DOI: https://doi.org/10.29298/rmcf.v12iEspecial-1.1086

Review article

Aportes de investigación del INIFAP en tecnología de la madera y sus procesos de industrialización

Research contributions of INIFAP on wood technology and its industrialization processes

Juan Carlos Tamarit-Urias[1], Patricia Aguilar-Sánchez[1], Rogelio Flores-Velázquez[2] y Martha Elena Fuentes-López[1*]

Resumen

La caracterización tecnológica de la madera de especies forestales de México es fundamental para determinar su uso potencial óptimo; y con ello lograr procesos de transformación e industrialización exitosos. En este contexto, el Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP) mediante líneas estratégicas de investigación en ciencia y tecnología de la madera, e industrias y productos forestales ha generado conocimiento científico que contribuye a mejorar los sistemas y procesos de producción en la industria, en el marco del desarrollo sustentable. Se presenta una compilación y síntesis de los resultados obtenidos a partir de trabajos relevantes en investigación básica y aplicada que se han realizado en el INIFAP durante los años 1986 a 2020. En el presente documento se abordan temas en tecnología de la madera referentes a la física, mecánica y química de la madera; en tanto que, en materia de procesos de industrialización se desarrollan aspectos de aserrío, secado y maquinado de la madera. Por la abundancia de taxones cuya madera, comúnmente, se cataloga como difícil de utilizar tales como el grupo de encinos y de otras denominadas comunes tropicales, se ha puesto énfasis en la caracterización y aprovechamiento en ese tipo de especies para las regiones templadas y tropicales de México. Además, se incluyen las perspectivas y retos de investigación en tecnología de la madera, industrias y productos forestales.

Palabras clave: Calidad de la madera, caracterización tecnológica, industria y productos forestales, procesos de transformación primaria, usos de la madera, xilotecnología.

Abstract

The technological characterization of the wood of forest species in Mexico is essential to determine its optimal potential use and, thereby, achieve successful transformation and industrialization processes. Within this context, the *Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP)* (National Institute for Research in Forests, Agriculture and Livestock) (INIFAP), through strategic lines of research in science and technology of wood and forest industries and products, has generated scientific knowledge that contributes to improving production systems and processes in the forest products industry within the framework of sustainable development. A compilation and synthesis of the most important results drawn from relevant works in basic and applied research carried out by INIFAP during the years 1986 to 2020 is presented herein. The topics addressed in the sphere of wood technology are physics, mechanics and chemistry of wood, while in terms of industrialization processes, aspects of sawing, drying and machining of wood are developed. Due to the abundance of taxa whose wood is commonly classified as difficult to use, such as the group of oaks and others known as common tropical, emphasis has been placed on the description and use of this type of species for temperate and tropical regions of Mexico. Also presented herein are research perspectives and challenges in wood technology, forest industries and products.

Key words: Wood quality, technological characterization, industry and forest products, primary transformation processes, uses of wood, xylotechnology.

Fecha de recepción/Reception date: 26 de febrero de 2021
Fecha de aceptación/Acceptance date: 10 de agosto de 2021

[1]Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Campo Experimental San Martinito. México.
[2]Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Centro Nacional de Investigación Disciplinaria en Conservación y Mejoramiento de Ecosistemas Forestales. México.
*Autor para correspondencia; correo-e: fuentes.martha@inifap.gob.mx

Introduction

Mexico has 64.9 million hectares of forests and tropical forests, ecosystems where 46 species of the *Pinus* genus (pine), around 150 species of *Quercus* (oak) and more than 62 tropical timber taxa of several genera coexist; together, these taxa make up 47.7 % of the national forest area. The timber production in 2017 was 8.5 million m^3 roundwood; pine contributed 70.87 %; common tropical species 13.39 % and oaks 9.84 % (Conafor, 2019).

The economic, social, and environmental potential represented by timber species leads to the generation of technological knowledge for the forest industry, which contributes to their better utilization, as well as to the achievement of successful transformation and industrialization processes. The correct use of wood requires a normalized knowledge with international standards for its attributes that may allow inferring its behavior in the transformation processes and in the different treatments required for the conditions of use to which it will be exposed.

The *Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP)* (National Institute for Research in Forests, Agriculture and Livestock) (INIFAP) has conducted research on wood technology, industries and forest products; it has also contributed to the knowledge and use of wood through xylotechnological characterization, based on research lines such as macro and microscopic anatomy, natural durability, preservation of hardwoods and softwoods, among others. However, this document only shows the main contributions derived from research related to the physical, mechanical and chemical aspects of wood, as well as to the primary transformation processes of sawmilling, drying and machining, with emphasis on taxa belonging to the group of commercially important conifers such as *Pinus*, broadleaved species of the *Quercus* genus, and some tropical species classified as hardwoods.

In order to integrate the most relevant research results on the topics of wood technology and forest industries mentioned above, a thorough and exhaustive documentary review of the official publications available in the INIFAP Series was carried out. Scientific literature was also consulted in the form of articles published by researchers of this institution. In order to outline a basic theoretical and discussion framework for each topic, specialized scientific literature was reviewed, and so were the technical standards for specific characterizations. To a lesser extent, publications of scientific personnel from outside the Institution were incorporated and used for contrast, reference and complementarity of the information provided.

Based upon the fundamental premise that the ultimate goal of wood technology will always be to provide scientific-technical elements for the forest industry to generate products that satisfy and solve society's needs, it is expected that with INIFAP's contributions in this area it will be possible to envision research perspectives with topics and lines of research that will constitute an updated priority and strategic agenda favoring innovation, growth and development; this will contribute to render Mexico's forest industry more efficient and competitive within the framework of sustainable development.

Wood physics and mechanics

The physical and mechanical properties of wood are the most important in determining its use as solid wood. These attributes serve as quality indexes to determine the most convenient use; they also influence the dimensional behavior of the wood in its transversal, tangential and radial planes in the face of climatic conditions that may cause undesirable effects. The strength of the wood is severely affected by moisture content and direction of loading, relative to the longitudinal plane. In the longitudinal direction, the bending strength is directly proportional to the density of the wood. The longitudinal cells are structures that provide stiffness and strength, since they receive the loads directly. The most studied physical properties are basic density (Bd), moisture content (MC), shrinkage, anisotropy ratio and fiber saturation point (FSP) (Kollman, 1959).

The physical properties of the wood of certain taxa of the *Quercus* genus have been determined in the states of *Puebla, Guanajuato* and *Oaxaca* (Fuentes and Flores, 1995; Honorato and Fuentes, 2001). Oaks are a taxonomic group with a wide distribution; they abound in Mexico and have a high productive potential. However, they are used for low value-added products. They are characterized by using the methods indicated in the American Standard ASTM D143 (Fuentes and Flores, 1995; Honorato and Fuentes, 2001). The physical properties of the following nine species of oak have been studied: *Quercus affinis* Scheidw, *Q. glabrescens* Benth., *Q. crassifolia* Bonpl., *Q. mexicana* Bonpl., *Q. laurina* Humb. & Bonpl., *Q. obtusata* Humb. & Bonpl., *Q. rugosa* Née., *Q. durifolia* Seemen ex Loes., and *Q. castanea* Née., whose timbers were classified as high density, and whose values ranged from 0.62 to 0.84 g cm^{-3} (Fuentes and Flores, 1995; Honorato and Fuentes, 2001).

Basic density is the most widely used indicator to determine and infer other properties of wood: performance and quality. Variation in the density of wood occurs between and within species and increases from the pith to the bark; it is the result of cell wall thickness, fiber diameter, number and size of vessels and chemical composition. In those with a high density, the contraction and expansion increases by moisture content. Wood becomes stronger as its increases in density, which is assessed from the level of moisture content at which its mass and volume are measured (Panshin and De Zeeuw, 1980).

Total radial shrinkage has been determined in the 4.3-5.52 range %; total tangential shrinkage, between 12.6-16.6 %; while total volumetric shrinkage is 16.21 to 19.0 % (Fuentes and Flores, 1995; Honorato and Fuentes, 2001). These values suggest high and very high dimensional changes, as well as a high anisotropy ratio, leading to a high propensity to deformation (cracking and splitting) and a lower dimensional stability. Large differences in shrinkage values between the radial and tangential planes can cause defects during drying, which are accentuated when the moisture content is below the Fiber Saturation Point (FSP) (Kollmann, 1959; Fuentes and Flores, 1995).

The FSP represents the turning point at which important changes in physical and mechanical properties occur. At INIFAP, moisture content percentages ranging from 25 to 35 % have been obtained. The anisotropy varies between 2.5 and 3.4 %, records that are related to abundant uniseriate and polyseriate rays (Fuentes and Flores, 1995; Honorato and Fuentes, 2001). These values are within the range established for angiosperm species with a distinct heartwood (Kollmann and Coté, 1968).

Mechanical properties define the behavior, aptitude and capacity of wood to resist external forces in its different planes; they have a proportional dependence upon density and moisture. Stiffness and mechanical strength are important in applications for structural purposes and in the dimensioning of different parts to evaluate their deformation and determine their resistance.

Static bending refers to the resistance of wood to loads; thus, when it is used as a beam (loads transverse to its longitudinal axis), deformations and compressive, shear and tensile stresses are produced (Honorato and Fuentes, 2001). The compression parallel to the grain corresponds to the resistance of wood to loads, when used as a column. The wood has its lowest tensile strength perpendicularly to the grain, and the highest (10 - 20 times higher), in the direction parallel to the grain; in the transverse direction there is a separation of the fibers, and in the longitudinal direction, breakage of the fibers (Vignote and Martínez, 2006).

Tensile strength is also density-dependent; in this respect, spring wood (which is lighter) is one-sixth as strong as summer wood. Shear strength is often reduced by knots or cracks in the wood and is equivalent to 10-15 % of the parallel tensile strength (Vignote and Martínez, 2006).

The values of the mechanical properties of oak wood were estimated in green condition, at 12 % moisture content (tables 1 and 2) (Fuentes and Flores, 1995; Honorato and Fuentes, 2001), based on the American Standard ASTM D143 (ASTM, 1992) and the French Standard AFN NFB51-009 (1985) for evaluating impact resistance. Static bending and compression parallel to the grain with stress at the proportional limit, modulus of rupture, modulus of elasticity, work at the proportional limit, and work at maximum load were also determined, as well as compression perpendicular to the grain, perpendicular tension, shear stress, cracking, hardness, and impact. Consistently, the values obtained at 12 % moisture were higher than those determined in green condition (Fuentes and Flores, 1995; Honorato and Fuentes 2001).

Table 1. Mechanical properties of the wood of species of the genus *Quercus*.

Species	MC	Static flexion ($kg\ cm^{-2}$)			Axial compression ($kg\ cm^{-2}$)			CPG	Impact		
		SLP	MOR	MOE	SLP	MOR	MOE	SLP	W	K	R
Q. affinis Scheidw	Green	471	667	117	323	332	76	73	3.2	0.48	159
	12%	1 110	2 133	251	540	621	113	153	6.3	0.81	279
Q. glabrescens Benth.	Green	508	732	123	356	370	84	78	4.4	0.62	176
	12%	984	1 384	195	568	650	124	132	5.3	0.69	260
Q. crassifolia Bonpl.	Green	471	692	112	335	357	86	90	3.2	0.49	155
	12%	1 006	1 410	190	598	678	140	144	4.6	0.60	243
Q. mexicana Bonpl.	Green	446	687	104	292	313	71	84	3.1	0.45	146
	12%	736	1 155	163	484	535	91	96	3.6	0.59	215
Q. laurina Humb. & Bonpl.	Green	486	723	115	340	350	77	86	3.7	0.45	159
	12%	1 024	1 845	182	435	496	86	153	4.0	0.51	190
Q. obtusata Humb. & Bonpl.	Green	459	681	263	295	331	348	81	4.0	0.28	209
	12%	750	1 108	434	499	590	328	190	5.6	0.32	224
Q. rugosa Née	Green	376	625	210	239	289	213	67	4.4	0.29	172
	12%	711	1 194	364	423	558	259	172	5.1	0.32	210
Q. durifolia Seemen ex Loes.	Green	398	608	235	230	276	229	85	3.5	0.28	188
	12%	662	1 022	298	439	539	331	140	3.4	0.30	190
Q. castanea Née	Green	545	767	309	257	313	240	85	3.1	0.31	187
	12%	885	1 256	377	539	628	425	148	4.8	0.32	200

Source: Fuentes and Flores (1995); Honorato and Fuentes (2001).

MC = Moisture conteSnt; SLP = stress at the limit of proportionality; MOR = Modulus of rupture; MOE = Modulus of elasticity ($kg\ cm^{-2}$ × 1000); CPG = Compression perpendicular to the grain; W = Breakage work ($KJ\ m^{-2}$); K = Coefficient of resilience; R = Instant reaction to breakage (kg).

Table 2. Other mechanical properties of the wood of species of the genus *Quercus*.

Species	Hardness PEG (kg)		Janka PAG (kg)		Cutting force MS (kg cm^{-2})		Cracked MS (kg cm^{-2})		PS MS (kg cm^{-2})	
	Green	12%	Green	12%	Green	12%	Green	12%	Green	12%
Q. affinis Scheidw	575	1 011	583	1 180	115	175	78	89	65	82
Q. glabrescens Benth.	730	908	696	1 042	120	152	73	93	66	67
Q. crassifolia Bonpl.	612	838	665	1 169	114	143	95	111	65	67
Q. mexicana Bonpl.	510	594	523	1 001	103	133	88	97	63	64
Q. laurina Humb. & Bonpl.	648	821	646	1 094	122	145	97	116	64	71
Q. obtusata Humb. & Bonpl.	792	1 320	799	1 443	109	208	93	99	66	66
Q. rugosa Née	733	1 234	752	1 361	114	192	72	95	46	57
Q. durifolia Seemen ex Loes.	658	904	674	1 099	121	184	85	112	62	68
Q. castanea Née	632	1 002	692	1 203	117	199	80	131	49	85

Source: Fuentes and Flores (1995); Honorato and Fuentes (2001).

PEG = Perpendicular to the grain; PAG = Parallel to the grain; MS = Maximum stress; PS = Perpendicular stress; Green = Green MC.

Wood has its minimum mechanical resistance in green condition and improves significantly by drying; thus, the compressive and bending strength doubles when its moisture content is 12 and 15 %. In green condition, the species analyzed and classified according to Dávalos and Bárcenas (1998), Dávalos and Bárcenas (1999) and Sotomayor (2005) were located in a medium level of unitary resistance to breakage in static bending, axial compression and elasticity stresses. The species were classified as woods of high and very high lateral and transverse hardness; with a moisture content of 12 % (a value used internationally for comparison purposes).

As the wood dries below the FSP, the cell walls become harder and stiffer; consequently, there is an increase in all its mechanical properties, except for tenacity. Unit resistances at break in static bending were classified as high and very high, and elasticity, as high to very high (Fuentes and Flores, 1995; Honorato and Fuentes 2001), which is evidence that they are very rigid woods that tend to deform very little. The modulus of elasticity in the longitudinal direction can be up to 100 times greater than in the perpendicular direction; and in the radial direction, the modulus of elasticity is twice as great as in the tangential direction. Unitary axial compression resistances were medium, while perpendicular compressive strengths were classified as high (Fuentes and Flores, 1995; Honorato and Fuentes 2001).

The working values at maximum load showed good damping capacity and high resilience; they exhibited their highest impact resistance in the tangential plane rather than in the radial plane, which indicates that they are woods with a high tenacity, whose fibers are difficult to separate.

Based on the results of the physical and mechanical characterization combined with the information from studies on the anatomy of wood (Pérez-Olvera, y Dávalos-Sotelo, 2008; Fuentes y Flores, 1995; Honorato y Fuentes 2001), it was deduced that the analyzed woods are suitable for use in the manufacture of value-added products such as construction structures, industrial flooring, sporting goods, as well as in handicrafts and furniture, due to their aesthetic characteristics, different shades of color, pronounced grain, coarse texture and annular porosity, which provide attractive tangential cut surfaces that are of great relevance in joinery and veneer.

The straight grain of *Quercus* species determines the ease with which their wood can be worked in the production of turned, carved and carved articles (Pérez-Olvera *et al*., 2015); in addition, it is used in cooperage, railroad ties, and charcoal; the latter, from residues generated in the sawmill industry in the form of branches, tips, stumps, shrubby taxa with sinuous growth, bark, trimmings, strips, and sawdust. The most important characteristic that defines the quality and quantity of flask formed during combustion is the amount of fixed carbon (greater than 70 %), linked to other properties and characteristics of oak trees such as high density, low ash content (3-6 %), volatile materials (15 %), and calorific value between 30-33 MJ kg^{-1} —values that represent important sources of energy (Bautista-Vargas *et al.*, 2017; De la Cruz *et al.*, 2020).

Chemical characterization of wood

It is important to know the chemical composition of wood, which varies within the same species according to the part of the tree: root, stem, or branch; the type of wood: normal, tension, or compression; the geographical location, climate, and soil conditions (Pettersen, 1984). Research conducted at INIFAP has determined that the content of chemical compounds may be slightly higher in the branches than in the wood of the main trunk at a height of 1.30 m (Honorato and Hernández, 1998). The cell wall of softwoods and hardwoods is mainly composed of cellulose, hemicellulose and lignin; their percentage contents range from 35 to 50 %, 10-35 % and 15-40 %, respectively (Chen, 2014).

The determination of cellulose, lignin and hemicellulose is essential to infer the application of wood in various industrial processes such as pulp for paper, tannins, energy, organic preservatives, boards, plastics, among others (Bautista and Honorato, 2005; Tamarit and López, 2007). The success of industries that consume large amounts of wood depends on the knowledge of its chemical composition (Honorato, 2002).

The diversity of the chemical compounds present in the cell wall, as well as in its structure, render them difficult, in certain species, to obtain, extract, purify and separate. This means that, in addition to applying classical analytical chemistry processes, modified methods and processes are used.

In Mexico, the chemical composition of wood is determined according to TAPPI (Technical Association of the Pulp and Paper Industry) and ASTM standards, which are adjusted according to the condition of the harvested material (sapwood, heartwood, bark, or blends) (Bautista and Honorato, 2005). For the quantitative evaluation of the chemical components, an additive analysis is performed, in which the sum of all components must be 100 % (Tamarit and López, 2007).

In species of the *Pinus* genus it has been estimated that the percentages of major chemical components vary from 43.9 to 45.6 % for cellulose; between 23.4 and 24.4

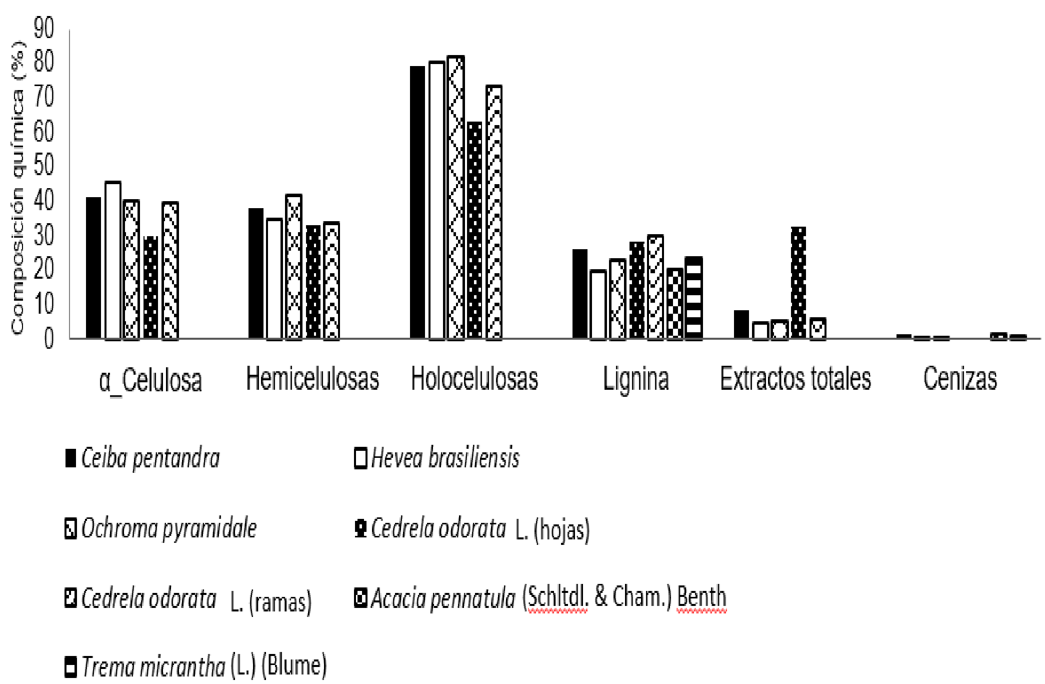
% for hemicellulose; between 66.7 and 70.0 % for holocellulose, and from 26.3 to 28.6 % for lignin (Honorato *et al*., 2016). The analysis of secondary components (extracts) was carried out with ethanol in percentages of 1.02 to 1.28 %, and of 3.5 to 12 % for ethanol-benzene soluble components. The ash content rate was 0.25 to 0.3 % (Honorato *et al*., 2016).

Mexican oak wood has been underutilized in the form of firewood and charcoal, due to misinformation and lack of knowledge of adequate techniques and procedures for higher-value uses (Honorato and Hernández, 1998; Santacruz and Espejel, 2004). The determinations of its main chemical compounds show that the cellulose content is 37 to 56 %; the hemicellulose content is 22-30 %, and the lignin content is 18-22 %. The pentosans were quantified in the proportion of 18-23 % (Honorato, 1998; Honorato, 2002; Bárcenas *et al*., 2008).

The content of oak extractives has been little studied due to the difficulty to purify and isolate substances. However, it has been determined that the importance of these compounds lies in the influence they exert on other properties, characteristics and treatments of wood. High concentrations of extractives and low pH values in wood have a negative effect on finishing processes and adhesive application (Honorato and Hernández, 1998, Honorato, 2002).

Soluble extractives in wood and bark have been made with solvents such as ethanol-benzene and 1 % sodium hydroxide (NaOH), in addition to the use of hot water. With the latter applied to bark, the content of extractives varied between 10.92 and 21.25 % in proportion to the total weight of the wood sample; when wood was used, the values ranged from 4.61 to 10.0 %. The contents of ethanol-benzene soluble components in the two types of materials were 5-13.23 % and 1.14-5.24 %, respectively. When using a 1 % NaOH solution on the bark, concentrations ranged from 31 to 44.90 % and for wood from 20.89-26 % of the total extractives present. The tannin content in oak bark corresponded to the range of 5.48-54.04 %, and in oak wood, from 0.59-33.44 % (Honorato *et al*., 2015; Rosales *et al*., 2016; Apolinar *et al*., 2017).

The chemical composition of the wood of the following tropical species has also been studied: *Ceiba pentandra* (L.) Gaertn. (kapok tree), *Hevea brasiliensis* (Willd. ex A.Juss.) Müll. Arg. (rubber tree), *Ochroma pyramidale* (Cav. ex Lam.) Urb. (balsa tree), *Cedrela odorata* L. (Spanish cedar), *Inga spuria* Humb. & Bonpl. ex Willd. (guama), *Juglans pyriformis* Liebm. (walnut tree), *Acacia pennatula* (Schltdl. & Cham) Benth. (sweet acacia), and *Trema micrantha* (L.) Blume (capulin) (Figure 1). The purpose of that research was to infer their possible applications as pulp for paper, and in the production of resins and adhesives, vanillin, carbohydrates, bioplastics, phenols, and flavonoids, among others, as well as to determine their energetic potential for fuel uses, measured through the calorific value, which ranges between 17.76 and 18.54 MJ kg^{-1} (Honorato, 2002; Honorato *et al.*, 2015; Rosales *et al.*, 2016; Apolinar *et al.*, 2017).



Source: Honorato *et al*. (2015); Rosales *et al*. (2016); Apolinar *et al*. (2017).

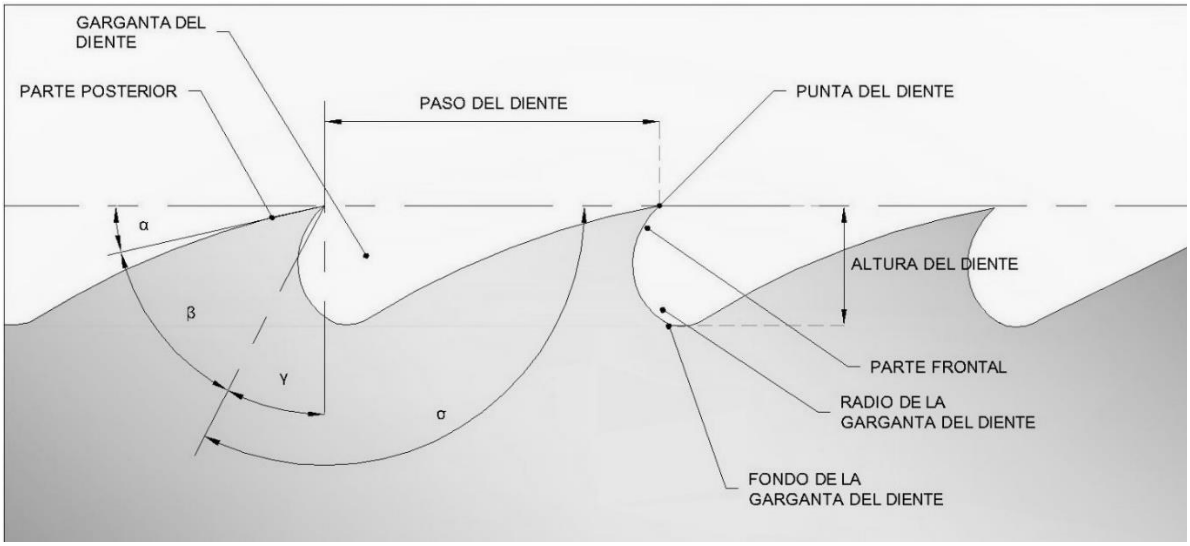
Figure 1. Chemical composition of the wood of tropical species.

The chemical composition of the studied taxa makes evident specific behaviors in different processes; thus, species with high alpha-cellulose and hemicellulose content, such as *Ceiba pentandra*, *Hevea brasiliensis*, and *Ochroma pyramidale*, are ideal for pulping and carbohydrate bioconversion processes.

Extracts are soluble in different solvents (alcohol-benzene, acetone, ethanol, cold water, hot water, among others) and can be classified into volatile acids, essential oils, resinous acids and polyphenols. Extracts are modifiers of physical properties, affecting the density and equilibrium moisture content of the wood and, consequently, indirectly modifying various mechanical properties. They also influence the durability, color, odor and flavor of the wood. Phenolic extracts provide resistance to rot and insect attack (Darmawan *et al*., 2011).

Species like *Ceiba pentandra* and the leaves of *Cedrela odorata* are rich in extractives; this indicates some degree of affectation in the sawing, drying, pulping, machining, gluing, and wood finishing processes (Honorato *et al.*, 2016). The most important inorganic contents (ashes) in the sawing and workability processes are crystals and silica, which have an impact on the increased wear of the cutting edge of the cutting elements; hence, the importance of the fact that *Acacia pennatula* (Schltdl. & Cham.) Benth and *Ceiba pentandra* have high ash contents, of 1.44 % and 1.59 %, respectively (Honorato *et al.*, 2016).

Lignin, rich in carbon and hydrogen, affects pulping and bioconversion processes and is mainly used in the production of polyurethane. The amount of lignin and extractables is closely related to the calorific value. Therefore, the species studied and shown in Figure 1 can be used for wood energy purposes in the industrial, domestic and residential sectors, although *Acacia pennatula* and *Ceiba pentandra* have high ash contents that influence their use as biofuels (Honorato *et al.*, 2016).



α= cleaning angle or free angle; β= tooth angle; γ= cutting angle or angle of attack; σ= front angle (γ + 90˚).

Figure 2. Bandsaw tooth geometry.

The chemical composition is responsible for the behavior in the different wood transformation processes; therefore, it is relevant to determine the main chemical components of the different taxa, and based on them, to define the specific industrial uses that guarantee the optimal and integral use of wood.

Sawmilling

Mexico is characterized by an underdeveloped industrial forest sector, with high production costs, obsolete technologies installed in low to medium-capacity production units, poorly trained personnel and the use of unsorted roundwood at high prices. In the band sawing or band sawmilling process, density and hardness combined with a low moisture content and the presence of mineral fouling in the wood are determining factors in the stresses to which the saw is subjected during cutting; they cause blunting, cracks or fissures and can lead to tooth fracture. With the adoption of adequate sawing parameters such as tooth angles (Figure 2), tooth pitch, throat depth, cutting width, among others, it is possible to obtain a good sawing quality, which is evaluated based on the uniformity in the thickness of the boards produced.

The most important part of the saw blades are the teeth, because they are the cutting elements. There are six major issues that impact on the potential benefits of band sawing: tooth symmetry, tooth maintenance, blade center cracks, saw blade twist, flywheel profile wear, and saw blade wear and tear; in addition to the ratio of speed and depth of cut, depending on the feed capacity of the groove (Zavala, 2003; Martínez *et al*., 2006).

With regard to sawmilling, INIFAP has conducted research on the competitiveness of the lumber industry, marketing channels, industry analysis, pine and oak wood cutting variation, among others. The determinations on the characteristics that band saws must meet to process oak wood stand out, among which the tooth geometry shown in Figure 2 (tooth pitch, gullet depth, lateral clearance, cutting angle, tooth angle and free angle) is relevant to increase wear resistance and increase yield, since a greater volume of wood is sawn with a good cutting quality (Kirbach, 1982; Zavala, 2003; Martínez *et al*., 2006).

The tooth pitch determines the amount of work a saw can do; for hard and very hard woods Sandvik (1964) indicated that the optimal tooth pitch spacing should be 1.25 to 2.75". Schrewe (1983) noted that the spacing is also related to the width and caliber of the saw, in addition to the diameter of the flywheels. Tooth pitch must be less on saws 3" to 6" wide, 18 to 19" gauge and 4 to 6 ft. diameter flywheels.; whereas, a larger tooth pitch is suitable for 12 to 16" wide saws, with 12 to 13" gauge and 8 to 10 ft diameter flywheels (Lunstrum, 1985).

For sawing oak wood, Flores *et al*. (2007a) recommend a tooth pitch of 1 to 2¼" (25.4 to 57.15 mm) based on the gauge of the saw, the thinner the saw, the smaller the tooth pitch (Figure 2). Flores *et al*. (2001) record that the tooth pitch for 8" wide saws is 1.5"; Martínez *et al*. (2006) document that for 5" wide saws the best result is obtained with a tooth pitch of 1.25".

The function of the gullet in the band saw is to accommodate the sawdust during sawing and, subsequently, to throw it out of the cut. Several studies agree that the appropriate gullet depth for hardwoods with undercut teeth is 1/3 of the tooth pitch (Sandvik, 1964; Schrewe, 1983), or close to 10 times the saw blade gauge (Quezada, 1998). When sawing oak with 8" saws, Martínez *et al.* (2006) obtained the best results by using a throat depth of 0.5"; Flores *et al*. (2001) refer that with 5" saws, the proper depth is 7/16".

The way in which the cutting edge of the saw teeth acts depends on their angles (i.e., cutting, tooth, and cleaning angles), in relation to the density of the wood to be sawn, the direction of the cut to be made (longitudinal or transverse), and the type of saw. The cutting angle (angle of attack) for hardwoods that provides good results varies from 20 to 30º (Sandvik, 1964; Schrewe, 1983; Quezada, 1998); the most common cutting angles are 20 to 22º (Lunstrum, 1985). In North America, an angle of attack of 30º is used with satisfactory results in bandsaws with undercut teeth (Koch, 1964). In Mexico, when evaluating 8" wide saws, the best results were obtained with an angle of attack of 25° (Martínez *et al.*, 2006); while acceptable results were achieved with 5" saws by using a cutting angle of 25 and 30º (Flores *et al*., 2001).

Regarding the tooth angle, it should not be too small to prevent the tooth tip from weakening and breaking under the effect of the cutting load, nor so large as to restrict the feed rate and cause higher power consumption. Martínez *et al.* (2006) indicate that an angle of 45° is ideal for sawing oak with 8" wide saws; with 5" wide saws, the tooth angle can be 44°, 50°, or 55° (Flores *et al*., 2001).

The cleaning angle (Figure 2) defines the free and clean cut of the saw, since the clearance between the saw and the wood must start right at the tip of the tooth in order to prevent the tooth spine from rubbing against the wood, which causes friction and overheating of the teeth. For sawing oak wood, a cleaning angle of 8 to 12° is recommended (Lunstrum, 1985). In North America, a 16° angle is used with wide band saw blades and angled teeth with good results. For 8" wide saws, Martínez *et* *al.* (2006) determined that an angle of 20° gives good results; with 5" saws, cleaning angles of 10, 15 and 16° were recommended (Flores *et al*., 2001).

For each type of saw, there is a lateral clearance to obtain the appropriate cutting width, which varies depending on the geometry of the teeth, the moisture content, the cutting edge, the alignment of the equipment and the type of wood to be cut. Hardwoods require the side clearance to be 25 % greater than the saw gauge (Lunstrum, 1985). In Mexico, it was determined that for sawing oak wood, the lateral clearance corresponds to a range of 0.8 to 0.9 mm (Flores *et al*., 2001).

From the difficulty of sawing *Quercus* wood, it is advisable to harden the cutting tip of the teeth, for which a coating can be applied with materials such as stellite 12, tungsten carbide, chromium platinum, vanadium, and high frequency hardening. This increases tooth wear resistance by up to 100 % when sawing softwoods, or by 12 times more for hardwoods. In the formation of the cutting tip of the tooth, some of the materials indicated are added, except when high frequency is used, in which case the steel of the saw is used (Kirbach and Bonac, 1982; Kirbach, 1984). The saw with teeth coated with stellite 12 has a higher resistance to blunting, which allows sawing a little more than twice the volume of oak wood, compared to the saw with angled teeth (Flores *et al*., 2001).

Drying

The process of removing the water contained inside the wood to the point where it is in hygroscopic equilibrium with the environment in which it will be used is known as drying. It is optimal when the wood dries in a short time, at the lowest cost and with the best quality. It is a necessary process for the timber industry that is rarely carried out in Mexico, partly because consumers are reluctant to pay the premium price. About 80 % of wood production is marketed freshly sawn or air-dried, in which case the wood only reaches moisture values in equilibrium with the environment (Fuentes *et al*., 2008); in order to obtain lower moisture contents, it is necessary to turn to artificial drying with conventional drying ovens (JUNAC, 1989).

The artificial or conventional drying of the wood of broadleaf trees such as oak, tropical species or eucalyptus requires considering the heterogeneity of their anatomical and physical characteristics.

According to Zavala (2000), hardwoods have numerous, large and wide radius elements with weaker intercellular bonds, which favors the appearance of cracks and deformations during drying as temperature, relative humidity, and air speed change to drier conditions. These hardwoods exhibit high and uneven shrinkages that favor excessive internal stresses; and therefore, the severity of defects is greater, contrary to what occurs with the drying of softwoods. One way to minimize defects such as cracks, splits, deformations, grooving and collapse in oak wood is through slow drying and sometimes pre-drying (Zavala, 2000).

Woods with a high content of tyloses are difficult to dry, since the water flow is obstructed by reducing the vessel diameter, making them impermeable, and therefore they need longer drying time. Tyloses are common in the heartwood of many angiosperms and in the wood vessels of temperate species such as oaks (Kollmann and Coté, 1968); high basic density and a high MC induce long drying time.

INIFAP has developed conventional kiln drying programs with temperatures below 100 °C for hardwood and coniferous species (Fuentes *et al.*, 1997). In its generation, drying variables, anatomical characteristics (porosity, vessel distribution, grain orientation, cell contents, sapwood to heartwood ratio) and physical properties (moisture content, density, shrinkage, anisotropy, and fiber saturation point) were considered in order to obtain quality dry wood (Fuentes *et al*., 1997; Zavala, 2000).

The problems of drying tropical woods in conventional kilns are also attributed to the difficulty to obtain large volumes of the same species and to the high costs involved in extracting small volumes. In this regard, it was determined that the best way to dry them is by forming groups of species with similar values of basic density, initial moisture content and board thickness (Zavala, 2000) (Table 3), which leads to a low defect intensity after drying.

Table 3. Drying programs for tropical and oak timber species.

Species	Thickness (in)	Drying program	Bd (g cm^{-3})
Bombax ellipticum Kunth.	4/4	English H	0.44
Brosimum alicastrum Sw.	4/4	T7 B3	0.73
Bucida buceras (L.)	4/4	English C	0.85
Bursera simaruba (L.) Sarg.	4/4	English D	0.41
Calophyllum brasiliense Cambess	4/4	T3 D4	0.55
Cedrela odorata (L.)	4/4	English F	0.36
Cordia dodecandra A. DC.	6/4	English C	0.89
Cordia eleagnoides (Ruiz & Pav.) Oken	6/4	English C	0.53
Enterolobium cyclocarpum (Jacq.)Griseb.	4/4	T8 F4	0.35
Lysiloma bahamensis Benth.	4/4	T3 C2	0.63
Lonchocarpus castilloi Standl.	6/4	English G	0.74
Manilkara zapota (L.) P. Royen	4/4	English R	0.90
Metopium brownei (Jacq.) Urb.	4/4	English C; T3 D3	0.89
Piscidia comunis (Blake) L. M. Jchnst.	4/4	English E	0.68
Platimiscium yucatanum Standl.	4/4	English C	0.67
Schizolobium parahybum (Vell.) Blake	4/4	T5 F4	0.30
Simarouba glauca DC.	4/4	English D; T9 A3	0.46
Swietenia macrophylla King.	4/4	T8 D5	0.42
Terminalia amazonia (J.F. Gmel.) Exell	3/4	T2 C3	0.66
Quercus sp	4/4	T4 D2	0.72
Q. laurina Humb. & Bonpl.	4/4	Special Modif I	0.73
Q. crassifolia Bonpl.	4/4	Special Modif I	0.76
Q. potosina Trel. Mem.	4/4	Special Modif I	0.76
Q. affinis Scheidw non M. Martens & Galeotti	4/4	Special Modif I	0.74
Q. falcata Michaux	4/4	T4 D2	0.59

In = inches; Bd = Basic density.

Zavala (2000) developed two programs to dry a mix of 33 tropical taxa grouped by their basic density. The first program was defined for low and medium density species; the second, for high density species. The final results in both programs did not affect the quality of dry wood. Drying time for softwoods ranged from 5 to 7 days and from 10 to 25 days for high density woods. The author concluded that for optimal processing, the medium to low density woods require subdivision into two additional groups, and the high density woods, into four groups. Table 3 includes some unpublished programs developed at INIFAP for different species, which are based on the parameters and variables described in JUNAC (1989) and in Simpson (1991).

Drying is a process that demands knowledge and attention; however, in *ejido* enterprises, it is generally carried out by staff with little training in the subject. In order to address the difficulties detected in small and medium-sized industries, Quintanar *et al*. (2009a and 2009b) made a guide for operating a drying kiln and a kiln drying manual for oak wood, whose aim is to facilitate this process for kiln operators in rural communities. Quintanar *et al*. (2012) developed a continuous improvement protocol to increase the quality of kiln-dried wood, which is aimed at optimizing the human and material resources used during the process; the protocol is based on three basic criteria: stacking of wood, operation of the kiln, and application of the drying schedule.

The solar lumber drying method has also been investigated at INIFAP. This is an intermediate process between conventional kiln drying and open air drying, in which solar energy is used as a heat source (Fuentes *et al.*, 1997). It has been determined that the success of solar dryers is restricted to areas with high solar radiation, which favors drying during summer and early autumn (JUNAC, 1989). Fuel scarcity and high fuel costs stimulate the industry's interest in looking to solar energy as an alternative source for drying hardwoods, which consume 60 to 70 % of the total energy used in the process (Chen, 1981).

Comparing solar drying, conventional kiln drying and open-air drying methods, Fuentes *et al.* (1997) point out that drying oak wood in a solar dryer has greater advantages, because it does not require great investment and operating costs, as when conventional kilns are used, nor such long drying times as in the open air, where wood quality is devaluated and the movement of capital in its commercialization is limited.

Solar dryers are efficient in drying softwoods and, particularly, hardwoods that are highly prone to develop defects and require slow drying. Hardwoods such as oak are rarely sawn into boards and planks, but pine is available in different commercial sizes in all sawmills in central and northern Mexico (Fuentes *et al.*, 2008). Therefore, when making the economic assessment of a solar greenhouse dryer using pine wood (Figure 3), Quintanar *et al*. (2011) and Quintanar (2017) obtained favorable results with a profitability of 240 % compared to the initial investment, demonstrating that the full investment cost is recovered in the fourth drying load. In order to determine the efficiency and optimal size of the solar dryer, the authors described the design method and calculations, as well as the evaluation per dried volume unit.

Figure 3. Solar greenhouse dryer for wood.

In Mexico, there are different designs of solar dryers, each with its particularities and advantages. The prototype dryer made at INIFAP corresponds to the modified Oxford type, which is promoted as a technology transfer and has been adopted by *ejidos* and cooperating communities in different states of Mexico. The results have been satisfactory for small and medium-sized industries (Quintanar, 2005; Bárcenas *et al.*, 2010).

The success of the dryers in rural communities is attributed to the fact that they are relatively inexpensive to build and simple to operate, and they produce good drying quality. This is explained by the fact that the temperature inside the dryer reaches its maximum value at around 14:00 hours, and the air inside the chamber cools during the night, which increases the relative humidity; drying during the day and increasing in moisture at night allows to release or reduce the drying stresses, which favors the quality of the dried wood (Fuentes *et al.*, 1997).

Machining

Wood machining (machinability) consists in the execution of operations performed in the second transformation industry, where it is made into wood pieces with machines and cutting tools, in order to give the desired dimensions and profiles with the desired aesthetics and quality, for subsequent use in the manufacture of finished products, in addition to preparing the surface for the application of artificial finishes (Tamarit and López, 2007). In this process, chips, shavings or sawdust are separated by the action of the cutting edge of cutting tools or through friction with sandpaper.

At the industrial level, machining is essential in the subsequent stages of wood transformation; when it is carried out properly, its quality is increased, and greater added value is given to the final product (Flores *et al*., 2002; Flores and Fuentes, 2002).

In Mexico, the machining quality of wood by taxon is determined based on tests indicated in ASTM D 1666-11 norm (ASTM, 2011), adapted to the technological characteristics of wood and the machines used in the national forest industry. The tests include planing, turning, molding, drilling and sanding; the quality is evaluated upon the presence and severity of defects on the surface of the machined specimens.

Hardwoods of tropical and *Quercus* species are more difficult to machine. In order to achieve an acceptable quality, particular working conditions are necessary for the machines and cutting tools, as well as for some wood characteristics.

The basic density of wood is related to its hardness and, therefore, to its resistance to penetration and cutting. Heavier woods have a smoother and more uniform finish when machined than lighter woods; this phenomenon is explained by the fact that the former have a lower proportion of empty spaces per volume unit and a higher lignin content, which favors a lower collapse of the cell wall at the fiber level due to the action of the cutting element tip (Thibaut *et al*., 2016); but also require a higher energy consumption. When the wood has a high MC, it has less resistance to cutting, but grain defect is more intense; with a low MC, the grain is chipped, and the resistance to cutting and blunting are higher (Tamarit and Flores, 2012).

The presence of silica and crystals makes wood abrasive and blunts the cutting element faster. The main factors inherent in the tools and cutting elements that influence the quality of machining are the type of steel, cutting angles, depth of cut, cutting speed, feed rate and number of knife marks per centimeter (Tamarit and Flores, 2012). These working conditions can be modified to improve machining quality.

Planing is the peripheral cut performed with the planing machine blades on the surface of both sides of the boards to obtain the desired, even thickness and a smooth surface. It is the most important machining operation, since any part must be planed before being used in the production of a final product, in order to give it added value. Hardwoods are best planed with the grain and with a blade cutting angle ≤ 20°. In very high-density woods, it is recommended to use tungsten carbide coated blades (Tamarit and López, 2007; Tamarit and Flores, 2012).

Commercial planers have a blade cutting angle of 30°; to reduce it, a bevel must be made on the blades. The action of the knives is distributed over the piece of wood, thus varying the feed speed, or the speed of rotation of the knife-holder head, which results in a certain number of knife marks (NKM) per centimeter on the planed surface (Flores *et al*., 2002; Tamarit and Flores, 2012).

In hardwoods, the planing quality is optimized when using the lowest knife cutting angle and the highest NKM cm^{-1} (up to 29); to increase the NKM, the feed speed should be reduced to 7 m min^{-1}. Quality is improved when the depth of cut is 1.5 mm for industrial planers and double for smaller capacity planers (Tamarit and Flores, 2012).

Turning provides a specific shape or profile to a piece of wood by turning it on a lathe against a blade or gouge, whose edge cuts in different positions. It is made to produce high quality and value-added decorative products. For the best finishing quality, the optimum lathe speed depends on the diameter of the piece of wood to be turned and the feed speed of the blade into the wood; it is recommended to have, at least, four turning speeds (500, 1 000, 1 500, and 3 000 rpm) (Flores *et al*., 2013). For large diameters, the turning speed should be reduced, and increased when turning small diameter parts (Tamarit and López, 2007).

High Bd and fine-textured woods with a MC of 12 to 14 % show the best turning quality; with lower MC, the intensity of defects is higher. Burning of the wood surface is avoided by not using a high rotational speed and by using a slow feed speed (Flores *et al*., 2007b).

Molding is used to give a predetermined profile and shape to one or more of the edges of the wood pieces; for this purpose, milling cutters mounted on spinning machines are used; the smoothness of the cut and the detail of the figure are important. For hardwood molding, the peripheral speed should be 40 to 60 m s^{-1} with HSS cutters, and 50 to 80 m s^{-1} with tungsten carbide cutters; the highest NKM cm^{-1} must be applied, with an average feed rate of 3 m min^{-1} to produce curved moldings, and 6 m min^{-1} for straight moldings. Spindle rotation speed varies from 4 000 to 10 000 rpm (Flores *et al*., 2002; Flores and Fuentes, 2002).

Drilling (boring) consists of drilling one or more holes of specific diameters in pieces of wood, with one or more drills placed vertically or horizontally in a drilling machine, in which the wood moves towards the drill or *vice versa*; it is useful for making joints or assemblies. In order to achieve strong joints, the cut must be clean and smooth, with minimal fiber tearing and of the correct size. Cutting speed has to be low, not exceeding 3 000 rpm; the quality is reduced as larger diameters and lengths of drill bits are used and as the vibration of the bit increases producing larger diameter holes than expected (Flores *et al*., 2002; Flores and Fuentes, 2002).

For high density woods, high speed steel, nickel-chromium steel or tungsten carbide drills are used; the penetration speed should be slow at the moment the drill bit contacts the wood, then increased to 75 cm min^{-1}, which will prevent a burned surface from occurring (Tamarit and López, 2007).

Sanding is the abrasive action of sandpaper on wood to calibrate its thickness, to obtain flat and smooth surfaces, to remove splinter marks and other defects, and also, to level the pieces that have been joined in order to prepare the surface for the application of an artificial finish. The most common abrasive is sandpaper with quartz grains. Aluminum oxide sandpaper is used in industrial-scale work.

The sanding speed is proportional to the amount of wood to be removed: a high speed produces a smooth, even surface and requires less energy per volume removed. Sanding is done parallel to the grain of the wood. The boards are first sanded with coarse grit (No. 60 or 80) to remove defects; then, a fine grit (No. 100 or 120) is used to give the final finish (Flores *et al*., 2002; Tamarit and López, 2007).

Works by INIFAP researchers have shown the machining quality of 37 hardwood species (Bd $\geq$ 0.55 g cm^3) (Flores and Fuentes, 1995; Zavala and Vázquez, 2001; Flores *et al*., 2002; Flores and Fuentes, 2002; Flores *et al*., 2007b; Tamarit and López, 2007; Flores *et al*., 2013).

They highlight the need to study the machining of wood from other taxa present in natural forests and commercial plantations, as well as new materials based on natural or chemically or thermomechanically modified wood, and bioengineered products such as boards, laminates and others made from agricultural residues. The performance of new materials (alloys) in the form of inserts or coatings on the cutting elements and their relationship with the quality of the machined surface, the effect on energy consumption, and the level of waste generated should also be assessed. Another area to be explored is the performance of automated machining processes using sensors and computerized numerical control (Thibaut *et al*., 2016; Nasir and Cool, 2018).

Research perspectives

The studies on wood technology carried out to the present date at INIFAP and other peer institutions include only a fraction of the total of tree species in Mexico. It is important to increase the number of basic studies aimed at technologically characterizing the timber of natural forest and tropical forest species, as well as commercial plantations that, due to their abundance, have the potential for commercial timber harvesting; in addition, their xylotechnological characteristics determine their response and suitability to different transformation processes.

It is also essential to update the protocols for the best sawmilling, drying and machining practices taking into account the characteristics of the Mexican forest industry, as well as the xylotechnological properties and dimensions of timber species; this will contribute, to some extent, to reduce the obsolescence of the practices of the forest industry. In this work, it is essential to involve forest products companies, as well as raw materials producers in the provision of resources and raw materials for the execution of research.

Although INIFAP has conducted research on the optimal use of lignocellulosic residues and other biomass sources, the innovative design of new wood-based engineered bioproducts; the analysis of life cycles of bioprocesses and timber products; the optimization of processes for the generation of wood energy from green biomasses; the exploration of thermochemical treatments of wood; the sustainable use of non-timber forest products; as well as the sustainable use of green biomasses; the exploration of thermochemical treatments of wood; and the sustainable use of non-timber forest products; the optimization of processes for the generation of wood energy from green biomass; the exploration of thermochemical treatments for wood; the sustainable use of non-timber forest products, and the generation, adoption and adaptation of new, innovative technologies. These topics are currently incipient in the Institute's lines of research, and therefore represent a wide field of action and a window of opportunity; at the same time, they constitute a challenge for further studies.

In addition, priority should be given to strategic lines of research that contribute to the innovation, growth, development, competitiveness and sustainability of the forest industry, such as: the modification of wood to make it a more durable, stable and competitive material; recycling of materials that are currently considered waste; quantification of byproducts from lignocellulosic waste. biorefineries and bioenergy; nanotechnology in the forest products industries, and the development of new technologies in the forest industry.

In an enunciative but not limiting way, all the aforementioned topics and lines of research can integrate an updated research agenda in wood science and technology in agreement with Teischinger (2010), involving such concepts as biotechnologies, eco-efficiency, bioeconomy, among others, are oriented to create a balance between technological development, environmental conservation, and socioeconomic development.

In regard to the Mexican forest industry, it is essential to initiate a gradual transition process to incorporate and profit from the full potential of the Industry 4.0 paradigm (fourth industrial revolution), in which, according to Legg *et al.* (2021), both sophisticated emerging technologies and techniques are adopted, incorporated and combined, as well as recent and related industrial applications of diverse nature that enable timber companies to be more efficient and competitive.

Conflict of interests

The authors declare that they have no conflict of interests.

Contribution by author

Juan Carlos Tamarit-Urías and Martha Elena Fuentes-López: conceptualization and organization of the research, data collection, and synthesis of documentary information; Patricia Aguilar-Sánchez and Rogelio Flores-Velázquez: contribution of bibliographic material and review of the document. All the authors participated in data analysis, as well as in the drafting and editing of the document.

References

Apolinar H., F., J. A. Honorato S. y G. Colotl H. 2017. Caracterización energética de la madera de *Acacia pennatula* Schltdl. & Cham. y *Trema micrantha* (L.) Blume. Revista Mexicana de Ciencias Forestales 8(39): 71-81. Doi:https://doi.org/10.29298/rmcf.v8i39.44.

American Society for Testing and Materials (ASTM). 1992. Standard methods of testing small clear specimens of timber. Book of ASTM Standards 143. Vol. 04.09. Wood American Society for Testing and Materials. Philadelphia, PA, USA. pp. 37-78.

American Society for Testing and Materials (ASTM). 2011. Annual book of ASTM standards. ASTM D-1666-11 Standard methods of conducting machining tests of wood and wood-based materials (reapproved 1994). Philadelphia, PA USA. pp. 226-245.

L'A Association Francaise de Normalization NFB (AFN). 1985. Norme Francaise, bois essai de Choc ou flexion dynamique. NFB51-009. Paris, France. https://m.boutique.afnor.org/xml/910127/false (15 de diciembre de 2020).

Bárcenas P., G. M., R. Ríos V., J. R. Aguirre R., B. I. Juárez F. y J. A. Honorato S. 2008. Composición química y densidad básica relativa de la madera de dos especies arbustivas de encino blanco de la Sierra de Álvarez, SLP, México. Madera y Bosques 14(3): 81-94. Doi: https://doi.org/10.21829/myb.2008.1431207.

Bárcenas P., G. M., J. L. Martínez C., R. Rodríguez A., y J. Quintanar O. 2010. Estufa solar de secado de madera. Paquete tecnológico. Comisión Nacional Forestal. Xalapa, Ver. México. 33 p. http://www.conafor.gob.mx/BIBLIOTECA/secado-madera.pdf (15 de diciembre 2020).

Bautista H., R. y J. A. Honorato S. 2005. Composición química de la madera de cuatro especies del género *Quercus*. Ciencia Forestal en México 30(98): 25-50. https://cienciasforestales.inifap.gob.mx/editorial/index.php/forestales/article/view/853 (1 de septiembre de 2020).

Bautista V., U., F. Ruíz A., W. Santiago G. y W. Santiago J. 2017. Evaluación de la calidad de carbón vegetal elaborado a partir de madera de encino en horno de ladrillo. Revista Mexicana de Agroecosistemas 4(2): 127-137. 2007-9559. https://www.resesrxhgate.net/profile/Faustino-Ruiz-Aquino/publication/322964063_EVALUACIO_DE_LA_CALIDAD_DEL_CARBOB_VEGETAL_ELABORADO_A_PARTUR_DE_MADERA_DE_ENCINI_EN_HORNO_DE_LADRILLO/links/5a3b3188458515a77aa8e8c7/EVALUACION-DE-LA-CALIDAD-DEL-CARBON-VEGETAL-ELABORADO-A-PARTIR-DE-MADERA-DE-ENCINO-EN-HORNO-DE-LADRILLO.pdf (4 de agosto de 2021).

Chen, H. 2014. Chemical composition and structure of natural lignocellulose. *In*: Chen, H. (comp.). Biotechnology of lignocellulose: theory and practice. Springer. Dordrecht, The Netherlands. pp. 25-71. Doi: https://doi.org/10.1007/978-94-007-6898-7_2.

Chen, P. Y. S. 1981. Design and test of a 500 BF solar kiln. Forest Products Journal 31(3): 33-38.

Comisión Nacional Forestal (Conafor). 2019. El sector forestal mexicano en cifras 2019. Secretaría del Medio Ambiente y Recursos Naturales. http://www.conafor.gob.mx:8080/documentos/docs/1/7749El%20Sector%20Forestal%20Mexicano%20en%20Cifras%202019.pdf (10 de diciembre de 2020).

Dávalos S., R. y G. M. Bárcenas P. 1998. Clasificación de las propiedades mecánicas de las maderas mexicanas en condición "verde". Madera y Bosques 4(1):65-70. Doi: https://doi.org/10.21829/myb.1998.411368.

Dávalos S., R. y G. M. Bárcenas P. 1999. Clasificación de las propiedades mecánicas de las maderas en condición "seca". Madera y Bosques 5(1): 61-69. Doi:https://doi.org/10.21829/myb.1999.511355.

Darmawan, W., I. S. Rahayu, D. Nandika and R. Marchal. 2011. Wear characteristics of wood cutting tools caused by extractives and abrasive materials in some tropical woods. Journal of Tropical Forest Science 23(3):345-353. http://www.frim.gov.my/.../345-353.pdf (10 de junio de 2021).

De la Cruz M., C., J. Herrera G., I. A. Ortiz S., J. C. Ríos S., R. Rosales S. y A. Carrillo P. 2020. Caracterización energética del carbón vegetal producido en el Norte-Centro de México. Madera y Bosques 26(2), e2621971. Doi: https://doi.org/10.21829/myb.2020.2621971.

Flores V., R. y M. E. Fuentes L. 1995. Características de maquinado de *Quercus affinis*, *Q*. *crassifolia*, *Q*. *glabrescens* y *Q*. *mexicana.* INIFAP. CIRCE. Puebla, México. Folleto científico No. 1. 14 p.

Flores V., R., M. E. Fuentes L. y J. Quintanar O. 2001. Desafilado de sierras banda en el aserrío de encinos. Ciencia Forestal en México 26(90): 55-71. http://cienciasforestales.inifap.gob.mx/editorial/index.php/forestales/article/view/913 (13 de noviembre de 2020).

Flores V., R., M. E. Fuentes L. y J. Quintanar O. 2002. Maquinado de dos especies de encino (*Quercus affinis* y *Q*. *crassifolia*) del estado de Guanajuato. Ciencia Forestal en México 27(91): 55-65. https://cienciasforestales.inifap.gob.mx/editorial/index.php/forestales/article/view/908/2162 (5 de febrero de 2021)

Flores V., R. y M. E. Fuentes L. 2002. Maquinado de la madera. *In*: Quintanar O., J. (Ed.). Características, propiedades y procesos de transformación de la madera de los encinos de México. INIFAP. CIRCE. Puebla, México. Libro Técnico No. 2. pp. 178-195.

Flores V., R., M. E. Fuentes L., J. Quintanar O., L. Vázquez S., J. C. Tamarit U. y H. M. Rodríguez C. 2007a. Aserrío de madera de encinos de Oaxaca en un aserradero portátil. INIFAP. CIRGOC. Puebla, México. Folleto técnico No. 43. 39 p.

Flores V., R., J. V. Rangel P., J. Quintanar O., M. E. Fuentes L. y L. Vázquez S. 2007b. Calidad de maquinado de la madera de *Quercus affinis* y *Quercus laurina*. Revista Chapingo Serie Ciencias Forestales y del Ambiente 13(1): 41-46. http://www.scielo.org.mx/pdf/rcscfa/v13n1/2007-4018-rcscfa-13-01-41.pdf (4 de diciembre de 2020). ISSN 2007-4018.

Flores V., R., M. E. Fuentes L., J. Quintanar O. y J. C. Tamarit U. 2013. Maquinado de cuatro especies maderables de encino de la sierra de Juárez, Oaxaca. Revista Mexicana de Ciencias Forestales 4(16): 22-33. Doi:https://doi.org/10.29298/rmcf.v4i16.438

Fuentes L., M. E. y R. Flores V. 1995. Propiedades físico-mecánicas de la madera de cinco especies de encino del estado de Puebla. INIFAP. CIRCE. Puebla, México. Folleto científico No. 2. 14 p.

Fuentes L., M. E., M. Fuentes S. y F. J. Zamudio S. 1997. Análisis comparativo de tres sistemas de secado con madera de cuatro especies de encino (*Quercus* spp.). Revista Chapingo Serie Ciencias Forestales y del Ambiente 4(1): 155-160. https://www.academia.edu/16250082/1997_analisis_comparativo_de_tres_sistemas_de_secado_con_madera_de_cuatro_especies_de_encino_quercus_spp_ (4 de noviembre de 2020).

Fuentes L., M. E., J. A. García S., F. J. Zamudio S. y J. A. Matus G. 2008. Políticas que afectan la competitividad de la producción de madera aserrada en México. Madera y Bosques 14(2): 29-39. Doi:https://doi.org/10.21829/myb.2008.1421210.

Honorato S., J. A. 2002. Química de la madera de encinos. *In*: Quintanar O, J. (Ed.). Características, propiedades y procesos de transformación de la madera de los encinos de México. INIFAP. CIRCE. Puebla, México. Libro Técnico No. 2. pp. 86-106.

Honorato S., J. A., F. Apolinar H. y G. Colotl H. 2016. Composición lignocelulósica de *Pinus ayacahuite* Ehrenb. ex Schltdl., *P. leiophylla* Schlecht. & Cham. y *P. herrerae* Martínez. Revista Mexicana de Ciencias Forestales 7(33): 47-56. Doi:https://doi.org/10.29298/rmcf.v7i34.82.

Honorato, S., J. A. y J. Hernández P. 1998. Determinación de componentes químicos de la madera de cinco especies de encino del estado de Puebla. Madera y Bosques 4(2): 79-93. Doi: https://doi.org/10.21829/myb.1998.421361.

Honorato, S., J. A., G. Colotl H., F. Apolinar H. y J. Aburto 2015. Principales componentes químicos de la madera de *Ceiba pentandra*, *Hevea brasiliensis* y *Ochroma pyramidale*. Madera y Bosques 21(2): 131-146. Doi:https://doi.org/10.21829/myb.2015.212450.

Honorato S., J. A. y M. E. Fuentes L. 2001. Propiedades físico-mecánicas de la madera de cinco especies de encino del estado de Guanajuato. Revista Ciencia Forestal en México 26(90): 5-28. http://cienciasforestales.inifap.gob.mx/editorial/index.php/forestales/article/ (15 de diciembre de 2020).

Junta del Acuerdo de Cartagena (JUNAC). 1989. Manual del Grupo Andino para el secado de maderas. Junta del Acuerdo de Cartagena. Lima, Perú. 418 p. https://books.google.com.mx/books?id=osBJAAAACAAJ (10 de noviembre de 2020).

Kirbach, E. D. 1984. New methods for reducing saw tooth wear and maintenance. Modern Sawmill & Panel Techniques 1. Vol. 1 Proceeding of North American Sawmill & Panel Clinic. OR, USA. pp. 40-49.

Kirbach, E. D. and T. Bonac. 1982. Dulling of sawteeth tipped with a stellite and two cobalt-cemented tungsten carbides. Forest Product Journal 32(9): 42-45.

Koch, P. 1964. Wood machining processes. Donald Press Company. New York, NY, USA. 530 p.

Kollmann, F. 1959. Tecnología de la madera y sus aplicaciones (Tomo I) Instituto Forestal de Investigación y Experiencias y Servicio de la Madera. Madrid, España. 675 p. http://libros.inia.es/libros/product_info.php?products_id=658 (15 de octubre de 2020).

Kollmann F. and W. A. Coté. 1968. Principles of wood science and technology. Vol 1: Solid Wood. New York, NY, USA. 592 p.

Legg, B., B. Dorfner, S. Leavengood and E. Hansen. 2021. Industry 4.0 implementation in US primary wood products industry. Drvna Industrija 72(2): 143-153. Doi: https://doi.org/10.5552/drvind.2021.2017.

Lunstrum, S. J. 1985. Balanced saw performance. U.S. Department of Agriculture, Forest Service, Forest Products Utilization. 12. Madison, WI, USA. Technical Report No. 17 p.

Martínez S., M., J. Quintanar O., R. Flores V., P. Juárez T., H. E. Alanís M. y M. Alarcón B. 2006. Manual técnico para el asierre y secado de madera de encino en el estado de Chihuahua. INIFAP. CIRNOC. Chihuahua, Chih., México. Folleto técnico No. 36. 41 p.

Nasir, V. and J. Cool. 2018. A review on wood machining: characterization, optimization, and monitoring of the sawing process. Wood Material Science and Engineering 1-16. Doi: https://doi.org/10.1080/17480272.2018.1465465.

Pérez-Olvera, C. P. y R. Dávalos-Sotelo. 2008. Algunas características anatómicas y tecnológicas de la madera de 24 especies de *Quercus* (encinos) de México. Madera y Bosques 14(3):43-80. Doi: https://doi.org/10.21829/myb.2008.1431206.

Pérez-Olvera, C., R. Dávalos-Sotelo, R. Limón G. y P. A. Quintanar I. 2015. Características tecnológicas de la madera de dos especies de Quercus de Durango, México. Madera y Bosques 21(3):19-46. http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1405-04712015000300002&lng=es&nrm=iso>. ISSN 2448-7597 (15 de julio de 2021).

Panshin, A. J. y C. de Zeeuw. 1980. Textbook of Wood Technology. Structure, identification, properties, and uses of the United States and Canada. McGraw-Hill, New York, NY, USA. 722 p.

Pettersen R., C. 1984. The Chemical Composition of Wood. *In*: Rowell, R. (ed). The Chemistry of Solid Wood. American Chemical Society. Washington, DC, USA. pp. 57–126. Doi: https://doi.org/10.1021/ba-1984-0207.ch002.

Quezada F., A. 1998. Acondicionamiento y manutención de sierras huinchas. Manual No. 22. Instituto Forestal Chile. Santiago, Chile. 106 p.

Quintanar O., J. 2005. Construcción y operación de un secador solar para madera. INIFAP. CIRCE. Puebla, México. Folleto Técnico No. 2. 46 p.

Quintanar O., J., M. E. Fuentes L. y R. Flores V. R. 2009a. Manual para el secado en estufa de madera de encinos de Oaxaca.. INIFAP. CIRGOC. Puebla, México. Folleto Técnico No. 50. 70 p.

Quintanar O., J., M. E. Fuentes L. y R. Flores V. 2009b. Planeación e instalación de estufas para secado de madera. INIFAP. CIRGOC. Puebla, México. Folleto Técnico No. 48. 48 p.

Quintanar O., J., M. E. Fuentes L. y J. C. Tamarit U. 2011. Evaluación económica de un secador solar para madera. Revista Mexicana de Ciencias Forestales 2(7): 97-104. Doi: https://doi.org/10.29298/rmcf.v2i7.561.

Quintanar O., J., M. E. Fuentes L. y R. Flores V. 2012. Protocolo de mejora continua para incrementar la calidad en el estufado de la madera. Revista Mexicana de Ciencias Forestales 3(13): 87-93. Doi: https://doi.org/10.29298/rmcf.v3i13.491.

Quintanar O., J. 2017. Secado solar: metodología para el diseño y evaluación de un secador solar tipo invernadero utilizado en el secado de madera. Revista de Aplicación Científica y Técnica 3(9): 18-23. https://ecorfan.org/spain/researchjournals/Aplicacion_Cientifica_y_Tecnica/vol3num9/Revista_de_Aplicacion_Cientifica_y_Tecnica_V3_N9_3.pdf (15 de octubre de 2020).

Rosales C., M., J. A. Honorato S., A. B. Santos G., M. E. Pérez L., G. Colotl H. y V. Sánchez M. 2016. Composición química de las hojas y ramas de *Cedrela odorata* L. de dos plantaciones forestales como fuente de materia prima lignocelulósica. Madera y Bosques 22(2): 131-146. Doi:https://doi.org/10.21829/myb.2016.2221330.

Sandvik. 1964. Manual sobre hojas de sierra cinta ancha para madera. Sandvik Steel. Sandviken, Suecia. 63 p.

Santacruz G., N. y A. Espejel R. 2004. Los encinos (*Quercus*) de Tlaxcala, México. Ed. Universidad Autónoma de Tlaxcala. Tlaxcala, Tlax., México. 41 p.

Schrewe, H. 1983. Manual de acondicionamiento y mantenimiento de la sierra cinta. FAO. Lima, Perú. 92 p.

Simpson, W. T. 1991. Dry Kiln Operator's Manual. United States Department of Agriculture Forest Service. Forest Products Laboratory. Agriculture handbook No. 188. Madison, WI: U.S. Department of Agriculture Forest Service. 274 p. https://www.fpl.fs.fed.us/documnts/usda/ah188/ah188.htm (26 de julio de 2021).

Sotomayor C., J. R. 2005. Características mecánicas y clasificación de la madera de 150 especies mexicanas. Investigación e Ingeniería de la Madera. Sociedad Mexicana de Ciencia y Tecnología de la Madera. Morelia, Michoacán. México. 24 p. https://www.researchgate.net/publication/260752809_Caracteristicas_mecanicas_y_clasificacion_de_150_especies_de_maderas_Mexicanas (4 de agosto de 2021)

Tamarit U., J. C. y J. L. López T. 2007. Xilotecnología de los principales árboles tropicales de México. Libro Técnico No.3. INIFAP.CIRGOC. Puebla, Pue., México. 264 p.

Tamarit U., J. C. y R. Flores V. 2012. El proceso de cepillado de maderas duras. INIFAP. CIRGOC. Puebla, México. Folleto técnico No. 75. 21 p.

Teischinger, A. 2010. The development of wood technology and technology developments in the wood industries from history to future. European Journal of Wood and Wood Products 68(3): 281-287. Doi:https://doi.org/10.1007/s00107-010-0458-2.

Thibaut, B., L. Denaud, R. Collet, R. Marchal, J. Beauchêne, F. Mothe, P. Méausoone, P. Martin, P. Larricq and F. Eyma. 2016. Wood machining with a focus on French research in the last 50 years. Annals of Forest Science 73(1): 163-184. Doi: https://doi.org/10.1007/s13595-015-0460-2.

Vignote P., S. e I. Martínez R. 2006. Tecnología de la madera. 3ª. Ed. Madrid. Ediciones Mundi-Prensa. Artes Gráficas Cuesta. Madrid, España. 678 p.

Zavala Z., D. 2000. Secado de maderas tropicales en estufas convencionales. Madera y Bosques 6(1): 41-54. Doi: https://doi.org/10.21829/myb.2000.611341

Zavala Z., D. y M. Vázquez R. 2001. Determinación de las características de maquinado de la madera de 34 especies tropicales. Revista Chapingo Serie Ciencias Forestales y del Ambiente 7(2): 169-183. https://revistas.chapingo.mx/forestales/revista/articulos/viewer.html?file=rchscfaVII361.pdf (11 de enero de 2021).

Zavala Z., D. 2003. Efecto del sistema de aserrío tradicional en las características de la madera de encinos. Madera y bosques 9(2): 29-39 Doi:https://doi.org/10.21829/myb.2003.921284.