				Mean
		0.30	1.30	3.00	6.00	
Diameter (µm)	Sapwood	17.27 (3.50)ab, B	17.01 (2.73)a, B	18.03 (3.35)b, A	16.78 (4.42)a, B	17.27 (0.54) B
	Heartwood	15.16 (2.93)a, A	15.79 (3.66)a, A	19.19 (5.23)b, A	14.14 (3.65)a, A	16.07 (2.19) A
DL (µm)	Sapwood	9.37 (2.29)ab, B	8.04 (1.98)a, B	10.80 (3.31)b, A	9.03 (3.81) a, B	9.31 (3.09) B
	Heartwood	3.79 (1.07)a, A	6.03 (2.54)b, A	10.55 (4.37)c, A	6.79 (2.86)b, A	6.79 (3.81) A
GP (µm)	Sapwood	3.95 (1.04)ab, A	4.49 (1.21)b, A	3.57 (0.78)a, A	3.87 (1.32)a, A	3.97 (1.15) A
	Heartwood	5.69 (1.33)c, B	4.88 (1.39)b, A	4.32 (1.08)ab, A	3.68 (1.19)a, A	4.64 (1.45) A
Longitudinal (µm)	Sapwood	1349.85 (248.99)a, A	1452.31 (192.23)b, A	1410.30 (172.06)ab, A	1492.58 (178.88)b, A	1427.56 (205.56) A
	Heartwood	1403.31 (233.30)a, A	1638.21 (201.29)a, A	1349.99 (190.77)a, A	1495.14 (120.57)a, A	1471.66 (199.03) A

*Note: DL is the lumen diameter and GP is the wall thickness. Equal lowercase letters in the direction of the rows indicate statistical equality ($p < 0.05$) and equal uppercase letters in the direction of the columns indicate statistical equality by the type of wood ($p < 0.05$). The values in parenthesis represent the standard deviation.

Uniseriate and multiseriate rays

Uniseriate rays are classified. Because of their width being extremely thin, the number of uniseriate rays per mm^2 are numerous (IAWA 1939), but according to the length are extremely low (Chattaway 1932). The rays of *Q. macdougallii* show 12 cells on average (Fig. 4). The above characteristics are similar to those reported for *Q. affinis* (Valencia and Barajas 1995) and are lower when compared to those reported for *Q. magnoliifolia* (De la Paz-Pérez and Dávalos-Sotelo 2008).

The dimensions of the rays are anatomic variables with greater influence in the drying process because they present a flexible primary cell wall (barely thickened). They constitute weak points in the wood due to the absence of the secondary wall (Metcalfe and Chalk 1985). The presence of abundant uniseriate rays can negatively affect the mechanical properties and the tangential contraction of the wood (Bárcenas *et al.* 2002).

Also, the wood of *Q. macdougallii* presented homogeneous, multiseriate, and aggregates woody rays. According to the width, they are classified as very wide (IAWA 1939) with an average of 14 series and by its length are classified as very high (Chattaway 1932) (Fig. 3). These characteristics are like those reported for *Quercus durifolia* von Seem (De la Paz-Perez and Davalos-Sotelo 2008) and *Q. castanea* (Palacios *et al.* 2013).

Multiseriate rays are the most distinctive characteristic of oak wood (De la Paz Pérez *et al.* 2015) due to the influence they have on the technological properties of wood. They intervene in the grain, texture, and shrinkage, causing cracks that decrease the quality of the wood during drying. The latter increases with the abundance of fibers and thick walls (Ávila 1985; De la Paz Pérez *et al.* 1998; De la Paz Pérez *et al.* 2005).

In both sapwood and heartwood, there was an increase in the length of the uniseriate rays as height increased (Table 3). The same behavior was observed with the number of uniseriate rays per mm^2.

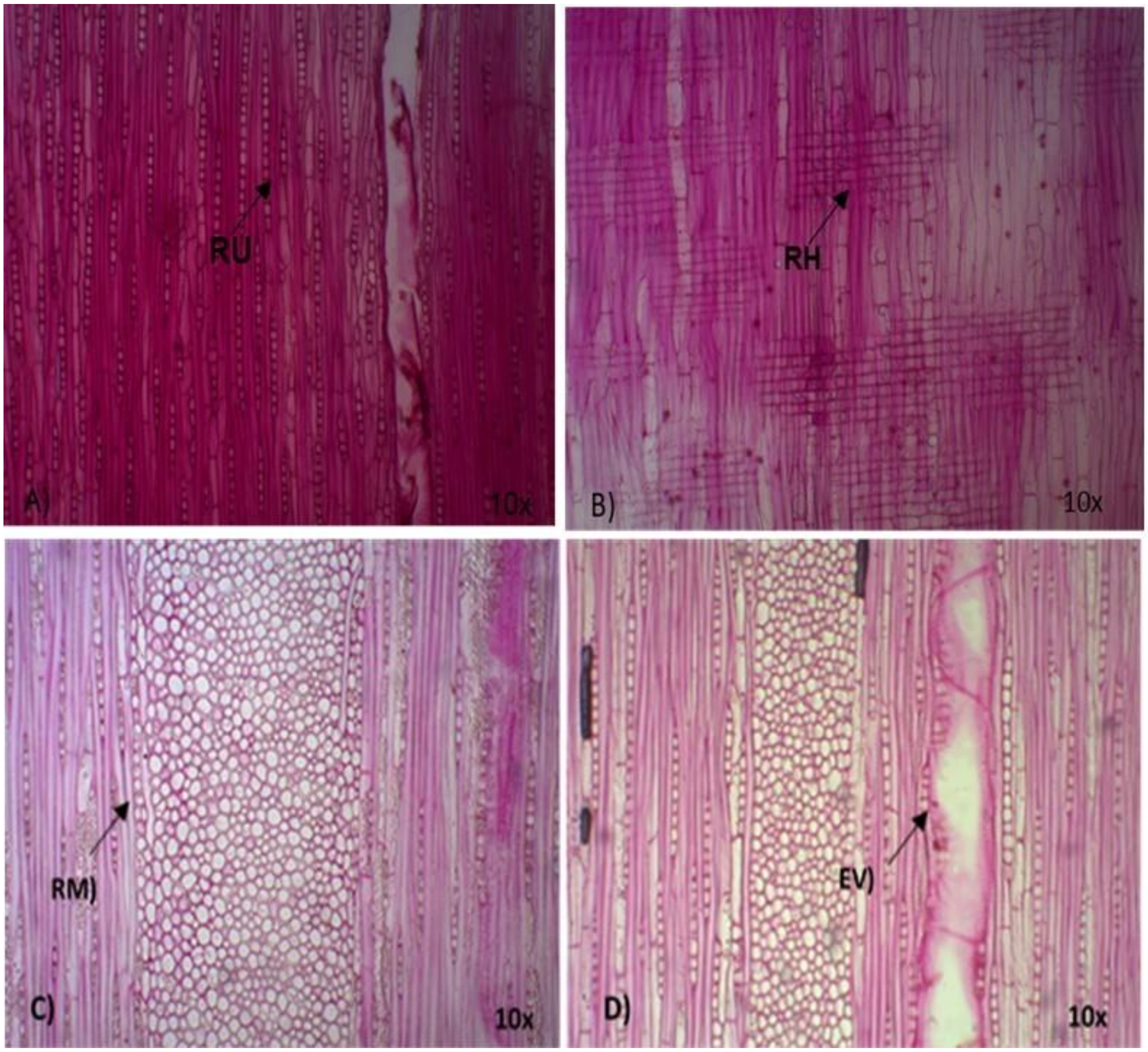

Fig. 4. Cellular elements of *Q. macdougallii*. A) tangential section RU: uniseriate rays (10x); B) radial section RH: homogeneous rays (10x); C) tangential section RM: multiseriate ray (10x); D) tangential section EV: vessel element (10x)

In the analysis of variance carried out for the uniseriate rays between sapwood and heartwood, a significant difference was found in the length ($p = 0.0001$) and in the number of rays per mm^2 ($p = 0.0001$). Significant differences were found in the width ($p = 0.0001$), length ($p = 0.0024$), and number of series ($p = 0.0001$). In all cases the dimensions are greater in sapwood in relation to the heartwood (Table 3), a similar behavior that was present in the wood of *Quercus faginea* (Sousa *et al.* 2014).

Pulp Quality Indexes for Paper

In both sapwood and heartwood, significant statistical differences were found in the pulp quality indices for paper at the sampling heights (Table 4), which agrees with the results shown in Tables 1, 2, and 3. The stiffness coefficient ranged from 0.42 to 0.75 (Table 4). Close values have been reported in the literature for other oak species (*Q. scytophylla* 0.47, *Q. resinosa* 0.78) (Vázquez-Gaviña *et al*. 2010). In relation to the flexibility coefficient, values ranging from 0.25 to 0.58 (Table 4) were like those found in other oak species (*Q. resinosa* 0.22, *Q. scytophylla* 0.53) (Vázquez-Gaviña *et al*. 2010).

Table 3. Dimensions and Number of Wood Ray Cells of *Q. macdougallii* by Height

Uniseriate Rays						
Dimensions	Type	Height (m)				Mean
		0.30	1.30	3.00	6.00	
Width (μm)	Sapwood	14.84 (4.01)ab, A	15.84 (4.39)b, A	14.82 (3.65) ab, A	12.97 (3.89)a, A	14.62 (3.99) A
	Heartwood	14.76 (3.99)b, A	15.01 (4.59)b, A	15.43 (4.67)b, A	11.97 (4.01)a, A	14.29 (4.41) A
Length (μm)	Sapwood	334.65 (103.39)a, B	355.19 (116.69) a, B	322.69 (106.43)a, B	275.01 (95.19)a, A	321.88 (104.35) B
	Heartwood	230.54 (69.93)a, A	250.49 a, A	252.58 (121.75)a, A	252.56 (115.51)a, A	246.54 (97.14) A
No. cells	Sapwood	10 (5.09)a, A	13 (5.79)a, A	13 (5.28)a, A	13 (5.19)a, A	12.16 (5.42) A
	Heartwood	12 (3.89)a, A	12 a, A	13 (5.84)a, A	13 (5.50)a, A	12.37 (5.03) A
No. (mm^{-2})	Sapwood	26 (5.02) b	20 (3.64) a	27 (4.86)b	32 (4.63)c	26.24 (4.48) A
	Heartwood	27 (6.28)a	35 b	43 (8.59)c	38 (7.24)b	35.92 (6.86) B
Multiseriate Rays						
Width (μm)	Sapwood	376.55 (115.68)c, B	279.88 (74.29)a, B	334.22 (68.13)bc, B	324.53 (71.76) b, B	328.79 (81.63) B
	Heartwood	257.19 (86.73)a, A	256.21 (71.85)a, A	272.53 (62.94)a, A	247.35 (74.87)a, A	258.39 (74.57) A
Length (cm)	Sapwood	2.97 (1.24)c, B	2.87 (0.86)bc, B	2.06 (0.77)a, A	2.24 (0.94)ab, A	2.54 (1.03) B
	Heartwood	2.42 (0.84)a, A	2.11 (0.68)a, A	2.20 (0.78)a, A	2.25 (0.84)a, A	2.25 (0.78) A
No. of series	Sapwood	18 (5.83)b, B	15 (3.29)a, B	15 (2.86)a, B	16 (3.81)ab, B	15.95 (4.21) B
	Heartwood	12 (3.08)a, A	13 ab, (3.31)A	14 (3.67)b, A	14 (3.54))b, A	13.46 (3.51) A

*Note: Equal lowercase letters in the direction of the rows indicate statistical equality ($p < 0.05$) and equal uppercase letters in the direction of the columns indicate statistical equality by the type of wood ($p < 0.05$). The values in parenthesis represent the standard deviation.

For the case of the slenderness index, the results obtained ranged from 76.68 to 109.43 (Table 4), close to values reported for other oak woods (*Q. laeta* 78.89, *Q. resinosa* 90.36) (Vázquez-Gaviña *et al*. 2010). Finally, for the Runkel index, data ranged from 0.74 to 3.21 (Table 4) and in general were consistent with previous reports for other oak woods (*Q. scytophylla* 0.88, *Q. glaucoides* 3.35) (Vázquez-Gaviña *et al*. 2010).

The average value of the stiffness coefficient for the fibers of the wood of *Q. macdougallii* is 0.55, which is close to *Quercus castanea* at 0.58. The thickness of the cell wall is classified as thick. The average value of the coefficient of flexibility is 0.47, close to *Q. obtusata* (0.45) (Vázquez-Gaviña *et al*. 2010). These values correspond to the classification of thick-walled fibers, which means that the fibers generate little contact surface and therefore have little bonding between them. This also means the fibers have little mechanical resistance in the paper (Villaseñor and Rutiaga 2000). These results agree with the classification of the density of sapwood (moderately heavy) and heartwood (heavy) of *Q. macdougallii*. This is because dense woods have fibers with thick to very thick cell walls (Ninin 1985).

The average value of Runkel's index for *Q. macdougallii* wood is 1.44, thus the fibers of this wood are classified as regular for paper (Villaseñor and Rutiaga 2000). Other Mexican woods of the same genus have obtained the same classification (*Q. obtusata*, *Q. castanea*, *Q. candicans*, *Q. laurina*, *Q. crassipes*, *Q. laeta*, and *Q. deserticola*) (Vázquez-Gaviña *et al*. 2010).

Table 4. Pulp Quality Indexes for *Q. macdougallii* by Height

Indexes	Type	Height (m)				Mean
		0.30	1.30	3.00	6.00	
CR	Sapwood	0.46 (0.08)bc, A	0.53 (0.10)a, A	0.42 (0.10)c, A	0.47 (0.15)ab,A	0.47 (0.12) A
	Heartwood	0.75 (0.07)a, B	0.62 (0.12)b, B	0.58 (0.12)c, B	0.53 (0.13)d, B	0.62 (0.15) B
CF	Sapwood	0.54 (0.08)ab, B	0.47 (0.10)c, B	0.58 (0.10)a, A	0.53 (0.15)bc, A	0.53 (0.12) B
	Heartwood	0.25 (0.07)d, A	0.38 (0.12)c, A	0.53 (0.12)a, B	0.47 (0.13)b, A	0.41 (0.15) A
IE	Sapwood	80.92 (21.13)b, A	87.51 (17.87)ab, A	81.44 (20.60)b, A	96.02 (30.72)a, A	86.47 (23.47) A
	Heartwood	95.43 (21.10)a, B	109.43 (23.82)a, B	76.58 (27.47)a, A	100.17 (24.02)a, A	95.40 (26.78) B
RR	Sapwood	0.88 (0.29)ab, A	1.22 (0.59)a, A	0.74 (0.31)b, A	1.16 (0.60)a, A	1.00 (0.70) A
	Heartwood	3.21 (1.10)A	1.97 (1.13)B	0.98 (0.51)C	1.30 (0.72)C	1.87 (1.24) B

Note: CR – stiffness coefficient; CF – flexibility coefficient; IE – slenderness index; RR – Runkel's ratio. Equal lowercase letters in the direction of the rows indicate statistical equality ($p < 0.05$) and equal uppercase letters in the direction of the columns indicate statistical equality by the type of wood ($p < 0.05$). The values in parenthesis represent the standard deviation.

Physical Properties

Moisture content

The moisture content of *Q. macdougallii* wood did not show significant differences between the different heights. However, by type of wood the moisture content in the sapwood was significantly higher in relation to the heartwood ($p = 0.0007$). Sapwood contains the cells responsible for the conduction of water, whereas the heartwood pores are obstructed by tyloses that block the conduction of water. This causes a reduction in the permeability of the wood, so the moisture content is low. The behavior presented in the wood of *Quercus suber* L. is the opposite to this convention (Leal *et al.* 2012).

Density

The basic density obtained for *Q. macdougallii* according to the mean is classified for sapwood as moderately heavy (Torelli 1982). This is like the reports for the wood of *Quercus sartorii* Liebm, *Q. mexicana* (Honorato 2002), and *Q. dealbata* (Sharma *et al.* 2011). Heartwood is classified as heavy (Torelli 1982), similar to that reported for *Quercus semiserrata* (Sharma *et al.* 2011), *Q. sideroxyla* (De la Paz Pérez *et al.* 2015), *Q. Mexicana*, *Q. uxoris* Mc Vaugh (De la Paz-Pérez and Dávalos-Sotelo 2008), and *Q. affinis* Scheid. (Bárcenas and Dávalos 1999).

In the densities analyzed, it was observed that they decrease when the height in the stem increases (Table 5). Knapic *et al*. (2011) and Leal *et al*. (2012) found similar behavior in *Quercus faginea* and *Q. suber* L., respectively. The anhydrous density of sapwood wood according to the mean is like the reports for *Q. sartorii* and *Q. mexicana* wood (Honorato 2002). However, it is lower compared to the reports for *Q. obtusata* (Honorato and Fuentes 2001).

Table 5. Wood Density of *Q. macdougallii* by Height

Density (g cm^{-3})	Type	Height (m)				Mean
		0.30	1.30	3.00	6.00	
Green	Sapwood	1.10 (0.04)b, A	1.03 (0.01)a A	1.01 (0.04)a, A	1.03 (0.01)a A	1.04 (0.05) A
	Heart-wood	1.15 (0.01)a, B	1.33 (0.34)a B	1.07 (0.01)a, B	1.04 (0.01)a A	1.15 (0.22) B
Normal	Sapwood	0.79 (0.08)b, A	0.78 (0.13)b, A	0.71 (0.03)ab, A	0.67 (0.01)a, A	0.73 (0.10) A
	Heart-wood	1.25 (0.16)c, B	1.06 (0.09)bc, B	0.79 (0.02)ab, A	0.81 (0.07)a, B	0.98 (0.22) B
Anhydrous	Sapwood	0.73 (0.05)b, A	0.70 (0.04)ab, A	0.66 (0.04)a A	0.66, (0.01)a A	0.69 (0.05) A
	Heart-wood	0.85 (0.02)c, B	0.79 (0.06)bc, B	0.71 (0.02)ab, B	0.69 (0.01)a, A	0.76 (0.08) B
Basic	Sapwood	0.58 (0.03)b, A	0.57 (0.03)ab, A	0.54 (0.03)a, A	0.54 (0.01)a, A	0.55 (0.03) A
	Heart-wood	0.64 (0.01)b, B	0.64 (0.05)b, B	0.58 (0.01)ab, B	0.56 (0.01)a, A	0.61 (0.05) B

*Note: Equal lowercase letters in the direction of the rows indicate statistical equality ($p < 0.05$) and equal uppercase letters in the direction of the columns indicate statistical equality by the type of wood ($p < 0.05$). The values in parenthesis represent the standard deviation.

The density of wood depends on the amount and type of cellular elements that constitute it (Navarro-Martinez *et al.* 2005). Most of the physical and mechanical properties of wood such as hardness, weight, impact resistance, and shrinkage rates are directly related to density (Rodríguez *et al.* 2015).

Woods with high densities have fibers with thick to very thick walls (Ninin 1985) and present a greater resistance to cutting and difficulty of workability (Navarro-Martinez *et al.* 2005; Leon 2010). They have a high natural durability and have fewer empty spaces that minimize the access of water. The thickness of the walls gives it weight and the hardness necessary for use in construction (Interián-ku *et al.* 2011).

Between the type of wood (sapwood and heartwood), significant differences were found in green density ($p = 0.0010$), normal density ($p = 0.0001$), anhydrous density ($p = 0.0001$), and basic density ($p = 0.0001$). In all cases, the density of the heartwood is greater than that of the sapwood. Heartwood has a greater density of fibers than of vessels, has fibers with thicker walls (Panshin and Dezeew 1980), and the heartwood has a greater amount of extractives compared to the sapwood. These are the reasons why there is a difference in density between both tissues (Kellogg 1981).

In studies conducted for species of the genus *Quercus*, it was found that the basic density of the wood of *Q. faginea* (Knapic *et al.* 2011) and *Q. suber* (Knapic *et al.* 2008) decreased radially from the pith to the bark. This is a behavior similar to the results reported in this study.

Fiber saturation point

The fiber saturation point (FSP) for sapwood (33.73) and heartwood (29.12) showed significant differences ($p = 0.0001$). This variation is due to heartwood having a higher presence of extracts that occupy places inside the cell wall, thus limiting the attraction between water molecules. Wood with a high content of extracts has a relatively low fiber saturation point (Panshin and Dezeeuw 1980). The FSP according to the average is classified as high (Sallenave 1955), in which similar values have been reported for *Quercus robur* wood (Kolin and Janezic 1996), *Q. convallata* Trel. (Honorato 2002), and *Q. suber* L. (Leal *et al.* 2012).

Shrinkage and anisotropy relationship

Tangential, radial, and volumetric shrinkage (Table 6) in relation to the mean, is classified as very high in sapwood and heartwood (Echenique *et al.* 1975). Tangential and radial shrinkage obtained in the wood of *Q. macdougallii* are within the range reported for the European oak species. Shrinkage varies between 4.0 to 6.6% and 8.6 to 13.0% in the radial and the tangential direction, respectively (Tsoumis 1991). High values in shrinkage indicate a lower dimensional stability of the wood, which requires more care in the wood drying process. There will be a greater tendency to the presence of jointing and fissures in the material (Ruiz-Aquino *et al.* 2018).

Table 6. Shrinkage and Anisotropy Relationship of *Q. macdougallii*

Type	Shrinkage				AR
	Tangential	Radial	Longitudinal	Volumetric	
Sapwood	12.73 (2.22) A	5.15 (0.86) A	0.20 (0.17) A	19.34 (2.58) A	2.52 (0.52) A
Heartwood	11.76 (1.15) A	6.31 (0.94) B	0.24 (0.17) A	19.63 (1.84) A	1.90 (0.38) B

*Note: AR is the anisotropy ratio. Values with the same letter in the direction of the columns indicate statistical equality ($p < 0.05$) and the values in parenthesis represent the standard deviation.

In the radial direction, the rays favor contractions restricting the dimensional movements (Boyd 1974). The radial walls of the wood cells have a lignin content greater than the content in the tangential walls. This explains the smaller values of shrinkage in the radial direction. Since the lignin is more rigid and less hygroscopic than the holocellulose, it limits the contraction (Bosshard 1956).

The anisotropy ratio (AR) is classified according to the mean for sapwood as very high and for heartwood as high (Echenique *et al.* 1975). AR expresses the relationship between the tangential and radial behavior. The larger and greater magnitude of the problem depends on the presence of uniseriate and multiseriate rays (Igartúa *et al.* 2009).

Chemical Analysis

The result of the chemical analysis is summarized in Table 7. The pH values ranged from 4.41 to 4.83 and had a weak acidic pH (Kollmann 1959). Heartwood was found to be more acidic than sapwood, which is consistent with the literature (Fengel and Wegener 1984; Rutiaga 2001). The pH values found here are slightly lower than those reported for wood from different oak species (4.6 to 5.9) (Rutiaga 2001), (4.74 to 5.10) (Herrera *et al*. 2017).

The content of mineral substances varied from 4.41 to 4.83% and these results generally coincide with previous reports for woods of the same genus (Rutiaga *et al*. 2000; Bautista and Honorato 2005; Herrera *et al*. 2017). The extractives can be extracted from wood or bark with polar and nonpolar solvents (Hillis 1987). In our study material most of the extractives correspond to polar substances, and this fact has also been recently observed in *Quercus faginea* (Miranda *et al.* 2017; Ferreira *et al.* 2018). Finally, heartwood has a higher proportion of solvent-extractable compounds than sapwood, and these values generally coincide with data for oak woods (Fengel and Wegener 1984; Rutiaga 2001; Bautista and Honorato 2005; Herrera *et al*. 2017).

In relation to cell wall chemicals, Runkel lignin values were 14.86% for heartwood and 16.79% for sapwood. These values are within the range reported for some oak woods (14.67 to 19.37%) (Herrera *et al*. 2017). In the case of holocellulose, the value obtained for both heartwood (73.58%) and sapwood (73.16%) is practically the same but is lower than that reported for other woods of the same genus (81.63 to 90.72%) (Herrera *et al.* 2017). However, this result generally coincides with the range reported for hardwoods (Fengel and Wegener 1984).

The low ash content, the low total solubility compared to the applied extraction sequence, and the low lignin content suggest that the wood of this oak species could be used in the chemical pulping process to obtain cellulose pulp for making paper.

Table 7. Summary of the Chemical Analysis of *Q. macdougallii* Wood

Analysis	Heartwood	Sapwood
pH	4.41 (0.05)	4.83 (0.03)
Ash (%)	0.59 (0.01)	0.49 (0.01)
Cyclohexane (%)	0.80 (0.24)	0.11 (0.80)
Acetone (%)	4.47 (0.22)	3.18 (0.96)
Methanol (%)	2.39 (0.07)	1.50 (0.37)
Hot water (%)	1.68 (0.20)	2.44 (0.00)
Total extractives (%)	8.35 (0.10)	7.24 (0.50)
Runkel lignin (%)	14.86 (0.10)	16.79 (0.22)
Holocellulose (%)	73.58 (0.75)	73.16 (0.58)
The values in parenthesis represent the standard deviation.		

Table 8 shows the result of the microanalysis of wood ashes from *Q. macdougallii*. Nine chemical elements were identified in the heartwood and eight in the sapwood. Aluminium was not detected in the latter. The chemical elements present in *Q. macdougallii* are practically the same as those reported in woods of the same genus identified by the same method (Rutiaga 2001; Herrera *et al.* 2017) with variations in concentration. The results obtained here reveal the typical presence of the chemical elements that are common in wood (potassium, calcium, and magnesium) (Fengel and Wegener 1984). In this oak wood, the presence of heavy elements was not detected.

Table 8. Microanalysis of *Q. macdougallii* ash (at%)

Element	Heartwood	Sapwood
Sodium	4.32 (0.28)	1.37 (0.31)
Magnesium	7.83 (0.66)	7.21 (0.04)
Aluminum	0.19 (0.11)	*
Silicon	0.64 (0.12)	0.42 (0.01)
Phosphorus	1.13 (0.09)	4.69 (0.05)
Sulfur	6.28 (0.63)	1.64 (0.21)
Potassium	49.48 (1.14)	57.46 (0.57)
Calcium	26.33 (0.09)	24.40 (0.67)
Manganese	3.29 (0.18)	3.12 (0.09)

*Note: * means undetected. The values in parenthesis represent the standard deviation.

CONCLUSIONS

1. The sapwood of *Quercus macdougallii* Martínez presented a very pale-yellow color in contrast to the reddish yellow of the heartwood, straight grain, low gloss, pronounced veining, and thick texture.
2. The fiber length increases from the base to the crown in sapwood.
3. The fiber diameter was classified as fine, the fiber wall thickness as medium, and the length as medium.
4. The width and length of the multiseriate rays are greater in sapwood than in heartwood, which are characteristics that influence the drying process negatively.
5. Basic density in sapwood (0.55 g cm^{-3}) and in heartwood (0.61 g cm^{-3}) is classified as moderately heavy and heavy, respectively.
6. The saturation point of the fiber is classified as high.
7. The basic density indicates better physical properties in the heartwood and the anisotropy ratio suggests high dimensional changes in the tangential direction, so radial cuts should be favored in the sawing process.
8. The fibers are classified as regular for paper manufacture and based on its chemical composition this wood could be used in the production of cellulose pulp for paper manufacturing.

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