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Article

Chemical-micrographic and dasometric characterization of three pine species and their viability for integral harvesting

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Introduction

Mexico has a forest surface area of 167 817.47 km^2, 80 % of which consists of pine trees used for timber and cellulose (Inegi, 2013). From a global point of view, the wood represents 85 to 90 % of the fibrous raw materials consumed for manufacturing various types of products in the timber, cellulose, paper and packing industries (Gellerstedt, 2009).

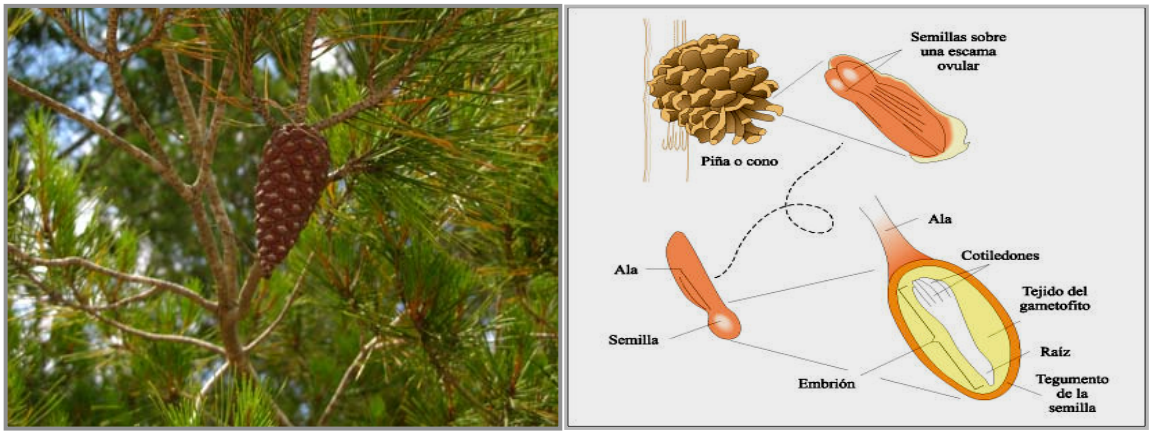
The species of the *Pinus* genus grow preferably in the conifer forests of the northern hemisphere, and the highest number of taxa is estimated to exist in Mexico ––75 out of the 110 taxa distributed across the world. Eguiluz (1998) points out that its main distribution area is located on the Western *Sierra Madre*, the Eastern *Sierra Madre*, the Southern *Sierra Madre* and the Neovolcanic Axis (Figure 1).

Source: Cotler, 2007.

Figure 1. Distribution of *Pinus* species in Mexico.

Among the characteristics of the pine trees, which belong to the conifers with soft, resinous, non-porous wood, we may quote the following: woody plants (Figure 2)

that reproduce through seeds located between the scales of the female cones (Perry, 1991). The needles usually have a taxonomic value; for example, certain pine trees have 2 to 3 needles and produce a solid, resinous wood with a bark that cracks or peels off in the form of scales, erect cones with thick scales and seeds with articulate wings; while species with five needles include individuals that produce a less solid, slightly resinous, somewhat pendulous cones whose scales have a thin tip and a marginal umbo (Martínez, 1992).



Source: Ciencia y Biología, 2017; Wordpress, 2017.

Figure 2. Needles, cones and seeds of the *Pinus* genus.

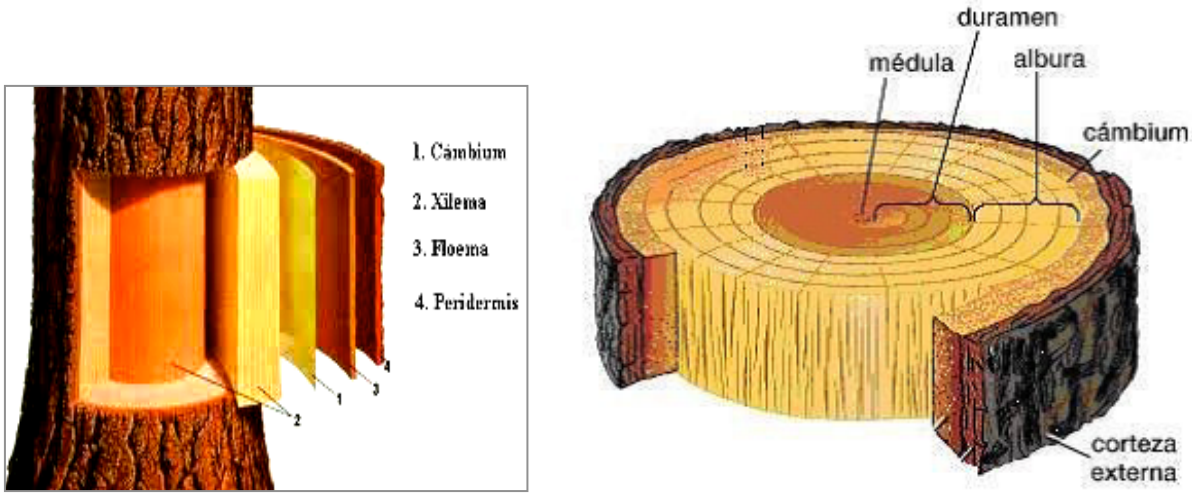
These are some of the characteristics of the taxa studied in the present research: *Pinus douglasiana* Martínez is native to Mexico; it measures up to 35 m in height and 70 cm in diameter, and has a pyramid-shaped crown; it grows in the states of *Sonora*, *Chihuahua*, *Durango*, *Sinaloa*, *Tepic*, *Jalisco*, *Michoacán*, *Guerrero* and *Oaxaca*, at a mean altitude of 2 000 masl and a temperature ranging between 15 and 18 °C (Martínez, 2013).

Pinus devoniana Lindl. (Sin. *Pinus michoacana* Martínez) reaches a height of 30 m and a diameter of 90 cm; it has a rounded crown with a twiggy foliage; it is distributed among the states of *Nayarit*, *Jalisco*, *Zacatecas*, *Colima*, *Michoacán*, *Estado de México*, *Puebla*, *Hidalgo*, *Guanajuato*, *Tlaxcala*, *Guerrero*, *Oaxaca,*

Veracruz and *Chiapas*. It grows at a mean altitude of 1 900 masl and a mean temperature of 18 °C (Aguilera, 2001).

Pinus oocarpa Schiede *ex* Schltdl. (fatwood pine) is native to Mexico; it measures up to 18 m in height and 40 cm in diameter and has a widely ramified crown. It has been found in *Sonora*, *Sinaloa*, *Zacatecas*, *Durango*, *Nayarit*, *Jalisco*, *Michoacán*, *Morelos*, *Puebla*, *Hidalgo*, *Tlaxcala*, *Guerrero*, *Oaxaca* and *Chiapas*; it grows at a mean altitude of 1 800 masl, at temperatures ranging between 13 and 23 °C (Gutiérrez *et al*., 2013).

According to Olvera (1985), these are some of the average characteristics of the pine tree stem (timber-yielding biomass): vertical, with horizontal branches that vary in length from the stem base to the tip; a height of 15 to 45 m and a diameter ranging between 25 and 100 cm, and, generally, with a cone-shaped outline. The cross-section of the stem (Figure 3) includes the following sections: outer bark or peridermis; inner bark, also known as phloem or bast; cambium, or living tissue; sapwood and heartwood, jointly known as xylem or useful wood.

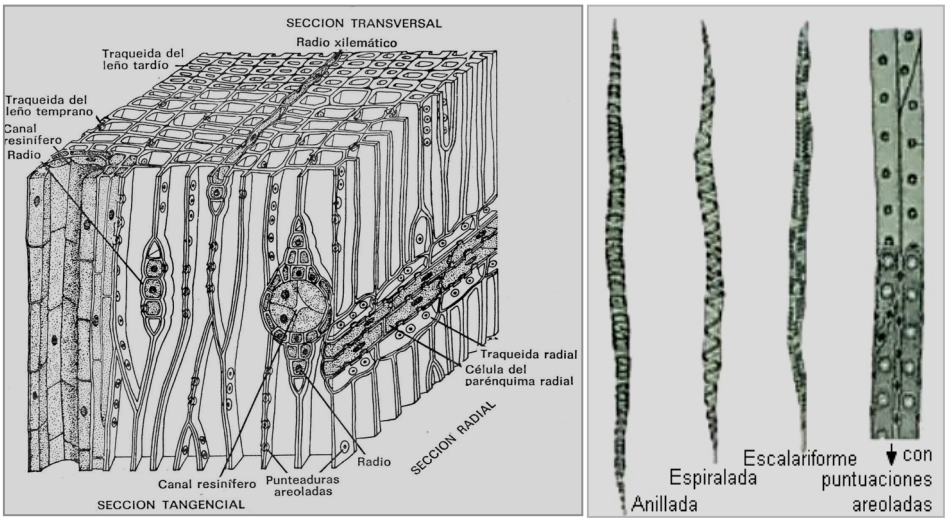


Source: González, 2013a; Rodríguez, 2014.

Figure 3. Sections or layers that make up the pine stem.

As for the constitution of the cell tissue, the wood of conifers has a simple cell composition and less cellular specialization than broadleaves or species with hard wood, which possess a large diversity of fibers, tracheids, vessels, parenchymatous cells, etc. The tissue of conifers (Figure 4) is made up of three different kinds of cells: fibers and tracheids (80-90 %), parenchymatous cells and rays (10 a 20 %).

Tracheids have the function of conducting water and providing support in the vegetal tissue; they connect through perforations in the cell wall known as areolated punctures, which allow the flow of fluids. They measure between 1.5 and 3.8 mm, depending on the species and the area of growth (Olvera, 1985). On the other hand, parenchymatous cells and rays are characterized by their cell content and prism shape, and they are horizontally and vertically oriented in the cell tissue of the wood (Figure 4); their function is to store, transform and conduct substances in the wood through punctures that connect them with the neighbor cells (Fengel and Wegener, 1989).



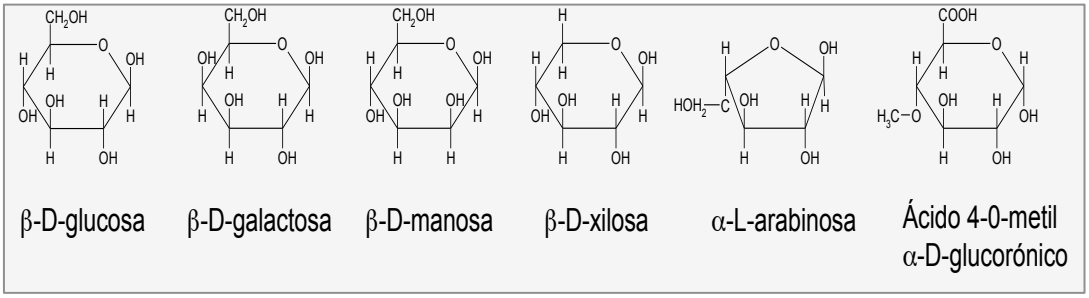
Source: Universidad Nacional del Nordeste, 2000; González, 2013b.

Figure 4. Detail of *Pinus* tissue and tracheids).

In relation to this, we must point out that the fibrous and chemical composition of the raw materials used in the manufacture of paper and cardboard across the world privilege *Pinus* and conifer species as sources of basic fibers to provide structural resistance (fibers and tracheids) to most writing and printing paper, up to a 50 %, and wrapping papers with a high physic-mechanical resistance normally use 80 to 100 % pine fibers (Zanuttini *et al*., 2008).

As for the chemical components present in pine trees and conifers, carbohydrates make up most of the biomass of the vegetal stem (bark, wood, branches and leaves); these compounds cannot be separated without affecting the physical structure of the cell wall (Timell, 1967).

Holocellulose, the carbohydrate fraction (68 to 90 %) is made up of cellulose and hemicellulose, which in turn are made up of hexosans and pentosans (Ávila and Herrera, 2012). In chemical terms, cellulose is a polysaccharide with a linear structure, constituted by glucose molecules (**β**-D-glucopyranose joined by **β**-1,4 links) with the empirical formula $C_6H_{10}O_5$ (Sjöstrom, 1993); and the carbohydrates with a low molecular weight (Figure 5) are polysaccharides made up of more than one type of monomer, joined by **β** (1-4) links that form a ramified linear chain together with the cellulose and at the same time re part of the microfibrils that form the cell wall of the tissues (Rowell, 2005).

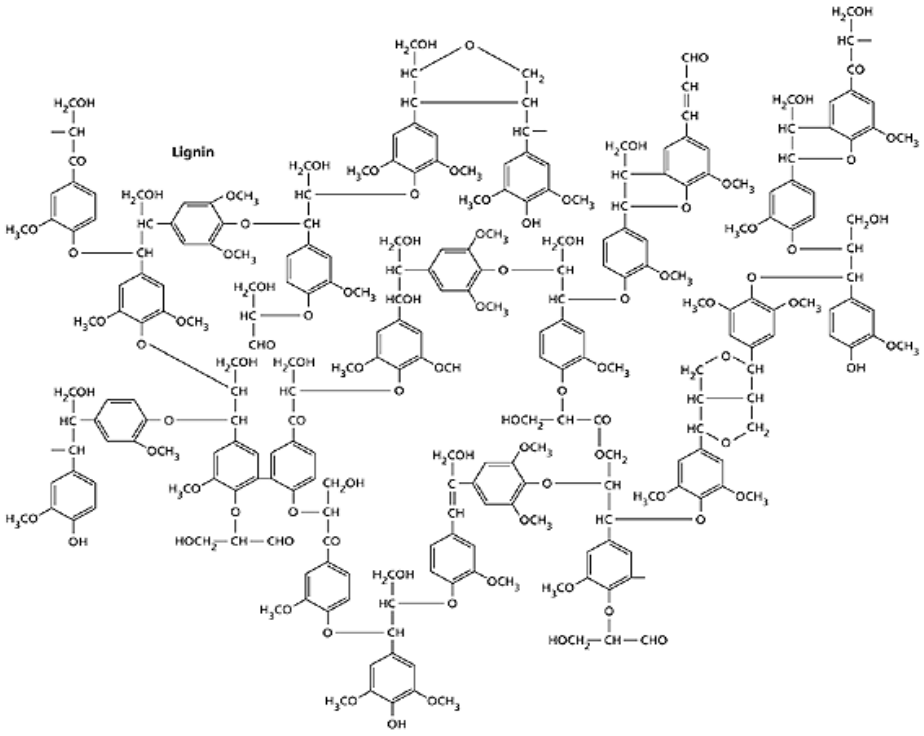


Source: Chapa, 2011.

Figure 5. Carbohydrate fraction.

For the application of cellulose and carbohydrates, Álvarez-Castillo *et al*. (2012) suggest obtaining whiskers and various materials made up of cellulose, and producing bioethanol from monomeric carbohydrates.

After the polysaccharides, lignin is the most abundant organic polymer in the vegetal world (15 to 35 %). It fulfills various functions in the wood, including acting as an interfibrilar glue, which besides joining and sticking, provides rigidity to the cell wall and resistance to the tissues, preventing attacks by microorganisms and infiltration of destructive enzymes (Rowell, 2005). Lignin polymers are structures that are transconnected to a molecular weight of 10 000 atomic units; they are the union of several acids and phenylpropylic alcohols that form various polymer structures (Figure 6). For this reason, it is not possible to define a structure of lignin; however, several models representing it have been proposed (Sjöstrom, 1993).

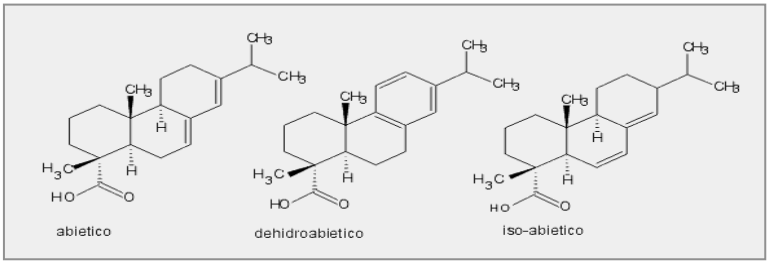


Source: García, 2015.

Figure 6. Lignin polymer.

Chávez-Sifontes and Domine (2013) points out that lignin can be applied in the form of lignosulfates (pesticide dispersers, emulsifiers and heavy metal sequestering agents), as a polymer or a copolymer (phenol-formaldehyde type resins, or ligning-polyolefins, lignin-polyesthers, lignin-polyurethanes). Lignin is also chemically modified and added to formulations to enhance the properties of resins and adhesives.

The fraction of extractables in pine trees consists of resin acids (60 -75 %), fatty acids (15 – 20 %) and a volatile fraction or turpentine (5 - 10 %). Resin acids (80 %) are compounds with a general formula, $C_20H_300_2$, that are classified into two series, according to their structure: abietane ––with a double bond system and an isopropyl group (substituent in the third ring) –– and pimarene ––with a vynil group and a methyl group in the same position (Figure 7).

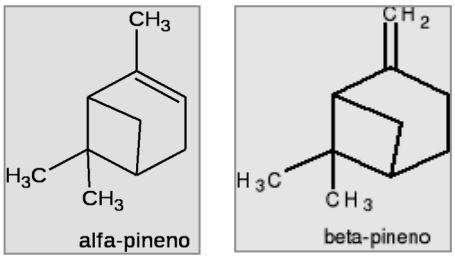


Source: Hevia *et al.*, 2008.

Figure 7. Main resin acids.

Goldstein (2017) points out that turpentine oil and colophonia are the main products of this type of resin acids. The fraction of fatty acids present in the pine extracts consists of 18 carbon atoms (C18), with a prevalence of oleic and the linoleic acids, and, to a lesser extent, palmitic and stearic acids. Finally, the volatile fraction basically constituted by turpentine or pine oil (a byproduct of the paper manufacture process), is obtained by separating, through distillation, the light

vapors of the resin acid fraction made up of a mixture of terpenes with the general formula $C_{10}H_{16}$, the most prominent of which are alpha and beta pinenes (Figure 8).



Source: Erick, 2016.

Figure 8. Main terpenes.

Based on the above, the *Instituto Nacional de Estadística Geografía e Informática*, (National Institute of Statistics, Geography and Informatics (Inegi, 2013) states that information on the chemical composition of specific pine plantations is scarce in Mexico and suggests carrying out concrete studies of their dasonomy, taxonomy and basic chemical composition, like the one included in this research. On the other hand, according to Álvarez-Castillo *et al.* (2012), among the natural resources, lignocellulosic materials play a major role due to their availability and to the various sources that generate them (wood, branches, leaves, bark, etc.), and therefore they propose using lignocellulosic biomass in new integral exploitation trends through which the lignocellulosic waste can be utilized to produce charcoal fibers from lignin with the Whiskers method, using cellulose and bioethanol, carbohydrates and other compound biological materials as sources.

Rodríguez (1994) attests that the utilization and industrialization of the forests favors the accumulation of high volumes of fibrous waste, particularly bark, during the process of cellulose extraction; he points out that the bark is characterized by containing extractables, especially tannins, which are low-cost raw materials for the generation of phenols and compounds that can be used as heavy metal absorbers and in the formation of proteins. In this sense, the first proposed objective was to

carry out a balance of the discarded biomass of each pine species (branches, bark and needles). The second objective was to determine the chemical compounds in the wood, the micrographic analysis and the physic-mechanical resistance properties of the paper, in order to identify, based on these results, which of the three species has the best characteristics in dasometric terms and in terms of usable biomass and of chemical fractions, as well as the best morphological and physic-mechanical characteristics, to suggest the viability of its integral exploitation.

Materials and Methods

Three trees of the species *Pinus douglasiana, Pinus devoniana* and *Pinus oocarpa* were planted in 1985, with a plantation density of 2 x 2 m at the School Forest of the University of *Guadalajara*, an experimental field (Huerta *et al.* 1985) located in the *La Primavera* forest in the community of *Cuxpala*, *Jalisco*, Mexico (Figure 9).

The conditions of the area have a mean annual temperature of 18.5 °C (4 – 35 °C), a semi-warm climate and a mean altitude of 1 480 masl. Its location, determined by a GPS, is between the coordinates 20°34'57.6'' N and 103°37'57.6'' W (Escoto *et al.*, 2013). The dasometric dimensions ––the stem diameter (DBH)–– of each of the selected specimens were measured with a Sthil logger 15 m tape; they were subsequently felled and debranched in order to measure the length of the stem and determine its height with a Haga altimeter; next, it was cut in several sections for better handling and classified by species and height with a Husquarna 365 chainsaw. The branches and needles were collected along with the sections (logs) of the stem and were transferred to the *Departamento de Madera, Celulosa y Papel del Centro Universitario de Ciencias Exactas e Ingenierías* (Wood, Cellulose and Paper Department at the University Center of Exact Sciences and Engineering) of the *Universidad de Guadalajara* (University of Guadalajara) (UDG).

Figure 9. Pine tree plantation in the School Forest experimental field (*La Primavera* forest, *Jalisco*).

The sections of the stems were selected with a chainsaw, measured and dried during two weeks before being debranched by hand; once they were dry and debarked, they were weighed and measured (Figure 10). The branches and needles, or foliage, were also weighted in order to establish a balance of the usable material of all the biomass (stem, branches, bark and needles) by pine species.

Figure 10. Measurement, debarking and drying of the logs.

The moisture content of each of the biomass fractions (wood splinters and chips, barks, branches and needles) was determined according to the TAPPI T 257 cm-85 technique in order to determine the dry weight and establish the usable fractions

with respect to the total biomass and carry out the balance by studied taxon (TAPPI, 1998).

The debarked logs were chipped in a type 980AH Bruks Mekaniska equipment; the chips were subsequently classified with a type FI-117 Lorentzen & Wettre equipment, on a 10 mm and 8 mm grooved plate, and on a plate with holes with a diameter of 10 mm. The fraction of the chips retained between the 10 and 8 mm grooved plates were used to obtain pulp using the Kraft process for manufacturing paper in the laboratory. The thin chips and splinters were ground in a *5657* SKI Retsch GmbH hammer mill; the sawdust was classified using a *Rx-29* Rotap W.S. Tyler equipment with 20, 40, 60, 100 and 120-size meshes, according to the Tappi methods (TAPPI, 1998).

The sawdust samples gathered in the 60-size mesh were analyzed in the fiber quality laboratory of the stated Department, following these methods: T 264 cm-97 preparation of the free sample of extractable substances, T204 cm-97 determination of the content of alcohol-/toluene-extractable compounds and T 207 cm-99 determination of the content of hot water-extractable compounds (Tappi, 1998).

Once the sawdust was extracted, the determinations of holocellulose (total carbohydrates) were carried out according to the Wise method, using acetic acid and sodium chlorite; the alpha cellulose was subsequently estimated using the T 9m-54 norm described by Cross and Bevan, through hydrolysis of the hemicelluloses with sulphuric acid at 3 %, and finally, the pentosans were determined by distillation and titration of the phurphural with chlorhydric acid, based on the norm T 223 cm-84 (TAPPI, 1998).

The Klason lignin was isolated according to the norm T 222 om-98 by hydrolysis of the carboydrates with sulphuric acid at 78 %. The determination of the ashes was carried out according to the norm T 211 om-93; the sawdust was first carbonized in a porcelain crucible and then incinerated in a M3600 Felisa muffle furnace at 575 $\pm$ 25 °C for a period of 3 hours (TAPPI, 1998).

The micrographic analysis corresponding to the fiber length (30 measurements per species) was carried out at the *Laboratorio de Microscopia* (Microscopy Laboratory) of the stated Department, on standard shredded paper samples in a M29799 Wild Heerbrugg electronic microscope.

The determination of the physico-mechanical properties on standard paper sheets was carried out in the *Laboratorios de Refinación de Pulpa y Tecnología del Papel* (Pulp Refining and Paper Technology) laboratories of the stated Department according to the norms T 205 sp-95 formation of standard sheets, T 414 om-98 resistance to tearing, T 404 cm-92 resistance to tension and T 403 om-97 resistance to explosion (Tappi, 1998).

Results and Discussion

Table 1 shows that the dasometric measurement of the three pine species indicates that *Pinus douglasiana* has the best development, as it had the greatest height (13.2 m), DBH (24.3 cm) and volume (0.602 m^3) compared to the specimens of the other two taxa. While *Pinus oocarpa* had more density (478 kg m^{-3}) and DBH (18.4 cm) than *Pinus devoniana*, it proved to be the shortest (9.85 m).

Table 1. Dasometric characteristics of the three pine species.

Dimension	***Pinus douglasiana***	***Pinus devoniana***	***Pinus oocarpa***
Normal diameter (ND or DBH)	24.3 cm	15.5 cm	18.4 cm
Height	13.2 m	12.8 m	9.85 m
Density	428 kg m^{-3}	435 kg $^{-3}$	478 kg m^{-3}
Volume	0.602 m^3	0.241 m^3	0.262 m^3

In regard to the balance of the biomass that is usable as wood, *Pinus douglasiana* (A) had the highest percentage (45 %) (Figure 11), while *Pinus devoniana* (B) and *Pinus oocarpa* (C) had lower values (38 % and 31 % respectively).

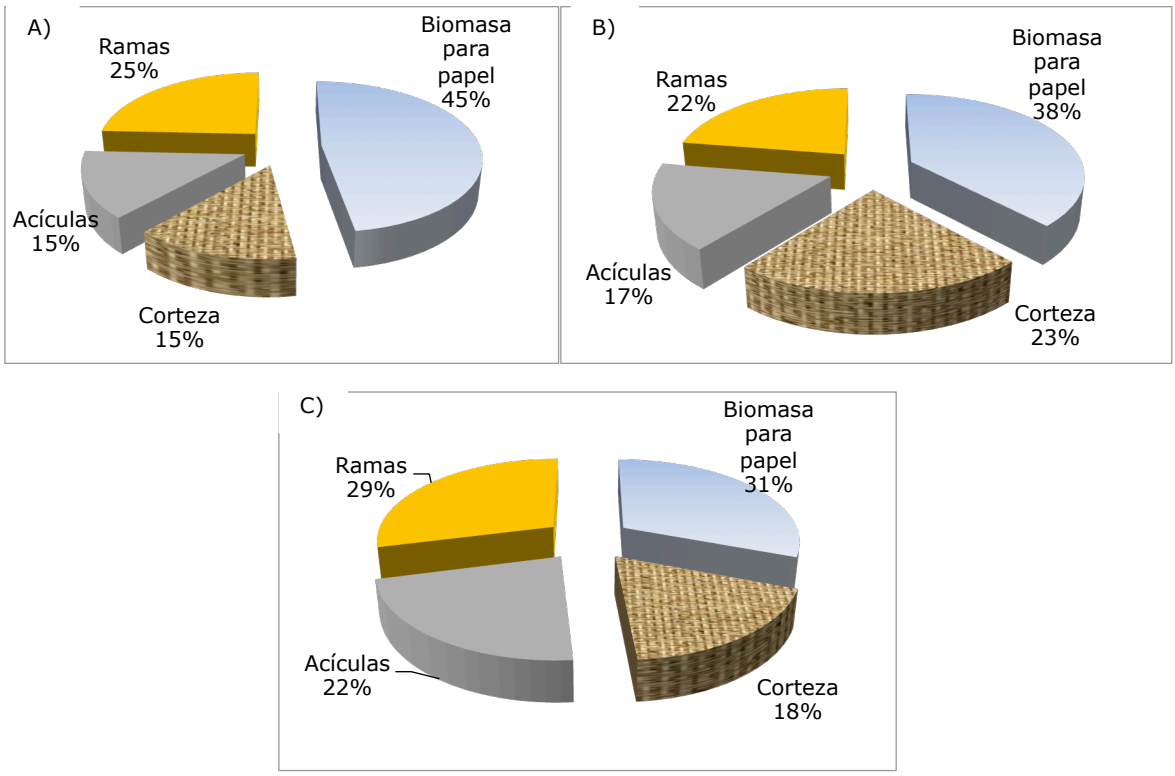


Figure 11. Biomass balance for A) *Pinus douglasiana* Martínez, B) *Pinus devoniana* Lindl. and C) *Pinus oocarpa* Schiede ex Schltdl.

As for the bark content (Figure 11), *Pinus devoniana* (B) stood out with 23 %; *Pinus oocarpa* (C) had an intermediate value (18 %), and *Pinus douglasiana* (A) had the lowest content (15 %). The highest percentage of needles (Figure 12) was estimated for *Pinus oocarpa* (C) (22 %). Finally, and according to Figure 11, the highest proportion of branches corresponded to *Pinus oocarpa* (C), with 29 %.

Based on the biomass balance, we suggest using *Pinus douglasiana* as timber in various products and derivates; *Pinus devoniana* proved to be the best for bark

applications (phenols and tannins), and *Pinus oocarpa*, the best for needle use (chlorophyll and essences) and resins (fatty and resin acids).

In this sense, the exploitation of the forest normally generates high volumes of fibrous waste of various natures. In the industry of cellulose for paper, the main waste is the bark, which is removed from the stem before chipping and is almost always burnt. Baeza (1989) mentions that the main components of the pine bark are polyphenols, phenolic acids, lignin and carbohydrates. The polyphenols with the lowest molecular weight can be water-soluble tannins and alcohol-soluble phlobaphenes. On the other hand, when they are extracted with NaOH, their yield is approximately 50 % of the bark. Murphey (1970) suggests that the exploitation of the bark requires determination of its structural differences, ––including its type, density and content of extractables––, as these will determine the suitability of a particular species for the obtainment of a specific product.

With regard to the chemical composition of the various fractions of biomass that can be used for paper (wood) of the three pine species, we observe (Table 2 and Figure 12) that the percentage of holocellulose was highest in *Pinus devoniana* (E), with 74.7 %, and in *Pinus douglasiana* (D), with 74.1 %. Bernabé-Santiago *et al*. (2013) register holocellulose contents in *Pinus oocarpa* (74.15 %), *P. teocote* Schiede ex Schltdl. *et* Cham. (71.54 %), *P. michoacana* (72.96%), *P. leiophylla* Schiede ex Schltdl. *et* Cham. (69.16 %) and *P. montezumae* Lamb. (68.14 %); these values are very similar to those documented in the present paper, and they are within the interval (68 – 78 %) cited by Fengel and Wegener (1989) for various pine species. However, Boonstra (2006) records contents of 79 to 81 % for *P. radiata* D.Don and *P. sylvestris* L.,, above those estimated in this study. These authors point out that they used the Rowell method, which differs from the Wise method used in the research documented herein.

Table 2. Average chemical composition.

Chemical compound	***Pinus douglasiana***	***Pinus devoniana***	***Pinus oocarpa***
Carbohydrate fraction in %			
Holocellulose Wise	74.1	74.7	72.2
Alpha cellulose Coss and Bevan	47.6	47.8	42.1
Pentosans	9.0	11.9	11.8
Fraction of lignin extractables			
Hot water extractables	1.8	2.6	2.35
Alcohol extractables / toluene	3.7	2.3	4.2
Klason lignin	30.4	31.3	32.1
Mineral fraction			
Ashes	0.53	0.27	0.38

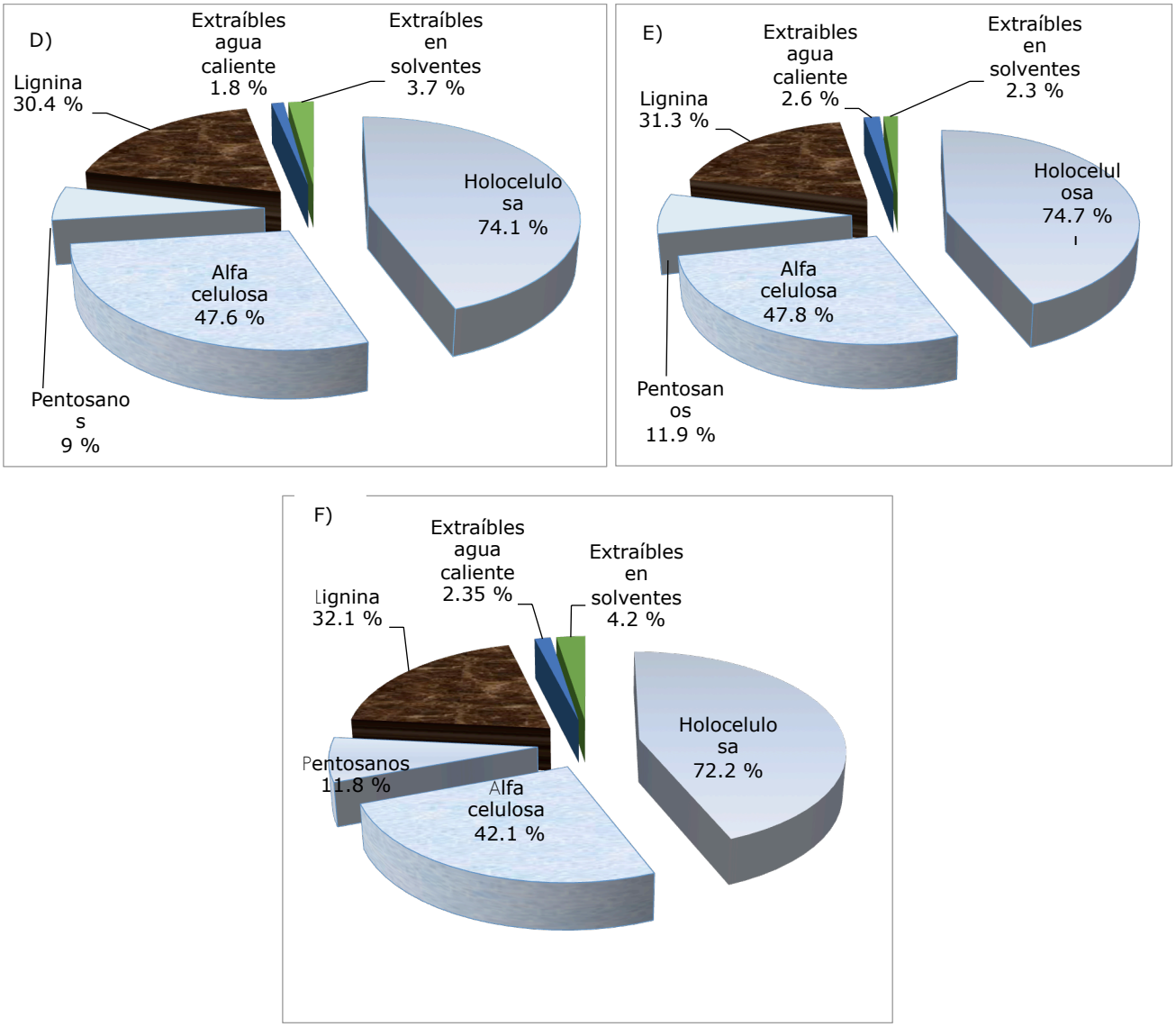


Figure 12. Main chemical fractions for D) *Pinus douglasiana* Martínez, E) *Pinus devoniana* Lindl. and F) *Pinus oocarpa* Schiede ex Schltdl.

On the other hand, the alpha cellulose fraction (Table 2, Figure 12) registered the highest content in *Pinus devoniana*, with 47.8 % and *Pinus douglasiana*, with 47.6 %; the lowest value corresponded to *Pinus oocarpa*, with 42.1 %. These results are within the interval of 41.22 to 50.79 % cited in the literature (Saka, 2001; Sjöstrom, 1999; Fengel, 1989).

The content of pentosans for the wood of the three pine species (Table 2 and Figure 12) show values between 9 and 11.9 %, which correspond to those recorded by Sjöstrom (999) and Fengel and Wegener (1989) (8 to 13 %) for pine trees. The lowest value was obtained for *P. douglasiana*, with 9.0 %, and the highest values, for *P. devoniana*, with 11.9 %, and *P. oocarpa*, with 11.8 %.

The fraction of carbohydrates, known as holocellulose (made up of alpha cellulose and pentosans) indicates the quality level of a fibrous source required for it to be suggested as raw material for the industry of cellulose and paper; in this case, *P. devoniana* had the highest percentage of holocellulose (74.7 %), alpha cellulose (47.8 %) and pentosans (11.9 %); therefore, it represents the best option for the obtainment of cellulosic pulp and for the manufacture of paper and cardboard.

The lignin content (Table 2 and Figure 12) was 32.1 % for the wood of *P. oocarpa*, 31.3 % for that of *P. devoniana*, and 30.4 % for that of *P. douglasiana*; these values are relatively higher than the interval of 19 to 30 % indicated when the T-222 TAPPI method is applied (TAPPI, 1998). In general, the lignin content in *P. oocarpa* (32.1 % is the best application option, according to Chávez-Sifontes and Domine (2013), for lignosulphates, polymer or copolymer of certain resins or adhesives.

As for the total content of hot water- and alcohol-/toluene- extractables (Table 2, Figure 12), the wood of *P. oocarpa*, with 6.55 %, had the highest content of total extractables. However, the contents are not low in *P. douglasiana*, 5.5 %, or in *P. devoniana*, with 4.9 %. It should be noted that the TAPPI T-204 cm-97 norm indicates values of 1.5 to 11 %; the results obtained in the present study are within this range.

Based on the above, the extractables of pine wood can have various applications. In this regard, Goldstein (2017) cites that turpentine oil and colophonia are the most important at an industrial level, and we therefore suggest this form of exploitation.

P. douglasiana was found to have the highest percentage (0.58 %) of ashes (Table 2), while the content of ashes of *P. devoniana* had the lowest (0.27 %); in this way

and compared with those reported by the T 211 om-93 technique, which is 0.25 to 0.50% (TAPPI, 1998), which covers the ash content determined in this work (0.38%). In relation to the content of ashes registered for the three studied species, it was noted that, during the process of cooking the wood to obtain cellulose for the manufacture of paper, the high content of ashes increases the consumption of reagents, as well as the likelihood of their being embedded in the feeder lines, and therefore *P. devoniana*, whose content of ashes proved to be the lowest, is the most adequate for this use.

The micrographic analysis (Table 3) showed the fibers of *P. devoniana* to be the longest (3.87 mm), compared to those of *P. douglasiana* (2.97 mm) and *P. oocarpa* (3.10 mm). Borja *et al*. (2001) measured the fiber length in *P. caribea* Morelet, for which they recorded a value of 4.41 mm, above those of the present study. However, this is normal, because the growth variation is established according to the species, the treatment and the climatic and topographic conditions.

Table 3. Average fiber length.

Species	**Length in mm**
Pinus douglasiana Martínez	2.97
Pinus devoniana Lindl.	3.87
Pinus oocarpa Schiede ex Schltdl.	3.10

The preparation of the samples for measuring the fibers and for their micrographic observation (Figure 13) was carried out on a base of standard paper with a refining treatment (60 minutes). The results indicated that the fibers of *P. devoniana* (H) have greater fibrillation and flexibility (bent fibers), which usually increases the contact surface and the interfibrillar linking; this, in turn, allows a better fibrillar

consolidation and a higher physic-mechanical resistance of the paper. The fibers of *P. oocarpa* (I) and *P. douglasiana* (G) did not have the same effect; furthermore, the fibers of *P. oocarpa* (I) had the lowest microfibrillation and the lowest flexibility.

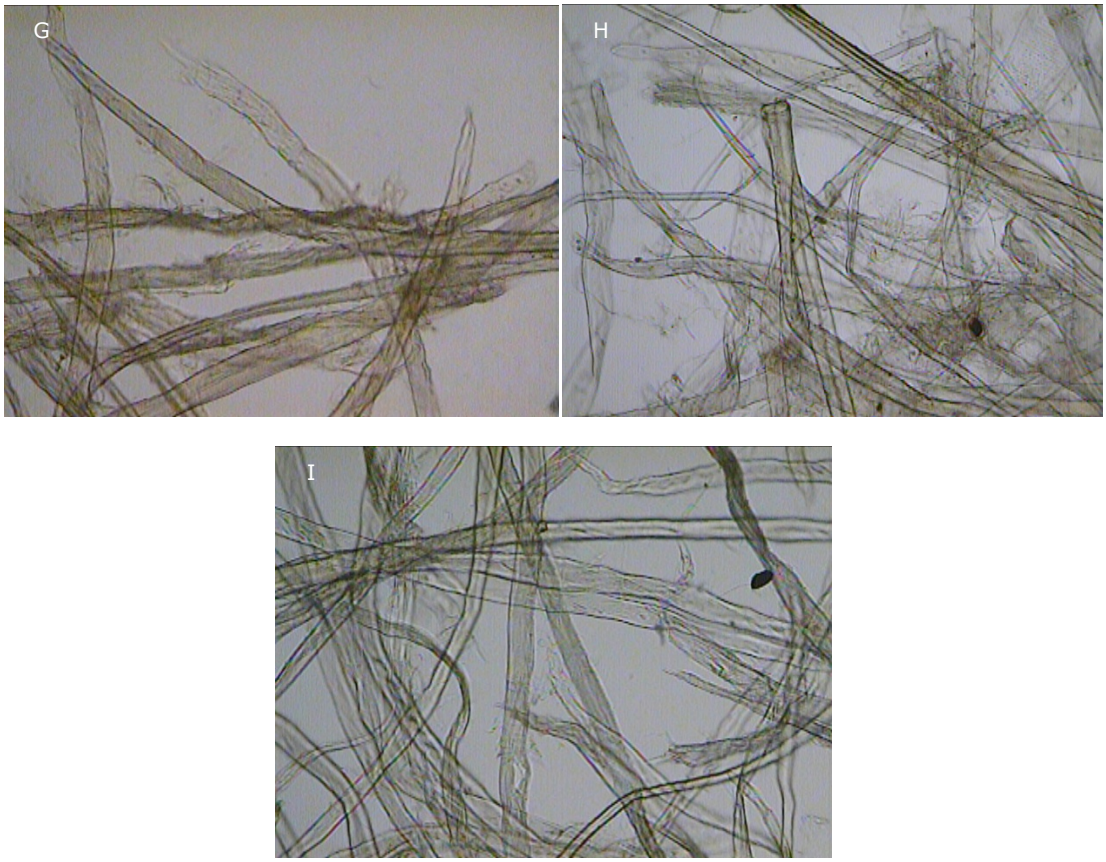


Figure 13. G) *Pinus douglasiana* Martínez, H) *Pinus devoniana* Lindl. and I) *Pinus oocarpa* Schiede ex Schltdl. wood micrograph. 50X.

The evaluation of the physico-mechanical resistance determined in standard paper sheets based on the cellulose content of each of the three pine species (Table 4, Figure 14); the highest indices of physic-mechanical resistance against tension (83.1 $N.mg^{-1}$) and against explosion (7.6 kPa. m^2g^{-1}) were estimated for *P. devoniana*. *P. douglasiana* paper had the best index for resistance against tearing (10.8 $N.m^2kg^{-1}$), and *P. oocarpa* registered the lowest indices for resistance against tension and explosion, although its index of resistance against tearing (9.9 $N.m^2$ kg^{-1}) was higher than that of *P. devioniana* (9.9 $N.m^2$ kg^{-1}).

Table 4. Average physico-mechanical resistance indices.

Species	Index of resistance against tension N.m g^{-1}	Index of resistance against explosion kPa.m^2 g^{-1}	Index of resistance against tearing N.m^2 g^{-1}
Pinus douglasiana Martínez	68.2	6.4	10.8
Pinus devoniana Lindl.	83.1	7.6	8.6
Pinus oocarpa Schiede ex Schltdl.	59.7	5.5	9.9
Average	70.3	6.5	9.7

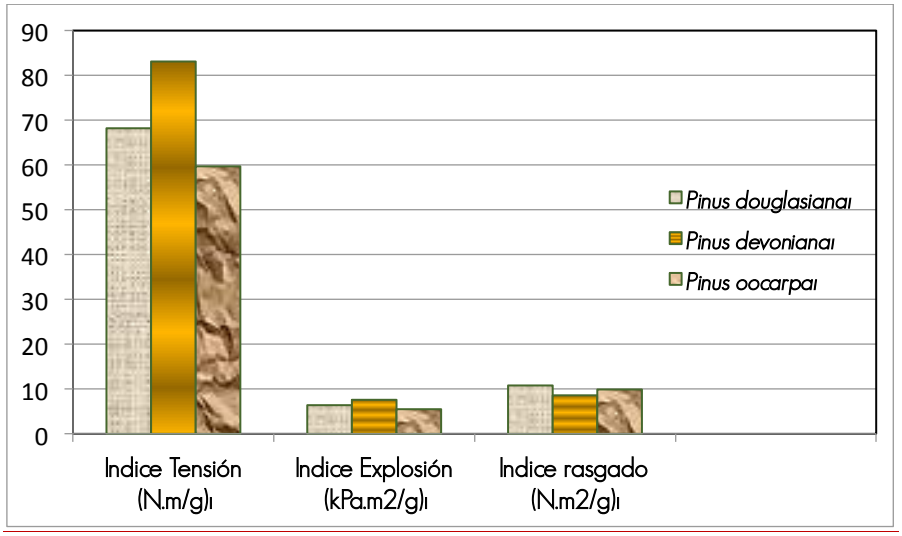


Figure 14. Physico-mechanical properties determined in standard paper sheets.

Zanuttini *et al.* (2008) register minimal indices of physico-mechanical resistance for kraft paper for sacks: index of resistance against tension (55 $N.mg^{-1)}$ and index of resistance against explosion (5.2 kPa.m^2 g^{-1}), and index of resistance against tearing (13.1 mN.m^2g^{-1}). The findings of the present study in terms of the index of

resistance against tension (70.33 N.m g^{-1}) and against explosion (6.5 kPa.m^2 g^{-1}) are above those cited by Zanuttini (2008); however, the average index of resistance against tearing (9.7) is lower.

Conclusions

The dasometric measurement indicates that *Pinus douglasiana* has the highest values for height (13.2 m), DBH (24.3 cm) and volume (0.602 m^3), which renders it a species that can be utilized as timber, as well as for the obtainment of cellulose for paper.

According to the balance of usable biomass for timber, *Pinus douglasiana* has the highest utilization percentage (45 %), although *Pinus devoniana* also has a good level of utilization (38 %), which confirms that these two species are liable to be used as timber and for the obtainment of cellulose for paper. On the other hand, the bark content of *P. devoniana* is higher (23 %), and therefore this species can be applied in the extraction of tannins and phenols. As for the utilization of the needles (for chlorophyll and essence) and resins (tar, colophonia and turpentine oil), *P. oocarpa* is the most adequate species, as it has the highest content of needles and branches (22 % and 29 %, respectively).

In regard to the chemical composition of the usable biomass (wood) for the manufacture of paper, *P. devoniana* has the highest content of holocellulose (74.7 %), alpha cellulose (47.8 %) and pentosans (11.9 %). The total content of lignin (32.1 %) and of hot water- and alcohol-/toluene-soluble extractables (6.55 %) is highest in *P. oocarpa*, while the content of ashes is lowest (0.27 %) in *P. devoniana*.

According to the micrographic analysis and the determination of the physico-mechanical properties of the standard paper, *Pinus devoniana* has the longest fibers (3.87 mm) and the highest indices of physic-mechanical resistance against tension (83.1 N.m g^{-1}) and against explosion (7.6 kPa. m^2g^{-1}).

It is concluded that the wood of *Pinus devoniana* has the highest viability for exploitation in the obtainment of cellulose and manufacture of paper because it has the best dasometric indicators, the highest amount of carbohydrates and the longest fibers (i.e. the best physico-mechanical properties of paper), as well as the lowest content of lignin and ashes (and consumes the lowest amount of reagents in the boiling process for pulp extraction). In contrast, the wood of *Pinus douglasiana* is recommended, firstly, for application as timber, and secondly, for the manufacture of paper; on the other hand, the utilization of *Pinus oocarpa* is suggested for the extraction of colophonia and pine oil (as it has the highest total content of extractables), and of charcoal fibers and adhesives (due to its high lignin content); its cellulose can be used in the production of cellulose whiskers or of bioethanol.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contribution by author

Teófilo Escoto García: concept and planning of the research, management and organization of the materials and chemical reagents for the development of the experiments, revision of the results and drafting of the manuscript; Nelson Beas Beas: development of the experimental part and drafting of the manuscript; Héctor Jesús Contreras Quiñones: counseling in the chemical analysis and revision of the manuscript; Antonio Rodríguez Rivas: counseling in forest management (dasometry) and the felling of specimens; Sara Gabriela Díaz Ramos: counseling in the biomass balance and botanical characterization of the species; José Anzaldo Hernández: counseling in the micrography and in the extraction of pulp to manufacture paper from the wood of the three pine species; Raúl Vega Elvira: counseling in regard to the basic chemical composition of the three pine species.