REVISTA CIENTÍFICA
Ciencia y Método
ISSN 3103-1072

EDITORIAL GRUPO AEA

Artículo Científico

Physical and mechanical properties of *Ochroma pyramidale* (Cav. ex Lam.) Urb. (balsa) wood growing in three Ecuadorian locations

Propiedades físicas y mecánicas de la madera de Ochroma pyramidale (Cav. ex Lam.) Urb. (balsa) creciendo en tres localidades ecuatorianas

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DOI / URL: https://doi.org/10.55813/gaea/rcym/v3/n3/81

Resumen: Ecuador actualmente es el primer productor de madera de *Ochroma pyramidale* en el mundo, incrementando el número de plantaciones e industrias procesadoras de madera. En este estudio, el objetivo fue evaluar las propiedades físicas y mecánicas de la madera de *O. pyramidale* creciendo en el centro del Litoral y norte de la Amazonia del Ecuador. Para ello, se consideraron edades y ubicación de las muestras al interior del segmento del árbol (basal, central y apical). Se consideraron las directrices de la norma ASTM D143 para la preparación y dimensionamiento de las probetas, así como para la ejecución de los ensayos. Se empleó un ADEVA sobre un Diseño completamente al Azar, y la prueba de Tukey para la determinación de diferencias significativas. De acuerdo con los resultados obtenidos, y tomando en consideración los usos que se le da a la madera de *O. pyramidale* las maderas de tres años de las provincias de Sucumbíos y Orellana presentan mejores propiedades tecnológicas que las de tres y cuatro años de Los Ríos, lo que sugiere que la madera de la zona oriental puede ser aprovechada antes que la madera de la zona costera, sin afectar las propiedades tecnológicas de la madera de *O. pyramidale*.

Palabras clave: propiedades de la madera; balsa, calidad de la madera, industria maderera.

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Received: 05/Sep/2025
Accepted: 09Sep/2025
Published: 17/Sep/2025

Cita: Crespo-Gutiérrez, R. S., Jiménez-Romero, E. M., Anchundia-García, J. J., Jara-Minaya, J. M., & Mora-Silva, W. F. (2025). Propiedades físicas y mecánicas de la madera de Ochroma pyramidale (Cav. ex Lam.) Urb. (balsa) creciendo en tres localidades ecuatorianas. *Revista Científica Ciencia Y Método*, *3*(3), 364-384. https://doi.org/10.55813/gaea/rcym/v3/n3/81

Revista Científica Ciencia y Método (RCyM)
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Abstract: Ecuador is currently the first *Ochroma pyramidale* wood producer in the world, increasing the number of plantations and wood processing industries. In this study, the objective was to evaluate the physical and mechanical properties of *O. pyramidale* wood growing in the center of the coast and north of the Ecuadorian Amazon. For this, the ages and location of the samples within the tree segment (bottom, centre and apex) were considered. The guidelines of the ASTM D143 standard were considered for the preparation and sizing of the test pieces, as well as for the execution of the tests. An ANOVA was used on a completely Random Design, and Tukey's test to determine significant differences. According to the results obtained, and taking into consideration the uses that are given to *O. pyramidale* wood the three-year-old woods from Sucumbíos and Orellana provinces presents better technological properties than the three and four-year-old woods from Los Ríos, which suggests that wood in the eastern zone can be harvested earlier than wood in the coastal zone, without affecting the technological properties of the *O. pyramidale* wood.

Keywords: wood properties; balsa; wood quality, wood industry.

1. Introduction

The *O. pyramidale* tree (balsa) grows mainly in the equatorial area between latitude 0º and 5º North and South. This tree is endemic from Ecuador (where more than 90% of the world consumption is produced), and in neighboring regions. It has also been introduced successfully to other regions of the world (Bonet et al., 2009). *O. pyramidale* is a forest and timber species that is in great demand on the international market. It is cultivated naturally and by reforestation, especially in the sub-tropical jungle of Ecuador, where it is one of the most widely used forest and timber resources; for this reason, it is one of the important economic items in the Ecuadorian economy (González et al., 2010).

The Ecuadorian region around Quevedo (a city midway between Guayaquil on the coast and Quito in the mountains) provides ideal growing conditions for the tree. The region has a damp but well-drained layer of moist topsoil of the jungles along Ecuador's Guayas River and its tributaries (Fletcher, 1949). Most of the commercially used *O. pyramidale* wood is harvested from plantations, particularly from Ecuador. *O. pyramidale*, with its low density and relatively high mechanical properties, is frequently used as the core in structural sandwich panels, in applications ranging from wind turbine blades to racing yachts (Borrega et al., 2015).

The wood properties of a tree are a combination of its genetic make-up and the environment where it is grown (Moore, 2011). According to Rozenberg and Cahalan (1997) the individual wood properties differ in the extent to which they are under environmental or genetic control. The density of wood varies greatly within any species. Many factors affect wood density, including age, tree vitality, location on the tree, geographic location within the range of species, site condition such as soil, water and slope, genetic resource, climate, stresses growth and species. Because many of these factors act in combination, it is difficult to separate the effects independently (Shmulsky and Jones, 2011).

The mechanical strengths of wood are closely related to its density, since density is the amount of woody substance present per volume unit of wood, and this amount of woody substance is what must resist stresses (Diaz-vaz and Cuevas, 1986). According to Senalik and Farber (2021) wood is a natural material, and the tree is subject to many constantly changing influences, such as humidity, soil conditions, and growing space, so its properties vary considerably, even in clean materials. Diaz-vaz and Cuevas (1986) affirm that the mechanical resistance values of the same species are variable. Pérez (1983) indicates that the values of the variables obtained in the static bending test vary from one tree to another, within the same species or class of wood and within the same tree, depending on the area where the sample is taken.

Wood characteristics often vary greatly within the range of a species, so does growth and adaptability. Often the wood of trees does not exhibit the same properties when they grow in considerably different environments. Environmental and genetic control of the wood can be simultaneously important when evaluating the properties of woods from different geographic sources within a species (Zobel and van Buijtenen, 1989).

2. Materials and methods

2.1. Material provenance

In Los Ríos province, in the littoral region, two sectors were chosen, while in the Amazon region one locality in Sucumbíos province and one locality in Orellana province. The locations, the provinces where they are located, and the geographic coordinates are presented in Table 1, as well as in Figure 1.

Table 1

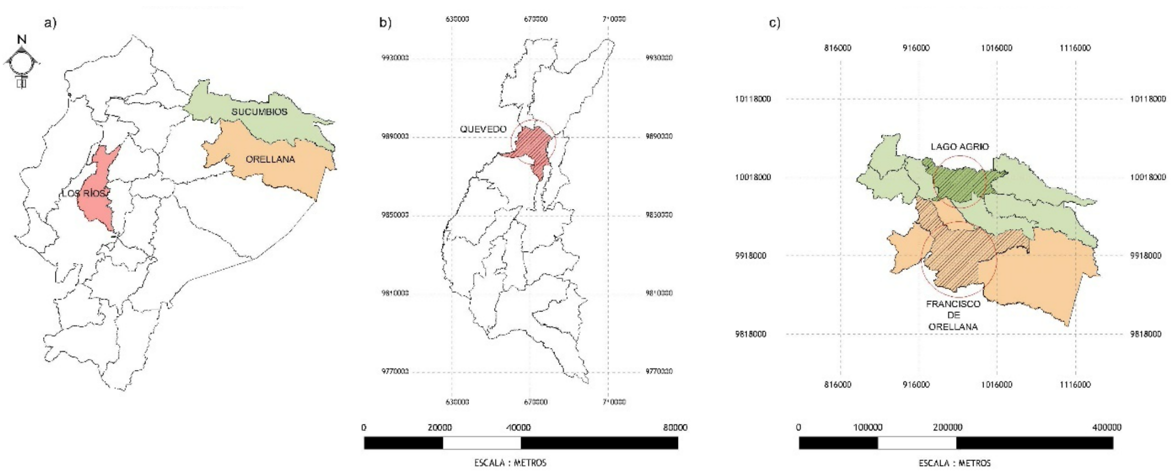
Sampling locations, province where they are located and geographic coordinates.

Locality	Province	Geographic coordinates	
		X	Y
Quevedo	Los Ríos	671231	9877600
Lago Agrio	Sucumbíos	952622	9949204
Francisco de Orellana	Orellana	963748	10019714

Note: Authors (2025).

Figure 1

Map of continental Ecuador.



Note: The figure shows a) Los Ríos, Sucumbíos and Orellana province's location in Ecuadorian territory. b) Quevedo canton location in the coastal province of Los Ríos. c) Location of the Amazonian cantons of Lago Agrio in the province of Sucumbíos and Francisco de Orellana in the province of Orellana (Authors, 2025).

From the total number of trees in the plantations, 6 trees were randomly selected per location, which presented excellent phytosanitary characteristics, straight and cylindrical stems, and were representative in terms of diameter and height. The selected trees were felled with a chainsaw. Subsequently, 3 logs were obtained from each tree of 2.50 m in length, corresponding to the lower, middle and upper part. From each log, 2 sections of 1.25 m in length were obtained, with a total of 36 logs per location. From each log, between 2 and 4 joists were obtained on average.

To obtain the specimens for the physical tests, of the 3 logs per tree (1 in the basal part, 1 in the central part and 1 in the apical part), 2 joists per section were obtained, giving a total of 36 joists per location and 144 joists in total for all the locations. For the mechanical tests, 2 joists were selected randomly per tree corresponding to the basal, central and apical part, giving a total of 12 joists per location and 48 in total for all the locations.

For the elaboration of the specimens for the tests of the physical and mechanical properties, guidelines established in the ASTM D143 (2009) standard were followed. For the physical tests, for each locality, 180 samples were obtained, giving a total of 720 samples for all the localities. With respect to the mechanical tests of 1 random section beam, the specimens for the static bending tests were obtained, while the specimens for the parallel and perpendicular compression tests to the fiber and Janka hardness were made from the second random section joist. 6 specimens were manufactured for each test, giving a total of 24 specimens for each location, with a total of 96 specimens for all the locations.

The planks from which the tests specimens for mechanical test were obtained were kiln dried after the test specimens' preparations, because these planks had to wait a time to obtain the test specimens.

2.2. Physical properties tested

The physical properties such as moisture content, green and anhydrous density, total radial, total tangential, total longitudinal and total volumetric shrinkage, and the total tangential/radial shrinkage ratio (T/R) of the wood were determined, following the specifications established in the ASTM D143 (2009) standards.

2.3. Mechanical properties tested

The mechanical properties evaluated in the Tinus Olsen universal testing machine, with their respective accessories, were fiber stress at the proportional limit (SPL), modulus of rupture (MOR) and modulus of elasticity (MOE) in static bending; SPL, MOR and MOE in parallel compression; SPL and MOR in compression perpendicular to the fiber; the maximum Janka hardness load on the radial, tangential and transverse face, in accordance with the provisions of ASTM D143 (2009). For each tested piece the moisture content was determined, since after obtaining the beams intended for the test pieces, they were subjected to kiln drying to an average moisture content between 6 and 8%, to prevent degradation by Xylophagous fungi, since they were not immediately tested.

2.4. Statistical analysis

Descriptive statistics were performed for the variables evaluated in the physical and mechanical properties. To determine the significant differences among treatments (Los Ríos 3 and 4 years; Sucumbíos 3 years and Orellana 3 years) and location of logs under three blocking criteria (bottom, center, apex), an analysis of variance (ANOVA) for a completely randomized block design was performed at 95% probability. For the separation of means by homogeneous groups, the Tukey test was applied at 0.05% probability.

3. Results

3.1. Physical properties

3.1.1 Moisture content

The percent of moisture content in green and dry state to the *O. pyramidale* wood of 3 and 4 years from different regions of Ecuador, as well as in accordance with the wood position in the tree, is detailed in table 2.

Table 2

Green and dry moisture content of O. pyramidale wood from different age and regions of Ecuador, and three different sections of the tree.

Physical properties	Treatment (locations and tree age in years)		Mean value (%)	Block (height in the tree)	Mean value (%)
Green moisture content	Los Ríos	3	266.53 a*	Bottom	250.76 a*
		4	244.05 ab		
	Orellana	3	225.28 b	Centre	232.93 ab
	Sucumbíos	3	187.25 c	Apex	208.00 b
Dry moisture content	Los Ríos	3	72.05 a*	Bottom	70.61 a*
		4	70.20 ab		
	Orellana	3	68.41 b	Centre	68.92 ab
	Sucumbíos	3	64.24 c	Apex	66.65 b

Note: * Values with different letters are statistically different at 95% probability (Authors, 2025).

According to table 2, with respect to the moisture content in the green and anhydrous state, the highest value was obtained in the wood from Los Ríos of three years with 266.53% and 72.45%, respectively, while the lowest record was gotten in the Sucumbíos wood with 187.77% and 64.27%, respectively. The percentage means show significant differences between the four analyzed localities. Regarding to wood moisture content at different heights in the tree, according to table 2, the highest values of green and anhydrous wood moisture content were recorded in the basal part of the tree, while the lowest values were obtained in the apical segment of the tree. Significant differences were found for the wood moisture content determined between the three segments of the tested tree.

3.1.2 Density

Table 3 summarizes the means values form green and dry density of *O. pyramidale* wood from different ages and Ecuadorian regions, and from the wood obtained at different heights of the trees.

Table 3

Green and dry density of O. pyramidale wood from different regions, with different ages, and at different tree heights.

Physical properties	Treatment (locations and tree age in years)		Mean value ($g.cm^{-3}$)	Block (height in the tree)	Mean value ($g.cm^{-3}$)
Green density	Los Ríos	3	0.34 a	Bottom	0.38 a*
		4	0.35 a		
	Orellana	3	0.32 a	Centre	0.32 b
	Sucumbíos	3	0.36 a*	Apex	0.32 b
Dry density	Los Ríos	3	0.09 b	Bottom	0.12 a*
		4	0.11 ab		
	Orellana	3	0.12 a	Centre	0.11 a

Sucumbíos	3	0.13 a*	Apex	0.11 a

Note: * Values with different letters are statistically different at 95% probability (Authors, 2025).

In accordance with what is reported in table 3, there were no significant differences for the green density values between the three analyzed localities, presenting green densities between 0.32 $g.cm^{-3}$ to 0.36 $g.cm^{-3}$. While for the density in anhydrous state, there were significant differences between the three analyzed localities, determining the highest value in the Sucumbíos wood of three-years-old with 0.13 $g.cm^{-3}$, whilst the lowest value was obtained in the three-year-old wood from Los Ríos with 0.09 $g.cm^{-3}$. Moore (2011) indicates that there is a stronger relationship between wood density and longitude, with sites in the East having higher density than those in the West.

Analyzing the density at different heights of the tree, in relation to the density in the green state, there were significant differences between the three analyzed segments. The highest value of green density was obtained in the basal segment with 0.38 $g.cm^{-3}$, while the lowest value was gotten in the central and apical segments with 0.32 $g.cm^{-3}$. Concerning to the density in anhydrous state, the means do not show significant differences between the three analyzed segments, being practically the same value in the three segments of the tree (Table 3).

3.1.3. Shrinkage

The total tangential, radial, longitudinal and volumetric shrinkage, and the radial/tangential shrinkage ratio from *O. pyramidale* wood of different ages and regions of Ecuador, besides to the wood position in the tree, is detailed in table 4.

Table 4

Tangential, radial, longitudinal and volumetric total shrinkage, and radial/tangential shrinkage ratio from O. pyramidale wood of different ages and regions of Ecuador, and three different sections of the tree.

Physical properties	Treatment (locations and tree age in years)		Mean value (%)	Block (height in the tree)	Mean value (%)
Total tangential shrinkage	Los Ríos	3	5.24 ab	Bottom	6.43 a*
		4	5.61 a*		
	Orellana	3	4.47 b	Centre	4.79 b
	Sucumbíos	3	4.64 b	Apex	3.76 c
Total radial shrinkage	Los Ríos	3	1.06 b	Bottom	1.41 a*
		4	1.88 a*		
	Orellana	3	0.69 c	Centre	1.08 b
	Sucumbíos	3	1.14 b	Apex	1.08 b
Total longitudinal shrinkage	Los Ríos	3	0.29 ab	Bottom	0.28 a*
		4	0.33 a*		
	Orellana	3	0.21 b	Centre	0.25 a
	Sucumbíos	3	0.24 ab	Apex	0.28 a
Total volumetric shrinkage	Los Ríos	3	6.59 b	Bottom	8.12 a*
		4	7.82 a*		
	Orellana	3	5.37 c	Centre	6.12 b

	Sucumbíos	3	6.01 bc	Apex	5.11 c
Radial/Tangential shrinkage ratio (T/R) (dimensionless value)	Los Ríos	3	3.21 b	Bottom	8.38 a
		4	6.88 ab		
	Orellana	3	14.57 a*	Centre	9.65 a*
	Sucumbíos	3	6.49 b	Apex	5.33 a

Note: * Values with different letters are statistically different at 95% probability (Authors, 2025).

According to table 4, there were significant differences for the total shrinkage in the tangential, radial and longitudinal directions, as well as for the total volumetric shrinkage and the tangential/radial shrinkage ratio, for *O. pyramidale* wood from the three locations. The highest total tangential, total radial, total longitudinal and total volumetric shrinkages were determined in four-year-old wood from Los Ríos province, with 5.61%, 1.88%, 0.33% and 7.82%, respectively, while the lowest values occurred in three-year-old wood from the Orellana province, with 4.47%, 0.69%, 0.21% and 5.37%, respectively. The highest tangential/radial shrinkage ratio was determined in three-year-old wood from the Orellana province, with 14.57, while the lowest value was found in wood from the Los Ríos province of three-years-old, with 3.21.

Regarding to the shrinkage of *O. pyramidale* wood at different heights of the tree, significant differences were detected for the total tangential, total radial and total volumetric shrinkage, while for the total longitudinal shrinkage and the tangential/radial shrinkage ratio, there were no significant differences. The highest value of total tangential shrinkage was obtained in the basal part, with 6.43%, while the lowest value was determined in the apical part, with 3.76%. The highest value of total radial shrinkage was obtained in the basal part (1.41%) while the lowest value was calculated in the central and apical part (1.08%). The highest value of 8.12% from total volumetric shrinkage was detected in the basal part, while the lowest total volumetric shrinkage of 5.11% was found in the apical part of the tree (Table 4).

3.2. Mechanical properties

3.2.1 Moisture content of tests specimens

According to Pérez (1983), since the moisture content of the wood is highly correlated with its resistance, it is essential that the moisture of all the specimens is obtained at the time of the test. Failure to determine this physical property makes the results of any test worthless for comparative purposes (Pérez, 1983). As indicated, at the time of mechanical tests on *O. pyramidale* wood from different locations, the moisture content in each test specimen to be tested was determined, and average moisture values were obtained, which are detailed in table 5.

Table 5

Average values of moisture content (%) in O. pyramidale wood test specimens from different locations and ages at the time of mechanical testing.

Mechanical properties test specimens	Moisture content		
	Treatment (locations and tree age in years)		Mean value (%)
Static bending	Los Ríos	3	5.97
		4	7.63
	Orellana	3	6.42
	Sucumbíos	3	6,38
Compression parallel to fibers	Los Ríos	3	5.55
		4	7.75
	Orellana	3	6.13
	Sucumbíos	3	6.42
Compression perpendicular to fibers	Los Ríos	3	5.55
		4	7.75
	Orellana	3	6.13
	Sucumbíos	3	6.40
Hardness	Los Ríos	3	5.55
		4	7.75
	Orellana	3	6.13
	Sucumbíos	3	6.40

Note: Authors (2025).

It should be noted that, according to Pérez (1983), any slight variation in moisture content, when it is less than the PSF (approximately 28%), establishes a large variation in the resistance of the wood. Therefore, each time the mechanical properties of wood species are delivered, they must be accompanied by the data of the wood moisture status to which they were determined (Pérez, 1983). In general, the lowest moisture content values of the test specimens used for the mechanical tests were obtained in the three-year-old wood from Los Ríos, while the highest moisture content values were determined in the four-year-old wood from Los Ríos (Table 5).

3.2.2. Static bending

The average values of the variables calculated in the static bending tests for *O. pyramidale* wood of three Ecuadorian provinces and two ages, just as at different height in the tree, are detailed in the table 6.

Table 6

Average values of variables obtained from static bending rehearsals in O. pyramidale wood specimens from different locations, ages and heights of the tree.

Mechanical property	Variables	Treatment (locations and tree age in years)		Mean value ($kg.cm^{-2}$)	Block (height in the tree)	Mean value ($kg.cm^{-2}$)
Static bending	Fiber stress at	Los Ríos	3	53.75 b	Bottom	60.58 b
			4	50.12 b		

the proportional limit (SPL)	Orellana	3	104.68 a	Centre	84.46 ab
	Sucumbíos	3	106.56 a*	Apex	91.30 a*
Modulus of rupture (MOR)	Los Ríos	3	141.36 a	Bottom	173.25 a*
		4	126.33 a		
	Orellana	3	146.69 a	Centre	140.04 ab
	Sucumbíos	3	163.96 a*	Apex	120.46 b
Modulus of elasticity (MOE)	Los Ríos	3	157560.20 a*	Bottom	122308.70 a*
		4	89722.40 a		
	Orellana	3	107713.70 a	Centre	143606.00 a
	Sucumbíos	3	115996.30 a	Apex	87329.80 a

Note: * Values with different letters are statistically different at 95% probability (Authors, 2025).

According to table 6, there were significant differences between localities for SPL only, while MOR and MOE did not have differences. Considering the wood position in the tree, there were significant differences in SPL and MOR, being higher the SPL in the apex zone, whereas MOR was higher in the bottom zone. MOE did not show differences across the tree height.

The SPL values of *O. pyramidale* wood from amazon provinces (Sucumbíos and Orellana) of the same age were statically equals, as well as the SPL of wood whit different ages from the coastal province (Los Ríos) did not show significant differences. The SPL values from wood of amazon provinces were higher than those determined from wood of the coastal province. This means that the wood from Amazonia support much more load to reach the proportional limit, in other words it is more elastic than wood from coast region.

3.2.3. Parallel and perpendicular compression to fibers

Mean values of the variables calculated in parallel and perpendicular compression to fibers tests, for *O. pyramidale* wood of 3 provinces and 2 ages, at different heights of the tree, are detailed in the table 7.

Table 7

Average values of variables obtained from parallel and perpendicular compression to fibers tests in O. pyramidale wood specimens from different locations from Ecuador, ages and heights of the tree.

Mechanical property	Variables	Treatment (locations and tree age in years)		Mean value (kg.cm^{-2})	Block (height in the tree)	Mean value (kg.cm^{-2})
Parallel compression to fibers	Fiber stress at the proportional limit (SPL)	Los Ríos	3	51.39 a	Bottom	72.07 a*
			4	67.63 a		
		Orellana	3	62.97 a	Centre	67.08 a
		Sucumbíos	3	76.54 a*	Apex	54.75 a
		Los Ríos	3	72.81 b	Bottom	105.41 a*

	Modulus of rupture (MOR)		4	111.31 a*		
		Orellana	3	98.03 ab	Centre	90.15 a
		Sucumbíos	3	110.55 a	Apex	98.96 a
	Modulus of elasticity (MOE)	Los Ríos	3	18900.41 b	Bottom	33214.85 a*
			4	34146.94 a		
		Orellana	3	33993.52 a	Centre	31496.76 a
		Sucumbíos	3	38837.83 a	Apex	29697.42 a
Perpendicular compression to fibers	Fiber stress at the proportional limit (SPL)	Los Ríos	3	8.70 b	Bottom	11.16 a*
			4	7.02 b		
		Orellana	3	11.94 ab	Centre	9.68 a
		Sucumbíos	3	17.43 a*	Apex	12.97 a
	Modulus of rupture (MOR)	Los Ríos	3	13.96 b	Bottom	21.52 a
			4	16.30 b		
		Orellana	3	19.38 b	Centre	17.67 a
		Sucumbíos	3	33.92 a*	Apex	23.49 a

Note: * Values with different letters are statistically different at 95% probability (Authors, 2025).

In compliance with table 7, in the test of parallel compression to fibers, the SPL did not show significant differences among localities and different heights of the tree, whereas the MOR and MOE showed significant differences between localities, but not between different heights of the tree. The MOE in parallel compression to fibers was higher in the wood from Sucumbíos and Orellana, both of three-years-old, and in the four-year-old wood from Los Rios, this means that this wood is more flexible. The MOE of the three-year-old wood from Los Rios was the lowest, which means that this wood is more rigid.

With respect to the perpendicular compression to fibers, the results shown in table 7 indicate that there were significant differences in SPL and MOR between localities, but not in different tree heights. The three-year-old wood from Sucumbíos yielded the highest SPL, while the four-year-old wood from Los Ríos registered the lowest. Meanwhile, the three-year-old wood from Sucumbíos reported the highest MOR, whereas the three-year-old wood from Los Ríos registered the lowest.

3.2.3. Hardness

The Janka hardness mean values in the radial, tangential and transverse directions for *O. pyramidale* wood of three locations and two ages, as well as different heights of the tree, are shown in table 8.

Table 8

Mean values of Janka hardness tests in the radial, tangential and transverse directions of *O. pyramidale* wood specimens from different locations, ages and height of the tree.

Mechanical properties	Treatment (locations and tree age in years)		Mean value (kg)	Block (height in the tree)	Mean value (kg)
Radial Janka hardness	Los Ríos	3	38.83 c	Bottom	50.67 b

		4	86.17 a		
	Orellana	3	46.89 bc	Centre	42.67 b
	Sucumbíos	3	59.89 b	Apex	80.50 a*
Tangential Janka hardness	Los Ríos	3	22.67 c	Bottom	49.42 a
		4	89.00 a		
	Orellana	3	34.55 bc	Centre	35.17 b
	Sucumbíos	3	40.11 b	Apex	55.17 a*
Transverse Janka hardness	Los Ríos	3	37.33 c	Bottom	79.62 a*
		4	97.83 a		
	Orellana	3	51.22 c	Centre	59.33 b
	Sucumbíos	3	74.78 b	Apex	56.92 b

Note: * Values with different letters are statistically different at 95% probability (Authors, 2025).

In compliance with table 8, there were significant differences between the Janka hardness determined in the radial, tangential and transverse directions of *O. pyramidale* wood. The highest Janka hardness value in all direction was recorded in the four-year-old wood from Los Ríos, with 86.17 kg, 89.00 kg and 97.83 kg for radial, tangential and transverse directions, respectively, meanwhile for the three-year-old wood from Los Ríos the values were lower in all directions.

With respect to the Janka hardness in *O. pyramidale* wood at different heights of the tree, significant differences were obtained for the three evaluated directions, being the highest value recorded for radial and tangential directions, with 80.50 kg and 55.17 kg, respectively, both in the apex tree section. Nevertheless, in the transverse section, the highest Janka hardness value was for the wood extracted from the bottom tree zone with 79.62 kg (Table 8). Furthermore, in this study it can be assumed that the hardness was related to specimen density as all the specimen results indicated a rise in hardness as the density becomes greater.

4. Discussion

Borrega et al. (2015) reported that the density values for *O. pyramidale* wood typically range between 0.10 to 0.25 g.cm^{-3}, although these can vary between 0.06 to 0.38 g.cm^{-3}. Wiselius (1998) also states that the density of *O. pyramidale* wood can range between 0.09 and 0.31 g.cm^{-3} at a moisture content of 12%. These density values are similar to those reported in table 3. In *O. pyramidale* wood, Eddowers (2005) reported that the density in the air-dry state ranges from 0.12 to 0.24 g.cm^{-3}, while Bootle (1983) reported for *O. pyramidale* wood from Ecuador an air-dry density of 0.17 g.cm^{-3}. According to Eddowers (2005) and Kotlarewski et al. (2016) the most desirable densities for commercial use, in the dry state, range from 0.12 to 0.18 g.cm^{-3}.

The anhydrous density value reported for the wood in Sucumbíos province is similar to that reported by CIRAD (2012) for *O. pyramidale* wood at 12% MC of 0.14 g.cm^{-3}, as well as that reported by Bhekti et al. (2017) of 0.14 g.cm-3 basic density. Ortiz

(2018) also reported similar density values for this species in Ecuador, with 0.16 g.cm^{-3} for wood from humid zones and 0.20 to 0.15 g.cm^{-3} for wood from dry zones. This author reported that there was a significant variation in density from one area to another, as well as between sites in the same area. According to Ortiz (2018), the density of wood is a very susceptible property that can vary between individuals of the same species found in different locations. For his part, Hocker (1984) indicates that density can be affected both by the origin of the genetic material and by environmental factors to which each individual is exposed during their growth.

Dry density at different tree heights in the present study did not show significant differences. These results differ from those reported by Ortiz (2018) who indicated that the density of *O. pyramidale* wood behaves in a quadratic manner at different heights of the tree. High values of density are observed in the lower section of the tree, then it decreases in the middle, and it tends to rise again in the upper section. Thus, the density tends to increase along with the height. According to this researcher, this may be due to the fact that the roots and the support of the stem are both at the bottom of the tree, causing the density to be higher at that point. In the case of the highest part of individuals, this characteristic tends to increase due to the need to support the full weight of the branches and leaves that form the tree's crown.

The difference in green density of the *O. pyramidale* wood can be attributed to the anatomical constitution of the wood. Borrega et al. (2015) stated that fibers are the main contributor to the large density variations in *O. pyramidale* wood. The volumetric fraction of the fibers decreases slightly with increasing density, but their solid fraction increases at least fivefold, due to the smaller cell lumen and thicker cell walls. The increase in cell wall thickness is prevalent due to the thicker S2 layer. Thus, the increase in cell wall thickness of the fibers with increasing density is mainly due to the presence of a thicker S2 layer, with only a small contribution from the middle sheet, and the S1 and S3 layers. In low-density *O. pyramidale* wood, the S2 layer is as thick as S1 and S3, and represents approximately 30% of the cell wall thickness. In high-density *O. pyramidale* wood, the S2 layer is 7 to 9 times thicker than S1 and S3, and represents approximately 73% of the cell wall thickness.

CIRAD (2012) reported that *O. pyramidale* wood presents a total tangential shrinkage of 5.2%, which is similar to the *O. pyramidale* wood from Los Ríos determined in this research. The same author informed a total radial shrinkage of 2.2%, higher than those showed in table 4 for localities and heights of the tree. According to these shrinkages, CIRAD (2012) classify the *O. pyramidale* wood as low shrinkage. CIRAD (2012) reported a tangential/radial shrinkage ratio of 2.4 for *O. pyramidale* wood, much lower those reported in table 4. CIRAD (2012) classifies *O. pyramidale* wood as moderately stable, but according to the values in table 4, for this research *O. pyramidale* wood may be classified as unstable. Wiselius (1998) states that shrinkage upon seasoning of *O. pyramidale* wood is low to moderate.

Yao (1969) as cited in Ruwanpathiranal et al. (1996) observed that tangential shrinkage decreased with increasing height in the tree, while longitudinal shrinkage increased. This affirmation is in accordance with the tangential and longitudinal shrinkages values reported in table 4. These trends are in line with the patterns of variation in wood density, confirming that shrinkage and density are related. In general, shrinkage seems to be related to factors such as rate of growth, position in the tree, and the presence of reaction wood, as well as to wood density (Ruwanpathiranal et al. 1996).

The MOR in static bending reported in this research is in accordance with the values reported in the literature, whereas the MOE values in static bending are greater than those reported in previous studies. For *O. pyramidale* wood with an air-dry density of 0.17 $g.cm^{-3}$ from Ecuador, Bootle (1983) reported a MOE of 38749 $kg.cm^{-2}$ and a MOR of 193.70 $kg.cm^{-2}$. In previous studies on *O. pyramidale* wood there have been reported values of MOE of 38749 $kg.cm^{-2}$ and a MOR of 193.70 $kg.cm^{-2}$ in dry wood from Salomon islands (Eddowes, 2005). CIRAD (2012) also reported a MOE of 52413 $kg.cm^{-2}$ and a MOR of 244.70 $kg.cm^{-2}$ for *O. pyramidale* wood to 12% of moisture content, they classify to *O. pyramidale* wood according to these values as low resistance and MOE. In *O. pyramidale* wood from Papua New Guinea, Wiselius (1998) informed a MOE ranged between 11778 - 16774 $kg.cm^{-2}$ and a MOR ranged from 86.68 - 127.5 $kg.cm^{-2}$. Senalik and Farber (2021) affirms that *O. pyramidale* wood from America, in static bending tests, have a MOE of 34670 $kg.cm^{-2}$ and a MOR of 220.30 $kg.cm^{-2}$. Tsoumis (1991) indicated a 26003 $kg.cm^{-2}$ of MOE and 193.70 $kg.cm^{-2}$ for MOR, for *O. pyramidale* wood from tropical America.

On their behalf, Kotlarewski et al. (2016) reported in static bending tests for *O. pyramidale* wood with an average of moisture content of 13% and a density ranged among 0.08 ≤ 0.12 $g.cm^{-3}$ a MOE of 12461 $kg.cm^{-2}$ and a MOR of 99.93 $kg.cm^{-2}$, while for wood with density range from 0.12 ≤ 0.18 $g.cm^{-3}$ a MOE of 20772 $kg.cm^{-2}$ and a MOR of 169.30 $kg.cm^{-2}$. They also argued that there is a relationship between the MOE and MOR value in static bending, specimens with a high MOE generated a high MOR value too.

According to Bhekti et al. (2017) the mean values of MOE and MOR in static bending for *O. pyramidale* wood is 46193.14 $kg.cm^{-2}$ and 233.50 $kg.cm^{-2}$ respectively. The authors emphasize that a significant positive correlation occurs between the static bending properties (MOE and MOR) and air-dry density, suggesting that air dry density is a good indicator for predicting mechanical properties in *O. pyramidale* wood.

According to the results of this research, the MOR in parallel compression to fibers was statistically the same and higher in wood from Sucumbíos of three years old (0.13 $g.cm^{-3}$ anhydrous density) and Los Ríos of four years old (0.11 $g.cm^{-3}$ anhydrous density), consequently this wood support more load until fracture, whilst the lowest value was determined in three years old wood from Los Ríos (0.09 $g.cm^{-3}$ anhydrous density) wood, which resist less load until fracture. According to Bhekti et al. (2017)

there is a significant positive correlation between air-dry density and MOR in parallel compression to fibers. Kollmann and Côté (1968) states that MOR in parallel compression to fibers is highly correlated with basic density. These statements may explain the significant differences between MOR in parallel compression to fibers obtained in this study.

Senalik and Farber (2021) affirms that *O. pyramidale* wood exhibits a MOR parallel to fibers of 151.90 kg.cm^{-2}. Eddowers (2005) reported a MOR parallel to fibers of 122.40 kg.cm^{-2} for *O. pyramidale* wood from Salomon islands. Coincidentally, for Ecuadorian *O. pyramidale* wood, with an air-dry density of 0.17 g.cm^{-3}, Bootle (1983) reported a MOR parallel to fibers of 122.40 kg.cm^{-2}. For their part, Tsoumis (1991) informed a MOR value parallel to fibers for *O. pyramidale* wood from tropical America of 91.77 kg.cm^{-2}. Bhekti et al. (2017) reported a MOR in parallel compression to fibers of 106.91 kg.cm^{-2} in *O. pyramidale* wood. In this research the MOR in parallel compression to fibers was higher than MOR in perpendicular compression to fibers. Goodrich et al. (2010) affirms that the compressive strength is greater when it is parallel to the fibers than when it is perpendicular (radial direction). In a *O. pyramidale* wood study from Papua New Guinea, Kotlarewski et al. (2016) informed for parallel compression to fibers tests in wood with 13% of moisture content and densities of 0.12 ≤ 0.18, 0.18 ≤ 0.22 and > 0.22 g.cm^{-3}, MOR values of 93.81, 150.90 and 158.1 kg.cm^{-2}, respectively. These results, in accordance with these authors, indicate that the compressive resistance of a specimen is greater with higher densities.

The *O. pyramidale* wood elasticity depends on its density, where a decrease in the wood porosity with corresponding increase in density, increases the Young's modulus (Shishkina et al. 2014). Borrega et al. (2015) also states that the axial compressive Young's modulus and strength in *O. pyramidale* wood vary linearly with density, reaching values up to 61183.00 kg.cm^{-2} for modulus and 407.90 kg.cm^{-2} for strength at the highest densities. According to Bhekti et al. (2017) the dynamic Young's modulus (DMOE) in O. *pyramidale* wood of slow-growth, medium growth and fast-growth from east Java ranged from 27226.42 kg.cm^{-2} to 55268.62 kg.cm^{-2}. When considering different height of the tree, these authors informed that there was not significant difference in DMOE, which coincides with the results obtained in this research (table 7). However, Bhekti et al. (2017) recorded a significant difference at the 5% level in DMOE among the trees in each category, suggesting that DMOE in *O. pyramidale* wood varies among trees with the same growth rate, which may account the differences between MOE of Sucumbíos and Los Ríos both of three-years-old (table 7).

Kotlarewski et al. (2016) in perpendicular compression to fibers tests in *O. pyramidale* wood from Papua New Guinea with an average moisture content of 11% and with densities of < 0.08 g.cm^{-3}, 0.08 ≤ 0.12 g.cm^{-3}, and 0.12 ≤ 0.18 g.cm^{-3}, reported a MOR values of 4.08, 6.12 and 11.22 kg.cm^{-2}, respectively. These results, according to these researchers, demonstrated that an increase in density does increase the compressive resistance perpendicular to the grain, and that the compressive ability is greater parallel to the grain. Likewise, Tsoumis (1991) informed to *O. pyramidale* wood from tropical America a MOR perpendicular to fibers of 10.2 $kg.cm^{-2}$.

Borrega et al. (2015) pointed out that fibers in the xylem were aligned axially along the trunk of the tree. However, some fibers showed a change in orientation in the axial–tangential plane, particularly where rays penetrated the wood structure. These researchers affirm that the mean fiber misalignment in *O. pyramidale* wood of medium density is 6.1º, and conclude, according to the affirmations of Vural and Ravichandran (2003) as well as Da Silva and Kyriakides (2007), that from a mechanical point of view, fiber misalignment is important because it leads to the development of shear stresses during compression and to initiation of failure by kinking in high-density *O. pyramidale* wood.

In *O. pyramidale* wood, failure in compression tends to occur in the axial–tangential plane with the failure mode transitioning from plastic buckling of fibers to kink band formation as the density increases. Kink band formation in high-density *O. pyramidale* wood is facilitated by local misalignment of fibers due to the presence of rays, which leads to the development of shear stresses during compression. In the transverse direction, compressive modulus and strength vary to the cube and square of density, respectively, due to bending of the fiber cell walls. Transverse compressive modulus and strength values are about an order of magnitude lower than those in the axial direction. The rays act as reinforcement when *O. pyramidale* is loaded in the radial direction, with this effect being more pronounced in low-density *O. pyramidale* (Borrega et al., 2015).

In general, according to table 8, the *O. pyramidale* wood has higher values of Janka hardness value in transverse face. Cave (1968) consider that the S2 layer in the cell wall of fibers is the most important layer in the cell wall with respect to axial mechanical properties of wood, and particularly with respect to stiffness. According to Barnett and Bonham (2004) and Donaldson (2008), this is due to the greater thickness of the S2 layer, but also to its lower MFA. Bootle (1983) informed for *O. pyramidale* wood from Ecuador a Janka hardness value of 40.79 kg. Tsoumis (1991) also reported a value of 40.79 kg of Janka hardness for *O. pyramidale* wood from tropical America. On their behalf, Eddowes (2005) in a study on dry *O. pyramidale* wood from Salomon islands, determined a Janka hardness value of 43.0 kg.

In *O. pyramidale* wood from Papua New Guinea, with a moisture content of 14%, Kotlarewski et al. (2016) reported averages Janka hardness for the tangential surface for wood density of 0.08 ≤ 0.12 $g.cm^{-3}$ of 19.99 kg, for wood density of 0.12 ≤ 0.18 $g.cm^{-3}$ of 31.30 kg, and for wood density of 0.18 ≤ 0.22 $g.cm^{-3}$ of 59.65 kg. Similarly, the results for the radial surface in order of the density class were 23.76 kg, 29.57 kg, 56.70 kg and in the transverse surface were 31.92 kg, 43.44 kg and 69.65 kg. These authors affirm that the transverse surface is far superior to the tangential and radial surface by almost doubling each value presented for each density class. In the present research, in all ages analyzed, may be concluded that the transverse Janka hardness is higher that radial and tangential Janka hardness (Table 7).

Borrega et al. (2015) claim that cellulose microfibrils contain both amorphous and highly ordered crystalline regions. The relative degree of crystallinity in *O. pyramidale* cellulose is about 39%, regardless the density. Considering that the cellulose content in *O. pyramidale* wood is between 40 and 45%, then cellulose crystallinity was about 80 - 90%, significantly higher than the 40 - 60% determined for other hardwoods. Besides cellulose microfibrils in the S2 are highly aligned with the fiber axis, with a mean micro fibril angle (MFA) in the vicinity of 1.4º, and the cellulose crystallites in the microfibrils is about 3 nm in width and 20 - 30 nm in length. The degree of cellulose crystallinity is between 80 and 90%, significantly higher than previously reported for other woods. The low MFA, coupled with the high crystallinity, is expected to confer excellent axial mechanical properties to *O. pyramidale* wood.

5. Conclusions

The physical properties that presented significant differences were the moisture content in the green and anhydrous state, the anhydrous density, the total tangential shrinkage, the total radial shrinkage, the total longitudinal shrinkage and the total volumetric shrinkage, as well as the radial/tangential shrinkage ratio.

The highest green and anhydrous moisture contents were obtained in the three-year-old wood from Los Ríos, while the lowest values were found in the three-year-old wood from Sucumbíos. The three-year-old wood from Orellana and Sucumbíos presented the highest anhydrous density values, while the three-year-old wood from Los Ríos exhibited the lowest value. The highest values of total tangential, total radial, total longitudinal and total volumetric shrinkage were for the four-year-old wood from Los Ríos, while the lowest values were for the three-year-old wood from Orellana. The highest value of the radial/tangential shrinkage ratio was detected in the three-year-old wood from Orellana, while the lowest value was found in the three-year-old wood from Los Ríos.

Regarding the position of the wood at different heights of the tree, there were significant differences for the moisture content in the green and anhydrous state, the density in the green state, as well as for the total tangential, radial and volumetric shrinkage. The highest values for these variables were detected in the bottom zone of the tree, while the lowest values were found in the apical zone of the tree.

The mechanical properties in which significant differences were detected were the fiber stress at the proportional limit in static bending, the modulus of rupture and the modulus of elasticity in compression parallel to the fiber, the fiber stress at the proportional limit and the modulus of rupture in compression perpendicular to the fibers, the Janka hardness on the radial, tangential and transverse faces.

The greatest value for fiber stress in the proportional limit in static bending were detected in the three-year-old wood from Sucumbíos and Orellana, while the lowest values were found in the three and four-year-old wood from Los Ríos.

In parallel compression to fibers, the highest values of modulus of rupture were detected in the four-year-old wood from Los Ríos and in the three-year-old wood from Sucumbíos. The lowest value was obtained in the three-year-old wood from Los Ríos. The highest modulus of elasticity was gotten in the three-year-old wood from Sucumbíos, four-year-old from Los Ríos and three-year-old from Orellana, while the lowest value was for the three-year-old wood from Los Ríos.

In perpendicular compression to fibers, the greatest fiber stress at the proportional limit was for the three-year-old wood from Sucumbíos, while the lowest values were obtained in the three and four-year-old wood from Los Ríos. The highest modulus of rupture was obtained in the three-year-old wood from Sucumbíos, while the lowest values were gotten in the three and four-year-old wood from Los Ríos, as well as in the three-year-old wood from Orellana.

The highest load withstood in Janka hardness on the radial, tangential and transverse faces was found in the four-year-old wood from Los Ríos, while the lowest supported load was detected in the three-year-old wood from Los Ríos.

Considering the location of the wood in the tree, there were significant differences for the fiber stress at the proportional limit and for the modulus of rupture in static bending, as well as for the Janka hardness in the radial, tangential and transverse faces. In static bending, the highest value of fiber stress at the proportional limit was detected in the wood of the apical zone, while the highest value of the modulus of rupture was found in the wood of the bottom zone. In Janka hardness, the highest load recorded on the radial face was for the wood of the apex, while for the tangential face the highest values were calculated in the bottom and apical zone, whereas for the transverse face the highest values were detected in the wood from the bottom zone.

According to the results obtained, and taking into consideration the uses that are given to the wood of *O. pyramidale*, the three-year-old wood from Sucumbíos and Orellana provinces gives better technological properties than the three and four-year-old wood from Los Ríos, which suggests that the wood of the eastern zone can be used in less time than the one of the coastal zone, without this affecting the technological properties of the *O. pyramidale* wood.

In general, taking into consideration the applications of *O. pyramidale* wood, the three-year-old wood from Sucumbíos and Orellana provinces has better technological properties than the three and four-year-old wood from Los Ríos. It can be concluded that the wood from the eastern provinces of northern Ecuador can be harvested one year earlier than the wood from the coastal zone, without this or the age difference affecting the technological properties of the *O. pyramidale* wood.

Acknowledgments

The authors thanks to Fondos Concursables para Investigación Científica y Tecnológica (FOCICYT) from the Universidad Técnica Estatal de Quevedo (UTEQ) and the Gurit-Balsaflex company for funding this research.

Disclaimers

The authors declare that they have no conflicts of interest.

Bibliographic References

ASTM D 143-09. (2009). *Standard Test Methods for Small Clear Specimens of Timber*.

Barnett, J. & Bonham, V. (2004). Cellulose microfibril angle in the cell wall of wood fibres. *Biological Review*, 79(2), 461-472. https://doi.org/10.1017/S1464793103006377

Bhekti, Y., Ishiguri, F., Aiso, H., Ohshima, J. & Yokota, S. (2017). Wood properties of 7-year-old balsa (*Ochroma pyramidale*) planted in East Java. *International Wood Products Journal*, 8(4), 227-232. https://doi.org/10.1080/20426445.2017.1394560

Bonet, X., Coello, J. & Andrade, H. (2009). *Overview of balsa wood as a core material in sandwich construction PRFV*. BALSEUROP ECUATO ESPAÑOLA, SL. (in Spanish).

Bootle, K. (1983). *Wood in Australia. Types, properties and uses*. McGraw-Hill Book Company.

Borrega, M., Ahvenainen, P., Serimaa, R. & Gibson, L. (2015). Composition and structure of balsa (*Ochroma pyramidale*) wood. *Wood Science and Technology*, 49(2), 403-420. https://doi.org/10.1007/s00226-015-0700-5

Cave, I. (1968). The anisotropic elasticity of the plant cell wall. *Wood Science and Technology*, 2(4), 268-278. https://doi.org/10.1007/BF00350273

CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement). (2012). *Balsa*. TROPIX 7. Fichiers Complementaires.

Da Silva, A. & Kyriakides S. (2007). Compressive response and failure of balsa wood. *International Journal of Solids and Structures*, 44(25-26), 8685-8717. https://doi.org/10.1016/j.ijsolstr.2007.07.003

Diaz-vaz, J. & Cuevas, H. (1986). *Mechanics of wood*. Teacher publication N° 23. Faculty of Forest Sciences. Austral University of Chile. (in Spanish).

Donaldson, L. (2008). Microfibril angle: measurement, variation and relationships - a review. *IAWA Journal*, 29(4), 345-386. https://doi.org/10.1163/22941932-90000192

Eddowes, P. (2005). *Solomon Islands timber*. Solomon Islands Forestry Management Project (SIFMP II). AusAID. https://www.fiapng.com/Solomon_Island_Timber_Species.pdf

Fletcher, M. (1949). Balsa Industry of Ecuador. *Economic Geography*, 25(1), 47-54.

González, B., Cervantes, X., Torres, E., Sánchez, C. & Simba, L. (2010). Characterization of the balsa cultivation (*Ochroma pyramidale*) in the The Rivers province of Ecuador (Caracterización del cultivo de balsa (*Ochroma pyramidale*) en la provincia de Los Ríos – Ecuador). *Ciencia y Tecnología*, 3(2), 7-11. https://doi.org/10.18779/cyt.v3i2.94

Goodrich, T., Nawaz, N., Feih, S., Lattimer, B. & Mouritz, A. (2010). High-temperature mechanical properties and thermal recovery of balsa wood. *Journal of Wood Science*, 56(6), 437-443. https://doi.org/10.1007/s10086-010-1125-2

Hocker, H. (1984). *Introduction to Forest Biology*. AGT Editor. (in Spanish).

Kollmann, F. & Côté, W. (1968). *Principles of wood science and technology. Volume I: Solid Wood*. Springer – Verlag.

Kotlarewski, N., Belleville, B., Gusamo, B. and Ozarska, B. (2016). Mechanical properties of Papua New Guinea balsa wood. *European Journal of Wood and Wood Products*, 74(1), 83-89. https://doi.org/10.1007/s00107-015-0983-0

Moore, J. (2011). *Wood properties and uses of Sitka spruce in Britain*. Forestry Commission Research Report. https://cdn.forestresearch.gov.uk/2011/03/fcrp015.pdf

Ortiz, M. (2018). *Characterization of the balsa wood density (Ochroma pyramidale) in two edaphoclimatic zones of the Ecuadorian coast* [Thesis in Environment and Development Engineering, Zamorano Pan-American School of Agriculture]. (in Spanish). https://bdigital.zamorano.edu/handle/11036/6383

Pérez, V. (1983). *Handbook of physical and mechanical properties of Chilean woods*. National Forest Corporation. (in Spanish).

Rozenberg, P. and Cahalan, C. (1997). Spruce and wood quality: genetic aspects (a review). *Silvae Genetica*, 46(5), 270-279.

Ruwanpathiranal, N., Amarasekera, H., & de Silva, M. (1996). Variation of *Pinus caribaea* wood density with height in tree and distance from pith, in different site classes. In: H. Amarasekera, D. Ranasingile & W. Finlayson. (Eds.). *Proceedings of the Second Annual Forestry Symposium. Management and Sustainable Utilization of Forest Resources* (pp. 49-57). https://doi.org/10.31357/fesympo.v0i0.1200

Senalik, C. & Farber, B. (2021). Mechanical properties of wood. Chapter 5. In: Ross, R. (Ed). *Wood handbook – Wood as an engineering material*. (pp. 5-1; 5-46). Forest Products Laboratory. United States Department of Agriculture. Forest Service. https://www.fpl.fs.usda.gov/documnts/fplgtr/fplgtr282/chapter_05_fpl_gtr282.pdf

Shishkina, O., Lomov, S., Verpoest, I. & Gorbatikh, L. (2014). Structure–property relations for balsa wood as a function of density: modelling approach. *Archive of Applied Mechanics*, 84 (6), 789-805. https://doi.org/10.1007/s00419-014-0833-2

Shmulsky, R. & Jones, P. (2011). *Forest Products & Wood Science – an introduction*. Sixth edition. Wiley-Blackwell.

Tsoumis, G. (1991). *Science and technology of wood: structure, properties, utilization*. Van Nostrand Reinhold.

Vural, M. & Ravichandran, G. (2003). Microstructural aspects and modeling of failure in naturally occurring porous composites. *Mechanics of Materials*, 35(3-6), 523-536. https://doi.org/10.1016/S0167-6636(02)00268-5

Wiselius, S. (1998). *Ochroma* Sw. In: M. Sosef, L. Hong & S. Prawirohatmodjo. (Eds.). *Plant resources of South-East Asia No 5(3). Timber trees: lesser-known timbers*. Backhuys Publishers.

Zobel, B. & van Biujtenen, J. (1989). The effect of provenance variation and exotic plantations on Wood properties. Chapter 2. In: *Wood variation – Its causes control*. Springer – Verlag.