Potential Use of *Phoenix canariensis* Biomass in Binderless Particleboards at Low Temperature and Pressure

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Binderless particleboards of *P. canariensis* were manufactured by hot pressing at a low temperature (120 °C) and low pressure (2.6 MPa). Nine different configurations were analyzed to study different palm tissues. The experimental panels were tested for their mechanical and physical properties according to the procedures defined by the European Union (EN) standards. The microstructure of the raw material was investigated by scanning electron microscopy (SEM) equipped with an energy dispersive X-ray detector for microanalysis (EDXA). The physical and mechanical behavior seemed to be influenced by the amount of parenchymatous tissue. Raw material and particle size have a profound effect on the board properties. The mechanism of self-bonding could have resulted from the high content of sugars, which were partly transformed into furfural. The use of this waste material could be beneficial to the environment because it is a method of carbon fixation, helping to decrease atmospheric CO_2.

Keywords: Palm tree; Self-bonded board; SEM observations; Eco-friendly; Microstructure; Without adhesive; Plant tissue

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INTRODUCTION

Phoenix canariensis is a large palm native to the Canary Islands, Spain. It is the main indicator species of the protected habitats in the Canary Islands by the Habitats Directive of the European Union. The palms are often used in ornamental landscapes around the world and have grown spontaneously in certain areas of Mediterranean countries, as well as in California, New Zealand, *etc*. It hybridizes naturally with the *Phoenix dactylifera* (date palm), but *P. canariensis* is stronger and has bigger leaves. Historically in Spain there have been no major incidents with pathogens or pests in palms, but in recent years exotic pests have arisen as a result of the importation of palms from different countries. The most dangerous pests are the red palm weevil (*Rhynchophorus ferrugineus Oliv.*) and the moth (*Paysandisia archon Burm.*). Prophylactic measures have been implemented such as quarantines, early detection, and the removal of infected palms. This procedure creates large amounts of biomass that are currently disposed of at a dumping site, though they could be used and valorized.

Particleboards have been generated using various species of palm trees as the main material such as date palm (Nemli *et al.* 2001; Hegazy and Aref 2010; Amirou *et al.* 2013; Saadaoui *et al.* 2013; Hegazy *et al.* 2015), Washingtonia palm (García-Ortuño *et al.* 2013), and oil palm (Laemsak and Okuma 2000; Hashim *et al.* 2011a; Rasat *et al.* 2011; Suhaly *et al.* 2012; Wad Nadhari *et al.* 2013; Jumhuri *et al.* 2014; Henao *et al.* 2014; Tajuddin *et al.* 2016). The behavior of the particleboard depends on the species of palm tree and the origin of the particles from the trunk or the leaf. Current investigations in vegetal biomass aim to obtain binderless particleboards without adhesives.

Several reviews of research on binderless particleboards have been published. Recently, Pintiaux *et al.* (2015) analyzed pressure, time, and particle size for their influence on particleboards. One important factor in the manufacture of binderless particleboards is the press temperature. Binderless particleboards without pretreatments need high temperatures, and there are reduced possibilities to produce boards at temperatures below 125 °C (Suzuki *et al.* 1998; Laemsak and Okuma 2000; Pintiaux *et al.* 2015). By using higher temperatures (above 180 °C), longer time, and more pressure than in conventional panels, the mechanical properties and stability of the boards improves (Boon *et al.* 2013). However, a high press temperature is not recommended due to its energy consumption. According to Widyorini *et al.* (2005), the size and shape of the particles have an important effect on the properties of binderless particleboards. Thus, determining the range of size of the particles is a key parameter to strengthen the bonding. Another factor to consider is the moisture content. The presence of water in raw materials is crucial to the heat transfer during the hot press, and the ideal content is 8% by weight (Hidayat *et al.* 2014).

It is still difficult to clarify the self-bonding mechanism that occurs when the particles are pressed. This makes the costs of the process and the performance of the products noncompetitive (Zhang *et al.* 2015). Because the raw material has cellulose, hemicellulose, lignin, and polysaccharides, the self-bonding of natural fibers is most likely due to fusion/glass transition of the degradation of the lignin and hemicellulose, although the contribution of each component remains unknown. Alternatively, particle self-bonding could depend on the content of starch and sugars in the vegetable materials (Lamaming *et al.* 2013; Nonaka *et al.* 2013).

P. canariensis sap has been used traditionally as a natural sweetener to produce molasses and liquor. Its chemical composition is 37.8% sucrose, 9.5% glucose, and 4.8% fructose (Luis *et al.* 2012). This characteristic renders its biomass as an ideal candidate to study the self-bonding mechanism. This paper examined *P. canariensis* as a raw material to manufacture binderless particleboards at a low temperature and pressure. The influence of the size and nature of the particles was analyzed. The results were compared with other authors, and SEM observations and EDS analysis were conducted in order to elucidate which processes are involved in the bonding.

EXPERIMENTAL

Materials

The raw material was the *Phoenix canariensis* palm tree. Palm residues were obtained from the Polytechnic School of Orihuela (Universidad Miguel Hernández de Elche). They were manually cut and classified into three groups: leaves, leaf sheaths, and trunks. From the first group, the leaflets were manually removed, leaving the rachis.

After 2 months exposed to open air in order to reduce the initial moisture content of 72±11%, the pieces were cut again in a laboratory-scale ring-knife chipper to obtain the particles, which were dried again in ambient conditions for 6 months, from March to August. During this period, particles were placed in layers of 5 cm thick and were manually stirred every 2 days. The moisture reduction is shown in the Table 1, and was evaluated by following the Standard EN 322 (1993).

The particles were classified by size in a horizontal screen shaker with sieves of < 0.25 mm, 0.25 to 1 mm, and 1 to 2 mm.

Water was procured from the public water supply network.

Table 1. Moisture Content (%) of the Particles Evaluated Following the Standard EN 322 (1993)

Leaf sheath		Trunk		Rachis	
Chipped	Dried	Chipped	Dried	Chipped	Dried
55.76±1.66	8.76±0.81	54.81±0,45	7.76±0,47	53.94±0.86	7.63±0.34

Methods

Mats were formed manually in stainless steel frames with a dimension of 700 mm x 400 mm. First 2000 g of particles were added, and 60 g of water (3% in weight) was sprayed over the surface. The mats were then pressed in a hot press under 2.6 MPa of pressure at 120 °C for 30 min. No adhesives or waxes were used.

Nine types of single-layer panels were made according to the part of the palm (rachis, leaf sheath, and trunk) and the particle size. Four replicate panels were made for each board type.

Table 2. Typologies of Particleboard

Type	Material	N	Particle diameter (mm)
1	Leaf sheath	4	< 0.25
2	Leaf sheath	4	0.25 to 1
3	Leaf sheath	4	1 to 2
4	Trunk	4	< 0.25
5	Trunk	4	0.25 to 1
6	Trunk	4	1 to 2
7	Rachis	4	< 0.25
8	Rachis	4	0.25 to 1
9	Rachis	4	1 to 2

All panels had dimensions of 600 mm × 400 mm × 6.825±0.415 mm after trimming the edges to avoid imperfections. After pressing, panels were placed in a vertical position to cool. Once cooled, samples were prepared to study the mechanical and physical properties of each of the nine types of panels. Prototypes were conditioned at 20 °C and 65% relative humidity prior to testing.

Physical and Mechanical Properties

From all 4 repetitions of each type of panel, samples were cut as shown in Fig. 1: 6 samples for MOR and MOE (1T, 2T, 3T, 1=, 2=, and 3=), 6 for density (3, 5, 6, 7, 8, and 9), 3 for IB (5, 6, and 8), and 3 for TS and WA (3, 7, and 9). The samples tested for density were reused, since the test does not ruin the samples. One sample that was used for thermal conductivity (λ) was thereafter divided into 3 samples, for the reaction to fire test.

The mechanical and physical properties of the boards were evaluated following the European standards for wood-based panels, as follows: density, EN 323 (1993); thickness swelling (TS) and water absorption (WA) after 2 and 24 h immersion, EN 317 (1993); flexural strength (modulus of rupture [MOR] and modulus of elasticity [MOE], EN 310

(1997); and internal bonding strength (IB), EN 319 (1993). The panels were also classified according to EN 312 (2010).

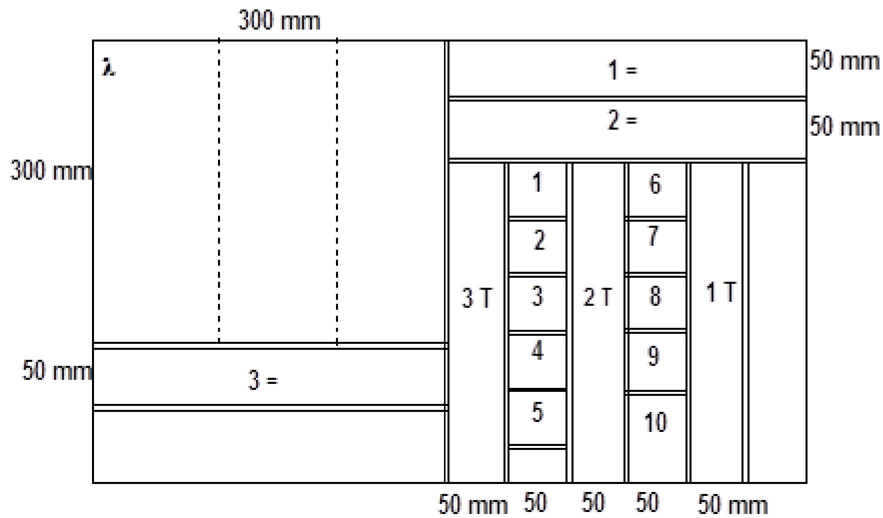

Fig. 1. Layout of the samples of the panels

Statistical Analyses

Data for each test were analyzed statistically using IBM SPSS Statistics v.22.0 software (IBM, New York, USA). From the average results, the standard deviation was obtained, and an analysis of variance (ANOVA) was conducted. Duncan test calculations ($P < 0.05$) were used to compare the differences among types.

Scanning Electron Microscopy (SEM)

The morphology of the interior of the three raw materials was evaluated using a scanning electron microscope (Hitachi S3000N, Tokyo, Japan) equipped with an X-ray detector (Bruker XFlash 3001, Billerica, MA, USA). Elemental analysis (quantitative and semi-quantitative) was conducted by energy dispersive X-ray spectroscopy (EDS). Pictures were taken from fractured cross sections of 5 mm × 5 mm.

RESULTS AND DISCUSSION

Physical Properties

The average values of the physical properties are shown in Figs. 2 and 3. Density ranged from 675.0 to 901.3 kg/m^3, demonstrating that the panels had medium density. Bigger particles are more difficult to compress, resulting in thicker panels with less density.

Thickness swelling (TS) after 2 h depended on the raw material and on the particle size, as 1 to 2 mm boards were the more affected in all cases. TS after 24 h showed the same tendency as TS after 2 h but, in this case, the results of the types with particles of < 0.25 mm and 0.25 to 1 mm increased an average of 70% compared with an average of 28% of the boards made of particles of 1 to 2 mm.

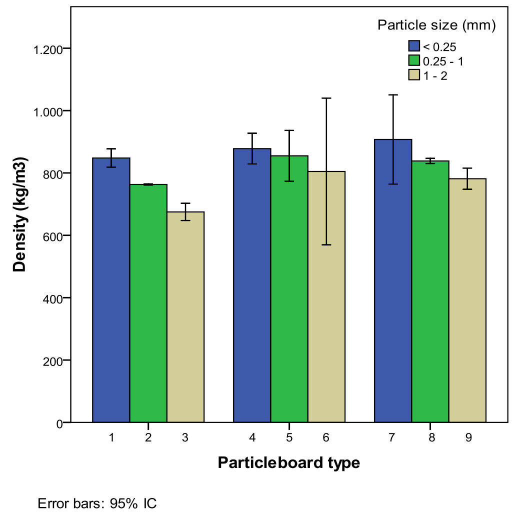

Fig. 2. Density of *P. canariensis* binderless particleboards

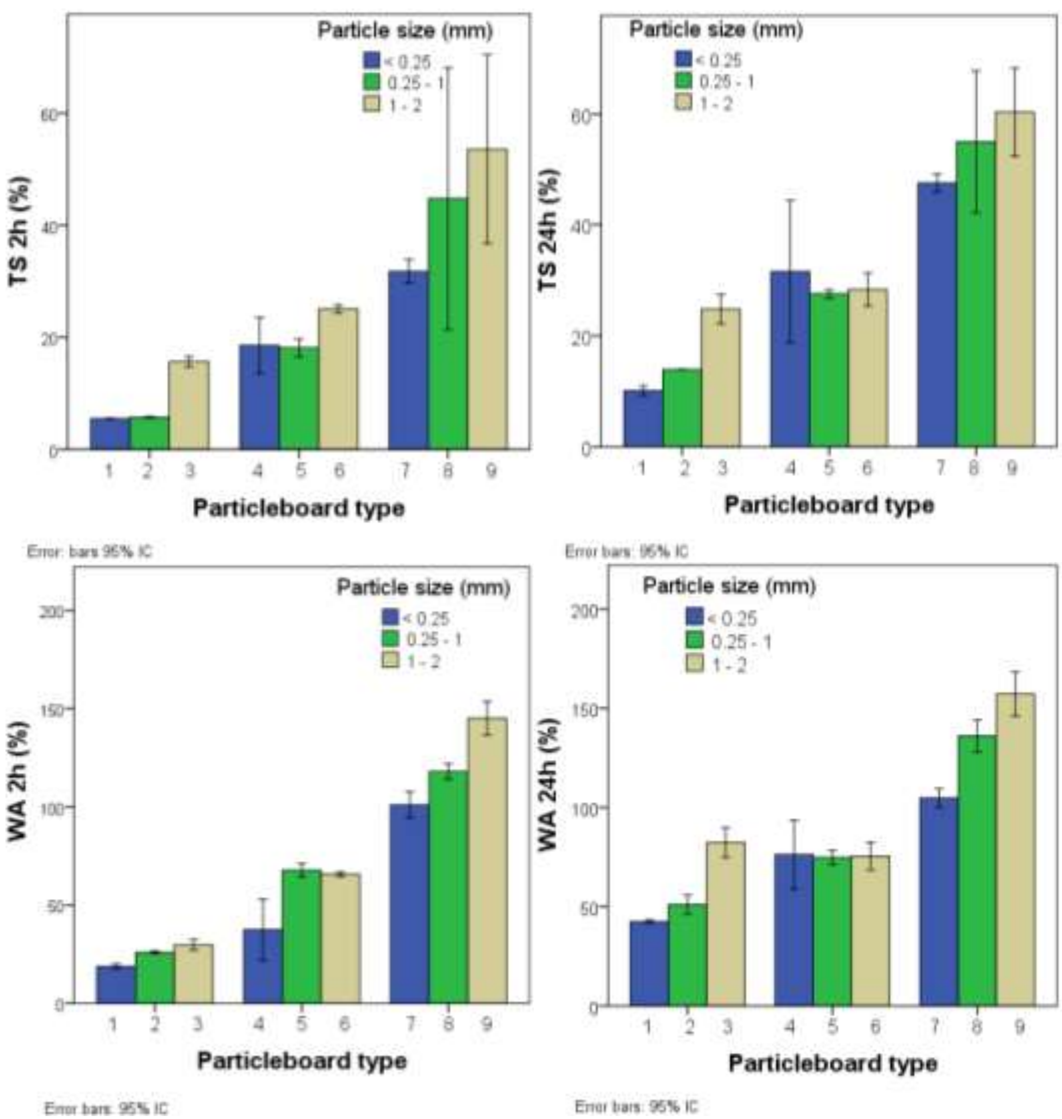

Fig. 3. Thickness swelling and WA values after 2 and 24 h for *P. canariensis* particleboards

There was a correlation between the results of TS and water absorption (WA). These results were probably caused by the porosity of the boards. Bigger particle size resulted in more porosity and less density. Once submerged, the gaps filled with water faster than the rest of the material.

In general, the physical properties of the particleboards depended on the material and particle size. Smaller particle size results in better physical behavior. The panels made of leaf sheath exhibited the lowest TS and WA followed by trunk panels and finally rachis boards.

Mechanical Properties

Flexural strength or modulus of rupture (MOR), the modulus of elasticity (MOE), and internal bonding strength (IB) test results are shown in Figs. 4, 5, and 6. The MOR values were higher in the samples made from trunk particles. This value depended on the material and particle size; poorer results were obtained with the biggest particle size for the three materials. Modulus of elasticity depended only on the raw material, reaching a maximum value of 1467.81 N/mm^2 (type 5) with particles of 0.25 to 1 mm from the trunk. Internal bonding strength test showed good results since ranged from 0.17 to 0.64 N/mm^2 and all but the type 9 panel exceeded the minimum requirement for a P1 type panel (EN 312 2010), which is 0.28 N/mm^2. This property depended on the raw material. Panels made from rachis had an average 40% lower IB compared with the others.

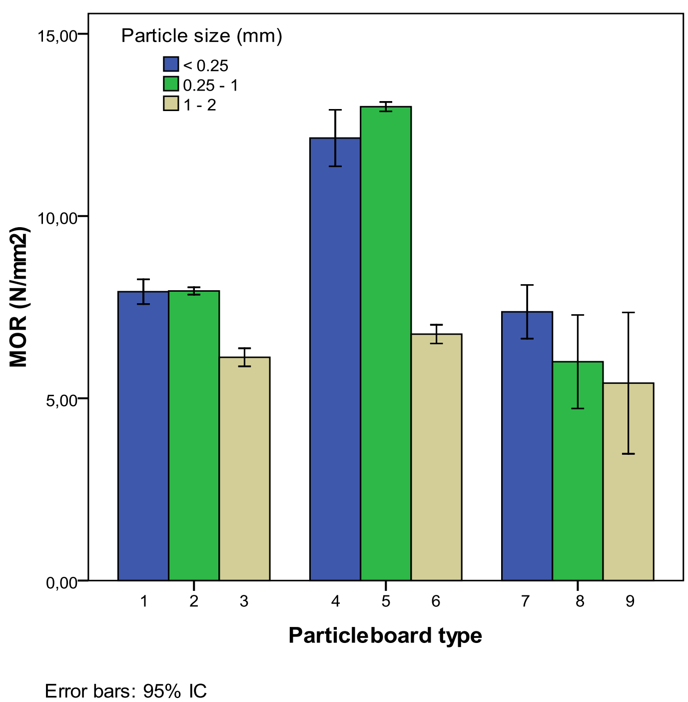

Fig. 4. Modulus of rupture values of *P. canariensis* binderless particleboards

In general, samples made from rachis had worse physical and mechanical properties with average values of TS 24h and WA 24h of 54.32 and 132.53% and average values of MOR, MOE, and IB of 6.26, 1045,92 and 0.29 N/mm^2. Samples made of leaf sheath had the best physical behavior with average values of TS 2h and WA 2h of 16.27 and 58.61%, and trunk panels had the best mechanical performance with average values of MOR, MOE and IB of 10.63, 1248.14 and 0.50 N/mm^2.

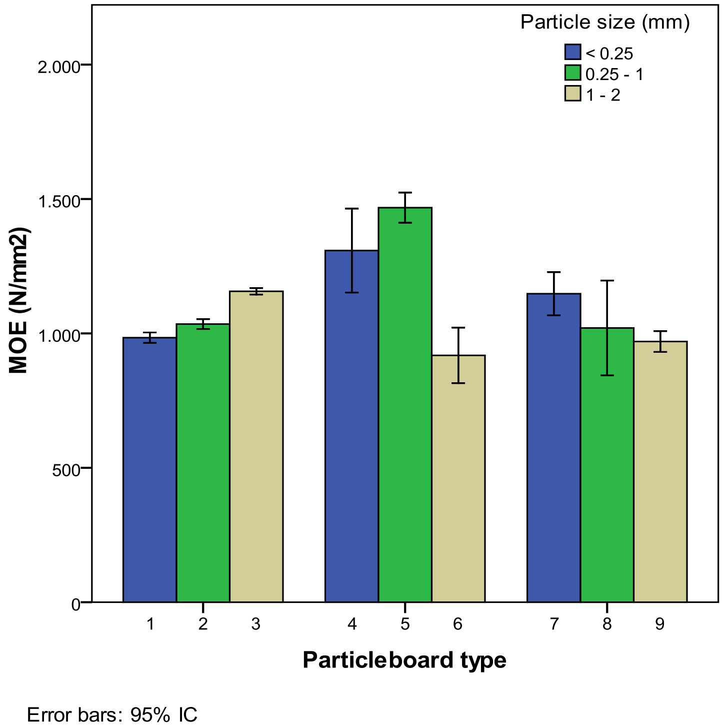

Fig. 5. Modulus of elasticity values of *P. canariensis* binderless particleboards

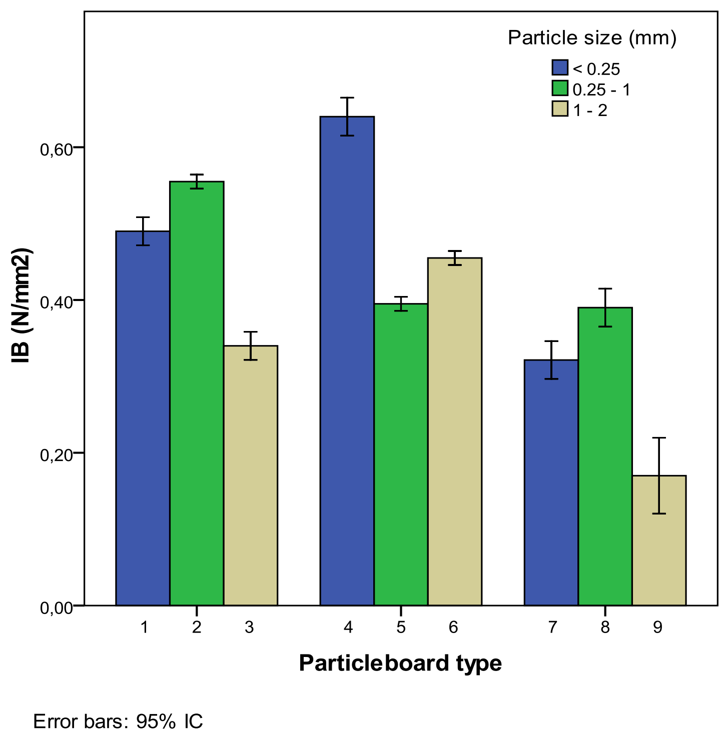

Fig. 6. Internal bonding strength values of *P. canariensis* binderless particleboards

Particle size had a profound effect on the board properties. According to EN 312 (2010), the minimum requirements for a P1 type panel (thickness from 6 to 13 mm) are a MOR value of 12.5 N/mm^2 and an IB value of 0.28 N/mm^2. There is no MOE requirement. The type 5 binderless particleboards (made from trunk of *P. canariensis* with particles of

0.25 to 1 mm) met these requirements (MOR and IB of 13.0 and 0.40 N/mm^2) and could be implemented in general applications.

Several authors have studied the properties of binderless panels made of other palm tree species. The results from these studies are compared in Tables 3 and 4.

Table 3. Processing Parameters of Binderless Particleboards Made of Palm Trees

Reference	Material	Density (kg/m^3)	Thickness (mm)	*T* (°C)	Pressure (MPa)	Time (min)	Particle size (mm)
Saadaoui *et al.* 2013	Date palm	1200	4	180	10	2	< 1.25
Hashim *et al.* 2011a	Oil palm	800	4.8	180	12	20	< 1
This study	*P. canariensis*	763.0, 838.5, 855.0	6.825	120	2.6	30	0.25 to 1

Table 4. Results of the Properties Obtained by the Authors of Table 3

Author	Material	Particle origin	TS 24 h (%)	WA 24 h (%)	MOR (N/mm^2)	MOE (N/mm^2)	IB (N/mm^2)
Saadaoui *et al.* 2013	Date palm	Leaf sheath	150	100	8.4	928	0.13
		Rachis	210	270	8.5	927	0.04
Hashim *et al.* 2011a	Oil palm	Trunk (core)	20	60	13.37		0.71
		Leaf	40	98	11.52		0.2
		Rachis	75	130	2.0		0.01
This study	*P. canariensis*	Leaf sheath	13.90	51.01	7.95	1034.80	0.56
		Trunk	27.56	74.79	13.00	1467.82	0.40
		Rachis	55.22	136.13	6.00	1020.22	0.39

Using date palm, Saadaoui *et al.* (2013) manufactured particleboards with higher temperatures and pressure, but in shorter time than the present study. In their paper, the panels obtained had higher density and TS, and lower MOR, MOE, and IB than the panels made of *P. canariensis*, which, in comparison with the present study, indicated that *P. canariensis* biomass was more suitable for producing binderless particleboards than the date palm.

The results obtained by Hashim *et al.* (2011a) with oil palm are in accordance with those reported in this study. They concluded that the self-bonding mechanism could be due to the sugars, having used high temperatures and pressure. The process used in the present study had less energy consumption. Their trunk panels showed the best results, although the bark of the palm was removed. In contrast, the *P. canariensis* trunk panels included the bark. It is possible that the removal of this spongy tissue could improve the properties of the panels, but further research must be conducted.

In another study, the addition of 20% sucrose enhanced the properties of binderless panels made of date palm (Lamaming *et al.* 2013). Apparently, sugars play a key role in the self-bonding mechanism. Because *P. canariensis* sap contains 37.8% sucrose, this mechanism could be attributed to this high amount of sugar.

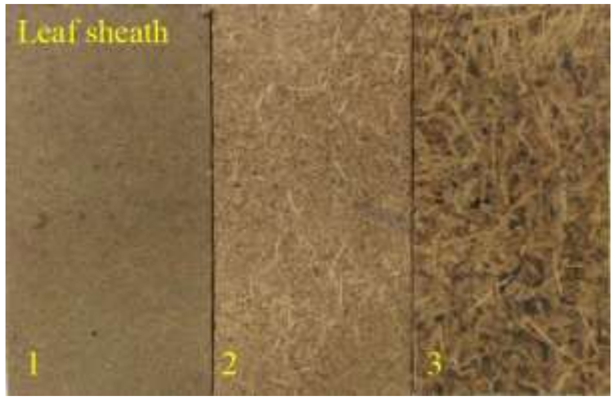

Fig. 7. Particleboards from leaf sheath of *P. canariensis* type 1 (<0.25), 2 (0.25-1), and 3 (1-2)

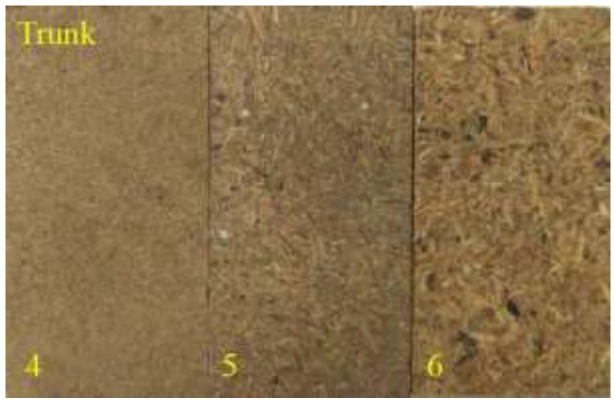

Fig. 8. Particleboards made from trunk of *P. canariensis* type 4 (<0.25), 5 (0.25-1), and 6 (1-2).

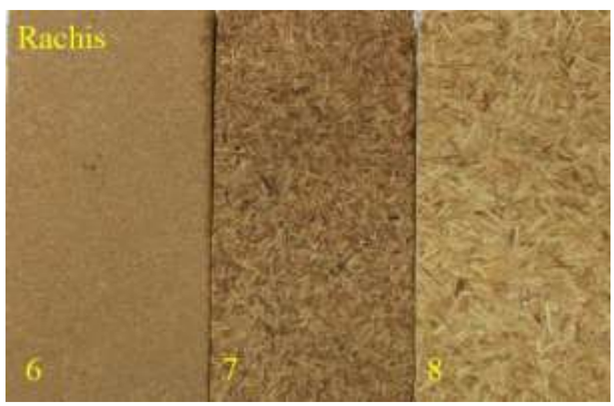

Fig. 9. Particleboards made from rachis of *P. canariensis* type 7 (<0.25), 8 (0.25-1), and 9 (1-2).

In the raw material, two types of particles were observed: slender white particles from the vascular bundles and small brown particles from the parenchymatous tissue. The physical and mechanical behavior was influenced by the amount of parenchymatous tissue, as noted by Hashim *et al.* (2011a).

As shown in Figs. 7, 8, and 9, the leaf sheath and trunk boards were darker than rachis panels, which could be explained by the higher amount of vascular bundle particles present in these parts of the palm tree.

SEM Observations and EDS Analysis

Cross section images of the leaf sheath, trunk, and rachis of *P. canariensis* are shown in Figs. 10, 11, and 12. The typical characteristics of the vascular bundles (fibers, vessels, and phloem embedded in the parenchymatous tissue) were observed, but no starch was found. The vascular bundles were covered by large amounts of siliceous phytoliths aligned in the trunk and rachis.

Similar to the particleboards, there was more parenchymatous tissue in the leaf sheath than in the rachis. As Mobarak *et al.* (1982) found in bagasse, this feature could increase the capacity of the particles to compress, resulting in a stronger bond and probably contributing to less TS in the leaf sheath and higher in the rachis particleboards.

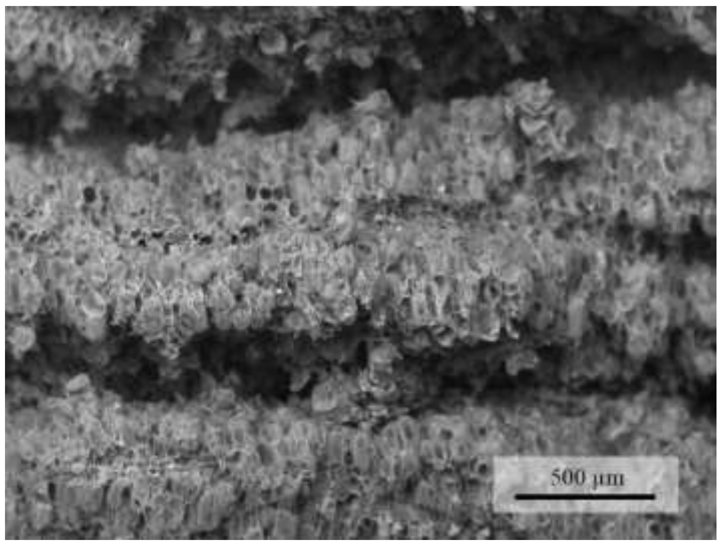

Fig. 10. Cross section micrograph of the leaf sheath

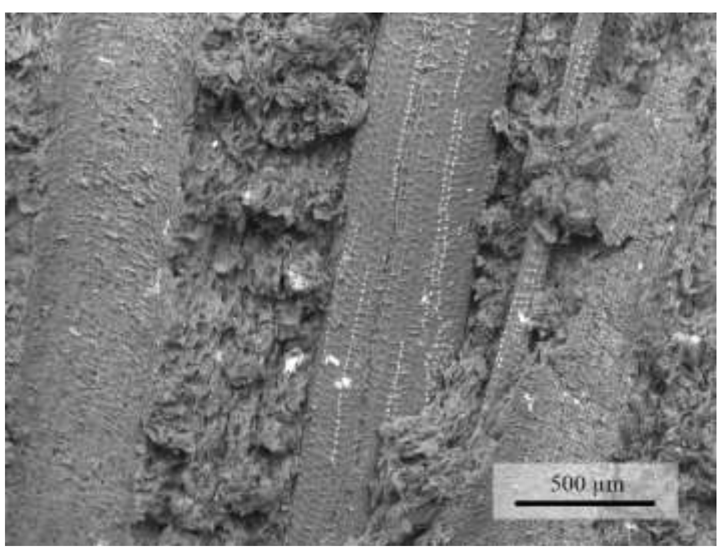

Fig. 11. Cross section micrograph of the trunk

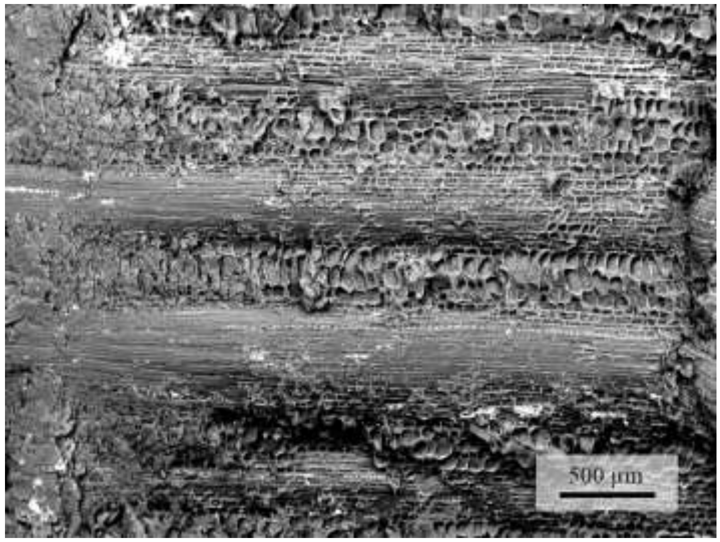

Fig. 12. Cross section micrograph of the rachis

The energy dispersive X-ray spectroscopy analysis results are shown in Table 5. The main difference in the composition of the tissues was that trunk samples had half of the amount of carbon atoms compared to the other tissues, but much more sulfur, potassium, and calcium. It is possible that these elements could have been present in oxide form because there was the same oxygen in the trunk as in the rachis and leaf sheath. Aluminum and phosphorus were found in the leaf sheath samples in tiny amounts, and there were more silicon and chlorine atoms in the rachis than in the other parts of the *P. canariensis*.

Silicon may influence the bonding (Hashim *et al.* 2011b), but this cannot be concluded from this study. Halvarsson *et al.* (2009) showed that the addition of $CaCl_2$ to wheat straw particles resulted in a 25% decrease in the WA of particleboards. In *P. canariensis*, the presence of Ca and Cl were higher in the leaf sheath and lower in the rachis, and this content could explain the TS and WA behavior of the panels.

Table 5. EDS Chemical Composition of Different Parts of the *P. canariensis*

		Leaf Sheath		Trunk		Rachis	
Element	AN	C norm.	C Atom. C	C norm.	C Atom. C	C norm.	C Atom. C
		[wt.%]	[at.%]	[wt.%]	[at.%]	[wt.%]	[at.%]
Carbon	6	51.56	60.17	22.56	32.51	49.14	57.84
Oxygen	8	43.01	37.68	50.92	55.08	45.03	39.78
Magnesium	12	0.26	0.15			0.27	0.16
Silicon	14	0.14	0.07			0.70	0.35
Sulfur	16	0.25	0.11	7.54	4.07	0.44	0.19
Chlorine	17	1.11	0.44	0.50	0.24	1.94	0.78
Potassium	19	2.61	0.94	11.12	4.92	2.47	0.89
Aluminum	13	0.22	0.12				
Phosphorus	15	0.21	0.10				
Calcium	20	0.59	0.21	7.35	3.17		

Study of the Self-bonding Mechanism

The elucidation of the self-bonding mechanism in binderless particleboards has been discussed in several reviews. One popular theory attributes the bonding to the glass transition of cellulose, hemicellulose, and lignin. Anglés *et al.* (1999) reported that the values of the glass transition temperature of these biopolymers are, in dry state, 220 °C, 170 °C, and 200 °C, respectively. Pintiaux *et al.* (2015) reported that this process is extremely dependent on the moisture content. According to this analysis, the glass transition temperatures decrease as the moisture content increases. In this paper, panels were made at 120 °C and 11% of total moisture content (an initial 8% of the particles and the 3% of water sprayed before pressed), thus it was feasible that some carbohydrates reached the temperature of glass transition and helped in the self-bonding.

Another suggested mechanism of self-bonding is the hydrolysis of sugars. By pressing and heating the particles in an acid aqueous media, some of the sugars could have been transformed into furfural, which then would solidify into a thermosetting resin. Peleteiro *et al*. (2016) showed that furfural could be obtained from different lignocellulosic materials at temperatures that are in accordance to the present paper. In another study, Suzuki *et al.* (1998) stated that the steam explosion of oil palm particles produced furfural, and the self-bonding was attributed to the link of lignin-furfural.

CONCLUSIONS

1. It is feasible to manufacture binderless particleboards of *P. canariensis* at a low temperature (120 °C) and pressure (2.6 MPa).
2. The best performance in terms of mechanical properties was obtained by using trunk particles from 0.25 to 1 mm. They exceeded the MOR, MOE, and IB values for the P1 grade (EN 312 2010).
3. Raw material and particle size have a profound effect on the board properties.
4. The mechanism of self-bonding could be due to the high content of sugars. At the pressing temperature of 120 °C, some of the sugars could have been transformed into furfural, enhancing the bond.

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REFERENCES CITED

Amirou, S., Zerizer, A., Pizzi, A., Haddadou, I., and Zhou, X. (2013). “Particleboards production from date palm biomass,” *European Journal of Wood and Wood Products* 71(6), 717-723. DOI: 10.1007/s00107-013-0730-3

Anglès, M. N., Reguant, J., Montané, D., Ferrando, F., Farriol, X., and Salvadó, J. (1999). “Binderless composites from pretreated residual softwood,” *Journal of*

Applied Polymer Science 73(12), 2485-91. DOI: 10.1002/(SICI)1097-4628(19990919)73:12<2485::AID-APP17>3.0.CO;2-G

Boon, J. G., Hashim, R., Sulaiman, O., Hiziroglu, S., Sugimoto, T., and Sato, M. (2013). "Influence of processing parameters on some properties of oil palm trunk binderless particleboard," *European Journal of Wood and Wood Products* 71(5), 583-589. DOI: 10.1007/s00107-013-0712-5

EN 310 (1993). "Wood-based panels. Determination of modulus of elasticity in bending and of bending strength," European Commission for Standardization, Brussels, Belgium.

EN 312 (2010). "Particleboards–Specifications," European Commission for Standardization, Brussels, Belgium.

EN 317 (1993). "Particleboards and fibreboards. Determination of swelling in thickness after inmersion in water," European Commission for Standardization, Brussels, Belgium.

EN 319 (1993). "Particleboards and fibreboards. Determination of tensile strength perpendicular to the plane of de board," European Commission for Standardization, Brussels, Belgium.

EN 322 (1993). "Wood-based panels. Determination of moisture content," European Commission for Standardization, Brussels, Belgium.

EN 323 (1993). "Wood-based panels. Determination of density," European Commission for Standardization, Brussels, Belgium.

García-Ortuño, T., Andreu-Rodríguez, J., Ferrández-García, M. T., Ferrández-García, C. E., Medina, E., Parades, C., Perez-Murcia, M. D., and Moreno-Caselles, J. (2013). "Evaluation of the different uses of *Washingtonia robusta* pruning waste," *Communications in Soil Science and Plant Analysis* 44(1-4), 623-631. DOI: 10.1080/00103624.2013.745371

Halvarsson, S., Edlund, H., and Norgren, M. (2009). "Manufacture of non-resin wheat straw fibreboards," *Industrial Crops and Products* 29(2-3), 437-445. DOI: 10.1016/j.indcrop. 2008.08.007

Hashim, R., Said, N., Lamaming, J., Baskaran, M., Sulaiman, O., Sato, M., Hiziroglu, S., and Sugimoto, T. (2011b). "Influence of press temperature on the properties of binderless particleboard made from oil palm trunk," *Materials and Design* 32(5), 2520-2525. DOI: 10.1016/j.matdes.2011.01.053

Hashim, R., Wan Nadhari, W. N. A., Sulaiman, O., Kawamura, F., Hiziroglu, S., Sato, M., Sugimoto, T., Seng, T. G., and Tanaka, R. (2011a). "Characterization of raw materials and manufactured binderless particleboard from oil palm biomass," *Materials and Design* 32(1), 246-254. DOI: 10.1016/j.matdes.2010.05.059

Hegazy, S. S., and Aref, I. M. (2010). "Suitability of some fast-growing trees and date palm fronds particleboard productions," *Forest Products Journal* 60(7-8) 599-604. DOI: 10.13073/0015-7473-60.7.599

Hegazy, S., Ahmed, K., and Hiziroglu, S. (2015). "Oriented strand board production from water-treated date palm fronds," *BioResources* 10(1), 448-456. DOI: 10.15376/biores. 10.1.448-456

Henao, E. M., Quintana, G. C., and Ogunsile, B. O. (2014). "Development of binderless fiberboards from steam-exploded and oxidized oil palm wastes," *BioResources* 9(2), 2922-2936. DOI: 10.15376/biores.9.2.2922-2936

Hidayat, H., Keijsers, E. R. P., Prijanto, U., Van Dam, J., and Heeres, H. (2014). "Preparation and properties of binderless boards from *Jatrophacurcas* L. seed cake,"

Industrial Crops and Products 52, 245-254. DOI: 10.1016/j.indcrop.2013.10.024
Jumhuri, N., Hashim, R., Sulaiman, O., Wan Nadhari, W. N. A., Salleh, K. M., Saharudin, N. I., and Razali, M. Z. (2014). "Effect of treated particles on the properties of particleboard made from oil palm trunk," *Materials and Design* 64, 769-774. DOI: 10.1016/j.matdes.2014.08.053
Laemsak, N., and Okuma, M. (2000). "Development of boards made from oil palm frond II: properties of binderless boards from steam-exploded fibers of oil palm frond," *Journal of Wood Science* 46, 322-326. DOI: 10.1007/BF00766224
Lamaming, J., Sulaiman, O., Sugimoto, T., Hashim, R., Said, N., and Sato, M. (2013). "Influence of chemical components of oil palm on properties of binderless particleboard," *BioResources* 8(3), 3358-3371. DOI: 10.15376/biores.8.3.3358-3371
Luis, G., Rubio, C., Gutiérrez, A. J., Hernández, C., González-Weller, D., Revert, C., Castilla, A., Abreu, P., and Hardisson, A. (2012). "Miel de palma: Composición nutricional de un edulcorante natural," *Nutrición Hospitalaria* 27(2), 548-552.
Mobarak, F., Fahmy, Y., and Augustin, H. (1982). "Binderless lignocellulose composite from bagasse and mechanism of self-bonding," *Holzforschung* 36(3), 131-135. DOI: 10.1515/hfsg.1982.36.3.131
Nemli, G., Kalaycioglu, H., and Alp, T. (2001). "Suitability of date palm (*Phoenix dactylifera*) branches for particleboard production," *Holz als Roh- Werkst* 59(6), 411-412. DOI: 10.1007/s00107-001-0257-x
Nonaka, S., Umemura, K., and Kawai, S. (2013). "Characterization of bagasse binderless particleboard manufactured in high-temperature range," *Journal of Wood Science* 59(1), 50-56. DOI: 10.1007/s10086-012-1302-6
Peleteiro, S., Rivas, S., Alonso, J. L., Santos, V., and Parajó, J. C. (2016). "Furfural production using ionic liquids: A review," *Bioresource Technology* 202, 181-191. DOI: 10.1016/j.biortech.2015.12.017
Pintiaux, T., Viet, D., Vandenbossche, V., Rigal, L., and Rouilly, A. (2015). "Binderless materials obtained by thermo-compressive processing of lignocellulosic fibers: A comprehensive review," *BioResources* 10(1), 1915-1963. DOI: 10.15376/biores.10.1.1915-1963
Rasat, M. S. M., Wahab, R., Sulaiman, O., Moktar, J., Mohamed, A., Tabet, T. A., and Khalid, I. (2011). "Properties of composite boards from oil palm frond agricultural waste," *BioResources* 6(4), 4389-4403. DOI: 10.15376/biores.6.4.4389-4403
Saadaoui, N., Rouilly, A., Fares, K., and Rigal, L. (2013). "Characterization of date palm lignocellulosic by-products and self-bonded composite materials obtained thereof," *Materials and Design* 50, 302-308. DOI: 10.1016/j.matdes.2013.03.011
Suhaily, S. S., Jawaid, M., Abdul Khalil, H. P. S., Mohamed, A. R., and Ibrahim, F. (2012). "A review of oil palm biocomposites for furniture design and applications: potential and challenges," *BioResources* 7(3), 4400-4423. DOI: 10.15376/biores.7.3.4400-4423
Suzuki, S., Shintani, H., Park, S. Y., Saito, K., Laemsak, N., Okuma, M., and Iiyama, K. (1998). "Preparation of binderless boards from steam exploded pulps of oil palm (*Elaeis guineensis* Jaxq.) fronds and structural characteristics of lignin and wall polysaccharides in steam exploded pulps to be discussed for self-bindings," *Holzforschung* 52(4), 417-426. DOI: 10.1515/hfsg.1998.52.4.417
Tajuddin, M., Ahmad, Z., and Ismail, H. (2016). "A review of natural fibers and processing operations for the production of binderless boards," *BioResources* 11(2), 5600-5617. DOI: 10.15376/biores.11.2.5600-5617

Wad Nadhari, W. N. A., Hashim, R., Sulaiman, O., Sato, M., Sugimoto, T., and Selamat, M. E. (2013). "Utilization of oil palm trunk waste for manufacturing of binderless particleboard: optimization study," *BioResources* 8(2), 1675-1696. DOI: 10.15376/biores.8.2.1675-1696

Widyorini, R., Xu, J., Umemura, K., and Kawai, S. (2005). "Manufacture and properties of binderless particleboard from bagasse. I: effects of raw material type, storage methods, and manufacturing process," *Journal of Wood Science* 51(6), 648. DOI: 10.1007/s10086-005-0713-z

Zhang, D., Zhang, A., and Xue, L. (2015). "A review of preparation of binderless fiberboards and its self-bonding mechanism," *Wood Science and Technology* 49(4), 661-679. DOI: 10.1007/s00226-015-0728-6

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