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Physical and Mechanical Properties of Particleboard Made from Palm Tree Prunings

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Abstract: Palm trees are very fast-growing species. Their management produces annually a large amount of biomass that traditionally has been either disposed of at dumping sites or has been burnt onsite. This paper presents an experimental study to obtain particleboard using this biomass in a low energy process (short pressing time and low pressing temperature), using particles of different sizes from the rachis (midrib) of the three palm species most representative of urban gardening in Spain: canary palm (*Phoenix canariensis* hort. ex Chabaud), date palm (*Phoenix dactylifera* L.) and washingtonia palm (*Washingtonia robusta* H. Wendl). Their physical and mechanical properties were tested, and the feasibility of their use as a construction material was evaluated. The results showed that the manufactured particleboard had similar performance to conventional wood particleboard and good thermal insulation properties. Boards made with the canary species showed better mechanical performance. The properties of the particleboard depended on the particle size and species. The use of the pruning waste of palm trees to produce durable materials such as particleboard could be beneficial to the environment since it is a method of carbon fixation, helping to decrease atmospheric pollution and reducing the amount of waste that ends in dumping sites.

Keywords: thermal conductivity; palm rachis; biomass; hot pressing; *Phoenix canariensis*; *Phoenix dactylifera*; *Washingtonia robusta*

1. Introduction

Climate change is a real long-term problem that requires a multidisciplinary global approach. One of the proposed strategies for responding to this issue is mitigation, understood as actions to limit the emission of greenhouse gases by capturing and storing atmospheric carbon dioxide (CO_2) in sinks such as forests [1]. The appropriate management of carbon sinks is needed in order to conserve and expand their size in a socio-economically sustainable manner. One manner of storing carbon is by transforming the biomass produced within forests into wood-based products. A few studies have been performed to assess the carbon flux through the life cycle of wood panels: Wang et al. [2] conducted a study to assess the contribution of the wood-based panels to CO_2 emissions and removal in different panels in China. They estimated the CO_2 emissions through panel production and the CO_2 stored during their useful lives, concluding that the wood-based industry can potentially contribute to climate change mitigation. Rivela et al. [3] studied the life cycle of particleboard and created a database to identify and characterize the manufacture of particleboard. They reported that environmental, economic and social considerations strengthened the hypothesis that the use of forest residues in particleboard manufacture is more sustainable than their use as fuel.

In the south-east of Spain, palm trees are extensively used in urban landscaping, as in most of the countries surrounding the Mediterranean Sea. Among the different species, the most abundant are: *Phoenix dactylifera* L. (hereafter called date palm), *Phoenix canariensis* hort. ex Chabaud (canary palm), and *Washingtonia robusta* H. Wendl (washingtonia palm). Apart from their ornamental use, the date palm can also be found in groves in the Alicante province, in two cities (Elche and Orihuela) forming a unique forest ecosystem.

Some palm species can live from 150 to 300 hundred years. As part of their management, they are pruned to remove old leaves (fronds) and inflorescences at least once a year, producing a large amount of biomass that has traditionally been disposed of either at dumping sites or has been burnt onsite.

Palm trees are a very fast-growing species. Their management produces an annual average dry mass of 49.34 kg/tree from *Phoenix canariensis* [4], 72.26 kg/tree from *Phoenix dactylifera* [4], and 35.70 kg/tree from *Washingtonia robusta* [5]. This biomass is classified as urban waste according to the European list of waste [6]. Several studies have been conducted focusing on the manufacturing of building materials using different palm residues. Particleboard with synthetic adhesives and different manufacturing procedures have been studied using fibers or chips of date palm [7–15], washingtonia palm [5,16–18], and canary palm [19–21]. Other studies have been performed using date palm pruning waste as a reinforcement in concrete [22–24], in gypsum [25], and in the manufacturing of different composites [25–27]. Most of these works were aimed at the use of palm pruning waste to produce thermal insulating materials [18,21,22,25,28–30]. These investigations showed different results depending on the palm species and the part of the plant used (generally the leaves or trunk). The particle size and production parameters can also affect the physical and mechanical properties of the resulting materials.

Particleboard is made by applying pressure and heat to particles of wood or other lignocellulosic biomass with the addition of an adhesive. The temperature in the hot press varies with the type of adhesive employed. For urea–formaldehyde (UF) the hardening occurs at 90 °C, but to shorten this process, temperatures over 200 °C are employed. Times of 3 to 4 min for a 20 mm thick particleboard are required when using UF at 180 °C. The majority of the world's production of particleboard is made of wood with densities ranging from 0.60 to 0.80 g/cm^3. Most of these are three-layered, with outer layers made of finer particles and a central section composed of coarser and cheaper chips, which improves the strength, stiffness, and appearance. In general, 9% and 12% of UF is needed to bond the particles of the core and the particles of the outer layers, respectively [31]. Although it is possible to manufacture particleboard from almost all types of wood, those with a specific weight smaller than 0.60 g/cm^3 are more suitable, since denser woods present difficulties when cutting [31]. The utilization of hard wood causes wear to chippers and other tools and requires higher pressures at the hot press [32]. However, the use of soft woods results in lower strength [33].

Several authors have studied the influence of different manufacturing parameters for particleboard. Of these parameters, Nemli et al. [34] studied the humidity of the mat, the amount of resin, the addition of wood powder, and the pressing time. Boonstra et al. [35] studied steam pretreatments at 200 °C and 210 °C. Han et al. [36] studied the press speed and the humidity of the raw material. Abdalla et al. [37] studied the density of the boards. Blanchet et al. [38] studied the amount of wood particles and UF (12%, 14% and 16%) in the outer layers (12%, 14% and 16%) and in the core (8%). Ashori et al. [9] studied the amount of UF (9%, 10% and 16%) in single-layer particleboards with 4, 5 and 6 min in the hot press, respectively. Wang et al. [39] studied the different adhesives in the board industry and their optimization. Current investigations are aimed at obtaining a new generation of biocomposites with a wide range of materials, such as plastics, plaster, cement, metal, glass and lignocellulosic residues.

The aim of this study was to obtain particleboard using a low energy process (short pressing time and low pressing temperature), using particles of different sizes from the rachis (midrib) (Figure 1) of the three most representative palm species in urban gardening in Spain. Their physical and mechanical properties were tested, and the feasibility of their use as a construction material was evaluated.

Figure 1. Frond and rachis of a palm tree.

2. Materials and Methods

The raw material used was the rachis of the fronds of three different palm species—date, canary, and washingtonia palm—that were kindly supplied by the municipality of the San Anton palm grove in Orihuela, Alicante (Spain). These rachises were obtained by trimming the leaflets from the fronds. They had an initial moisture content of 73% and were air dried for 8 months to an approximate moisture content of 8%. Particles were obtained using a laboratory-scale ring-knife chipper, after which they were sieved using a horizontal screen shaker with sieves of 8, 4, 2, 1 and 0.25 mm to remove oversize and undersize (dust) particles. A combination of the fractions retained on each sieve was used for the panel manufacture: 0.25 to 1 mm, 1 to 2 mm and 2 to 4 mm.

The particleboard manufacturing method applied was the conventional dry process used in the industry. Particles were mixed by injection with 8% UF with a 65% solid content in a resin blender for 5 min. The mixture was placed into iron molds measuring 600 × 400 mm to form the mat. The amount of material used was variable since the thickness of the panels was fixed to 10 mm. Mats were then pressed in a hot plate press under 2.6 MPa of pressure for 5 min at 130 °C. A total of 9 types of particleboard (Figure 2) were made using three different particle sizes from the 3 different palm species studied. Five replicate panels were made for each type; therefore, a total of 45 particleboards were produced.

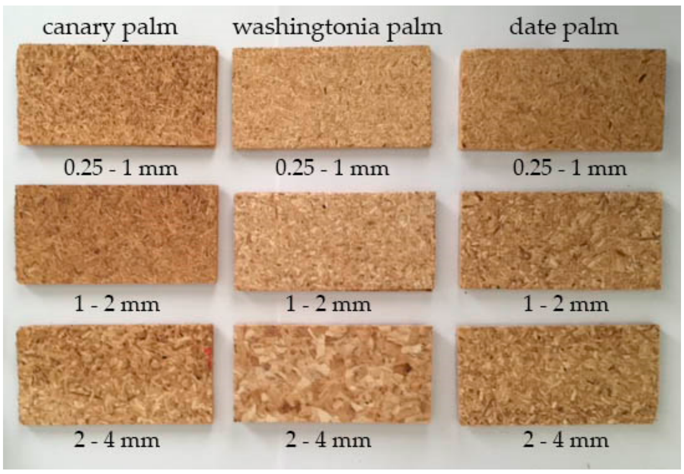


Figure 2. Particleboards made with rachises of different palm species.

After pressing, the particleboards were conditioned at 20 °C and 65% relative humidity for one week in a vertical position. The finished particleboards were trimmed to avoid edge effects to a final size of 600 mm × 400 mm × 10 mm, and then cut into various sizes for property evaluation according to EN 326-1:1994 [40] (Figure 3).

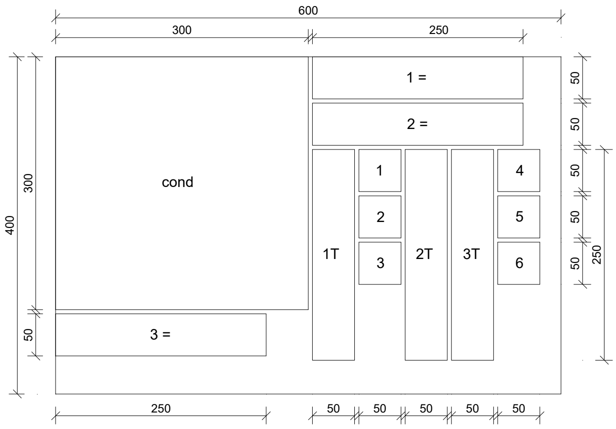


Figure 3. Cutting scheme of particleboards.

Some physical properties were determined in accordance with appropriate EN standards for wood products: density [41], water absorption (WA), thickness swelling (TS) after 2 and 24 h of water immersion [42] and the thermal conductivity was measured following the heat flow meter method [43]. The mechanical properties determined were the modulus of rupture (MOR) and modulus of elasticity (MOE) [44], and internal bond strength (IB) [45]. Each panel was cut to obtain six density samples (50 mm × 50 mm), three WA/TS samples (50 mm × 50 mm), six MOR/MOE samples (different lengths, depending on the thickness, ×50 mm width), and three IB samples (50 mm × 50 mm). Table 1 shows the relation between the samples and the properties tested. The tests for the mechanical properties, WA, TS, and density were conducted on an Imal universal testing machine (Model IB600, Modena, Italy). Samples of 300 × 300 mm were used to test the thermal conductivity using a heat flow meter (Model HFM 436/3/0, NETZSCH Gerätebau GmbH, Selb, Germany).

Table 1. Name of the samples and tests conducted.

Property	Name of the Samples	Number of Samples	Dimensions (mm)
Density	1, 2, 3, 4, 5, 6	6	50 × 50
TS, WA	2, 4, 5	3	50 × 50
MOR, MOE	1=, 2=, 3=, 1T, 2T, 3T	6	250 × 50
IB	1, 3, 6	3	50 × 50
Conductivity	cond	1	300 × 300

Particleboards were classified in accordance with the European standard [46] considering the requirements for wood particleboard with a thickness range of 6–13 mm.

The results were analyzed using the IBM SPSS v.24.0 software (Amonk, NY, USA). Average values and the standard deviation of the properties of the panels were obtained to determine the variability. One-way analysis of variance was conducted to identify the influence between the manufactured process (material and particle size) and the properties of the particleboard.

3. Results

3.1. Physical Properties

The experimental particleboard can be considered to be of medium density (Table 2). The average values obtained were 841.55 kg/m^3 with canary, 813.20 kg/m^3 with washingtonia and 797.38 kg/m^3

with date palm rachis. The boards with the highest density were achieved with the smallest particle size (0.25–1 mm) for the three species. There was no significant deviation in the thickness of the panels since this was a fixed variable of the manufacturing process.

Table 2. Average values of the physical properties of the palm rachis particleboard.

Material	Particle (mm)	Thickness (mm)	Density (kg/m^3)	TS 2 h (%)	TS 24 h (%)	WA 2 h (%)	WA 24 h (%)
Canary	0.25–1	10.42 (0.24)	856.37 (28.67)	37.83 (5.60)	49.74 (8.11)	72.14 (5.49)	85.91 (8.12)
Canary	1–2	10.63 (0.38)	840.31 (17.54)	25.22 (2.65)	38.21 (2.46)	54.31 (3.90)	71.56 (4.64)
Canary	2–4	10.68 (0.10)	818.95 (7.54)	32.11 (2.09)	39.44 (2.43)	59.43 (3.26)	71.15 (4.52)
Washingtonia	0.25–1	10.53 (0.31)	878.25 (47.17)	31.35 (7.94)	39.95 (9.93)	63,43 (9.94)	77.29 (12.52)
Washingtonia	1–2	10.61 (0.97)	815.32 (41.22)	29.86 (6.46)	38.33 (5.86)	59.86 (9.90)	79.43 (14.02)
Washingtonia	2–4	10.57 (0.55)	746.30 (35.80)	26.65 (4.40)	38.90 (5.84)	61.35 (8.64)	72.72 (11.83)
Date	0.25–1	10.48 (0.35)	841.73 (32.01)	25.51 (1.79)	31.96 (4.79)	61.90 (9.96)	82.78 (6.59)
Date	1–2	10.68 (0.51)	765.49 (23.24)	23.57 (2.61)	33.03 (3.83)	62.62 (4.73)	74.91 (8.89)
Date	2–4	10.26 (0.25)	784.92 (25.56)	19.99 (3.93)	34.09 (4.91)	47.84 (2.51)	61.26 (8.41)

( ) Standard deviation. TS: Thickness swelling after 2 and 24 h of water immersion. WA: Water absorption after 2 and 24 h of water immersion.

The TS average values after 2 h of water immersion ranged from 19.99 to 37.83%; after 24 h they ranged from 31.96 to 49.74% (Figure 4). The date palm particleboard showed the lowest TS results, while the canary palm particleboards showed the highest TS results. As can be observed in Figure 4a, the TS value did not depend on the particle size.

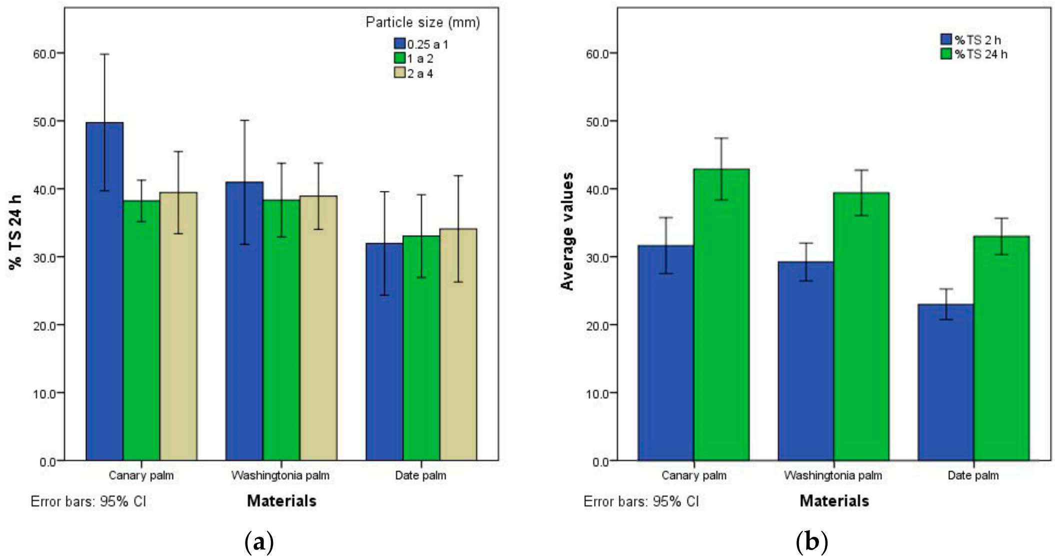
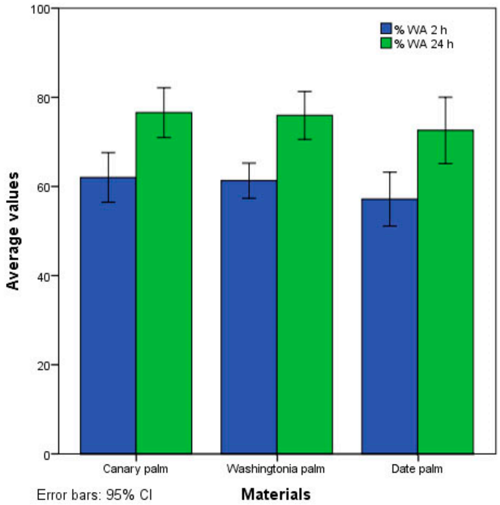
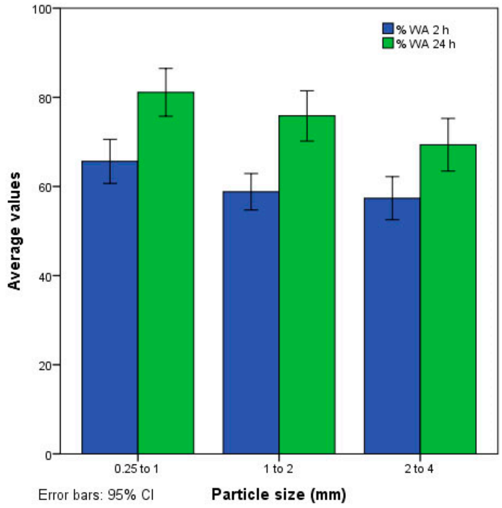


Figure 4. (**a**) Average TS values after 24 h of water immersion according to the palm species and particle size (**b**) Average TS values after 2 and 24 h according to palm species.

The average WA results after 2 h of water immersion ranged from 47.48 to 72.14%, and after 24 h from 61.26 to 85.91% (Figure 5). Particleboards manufactured with smaller particles (0.25 to 1 mm) absorbed a larger amount of water and had greater TS values.



(**a**)



(**b**)

Figure 5. (**a**) Average WA values after 2 and 24 h of water immersion according to palm species. (**b**) Average WA values after 2 and 24 h of water immersion according to particle size.

3.2. Mechanical Properties

Canary palm particleboards had an average MOR performance of 13.97, 19.85, and 12.68 N/mm^2 from the smaller to bigger particle size respectively The MOR achieved by the washingtonia palm particleboards was 16.95, 12.40, and 7.38 N/mm^2. The date palm boards had the lowest MOR values with 13.51, 10.76, and 7.85 N/mm^2 (Table 3). The highest MOR value was obtained with canary palm, with 1–2 mm of particle size. The MOE showed the same tendency as the MOR, and was higher for the canary palm boards and lower for the date palm panels. The IB values ranged from 0.72 to 0.99 N/mm^2, with the canary palm boards having the lowest values.

Table 3. Average mechanical properties of particleboards from different palm rachis species.

Material	Particle (mm)	MOR (N/mm^2)	MOE (N/mm^2)	IB (N/mm^2)
Canary	0.25–1	13.97 (0.45)	1567.16 (49.12)	0.75 (0.07)
Canary	1–2	19.85 (0.74)	2018.63 (106.11)	0.97 (0.12)
Canary	2–4	12.68 (0.41)	1373.56 (87.24)	0.72 (0.06)
Washingtonia	0.25–1	16.95 (1.52)	1526.40 (161.00)	0.95 (0.15)
Washingtonia	1–2	12.40 (1.07)	1208.22 (139.39)	0.97 (0.15)
Washingtonia	2–4	7.38 (0.34)	662.98 (49.40)	0.99 (0.13)
Date	0.25–1	13.51 (0.80)	1263.07 (59.93)	0.93 (0.07)
Date	1–2	10.76 (1.07)	988.14 (63.73)	0.98 (0.06)
Date	2–4	7.85 (0.32)	694.96 (45.01)	0.91 (0.07)
P1 [46]		10.5	-	0.28
P2 [46]		11	1800	0.40
P3 [46]		15	2050	0.45
P4 [46]		16	2300	0.40

( ) Standard deviation. MOR: Modulus of rupture. MOE: Modulus of elasticity. IB: Internal bond. Pn. Standard reference values [46].

European standards classify wood particleboard according to its physical and mechanical properties [46], starting with the P1 grade for general indoor uses, to the P7 grade for structural uses.

All three types of particleboard made of canary palm particles exceeded the requirements for grade P1 or higher (Figure 6). Panels made with washingtonia and date palm with particle sizes of 0.25–1 and 1–2 mm could be classified as grade P1. Boards made with canary palm with a particle size of 1–2 mm reached the grade P2. Washingtonia and date palm boards made with a particle size of 0.25–1 mm met the minimum values of MOR and IB of P2 but not the required MOE value. None of the particleboards achieved the grade P3, which requires a minimum MOE value of 2050 N/mm^2.

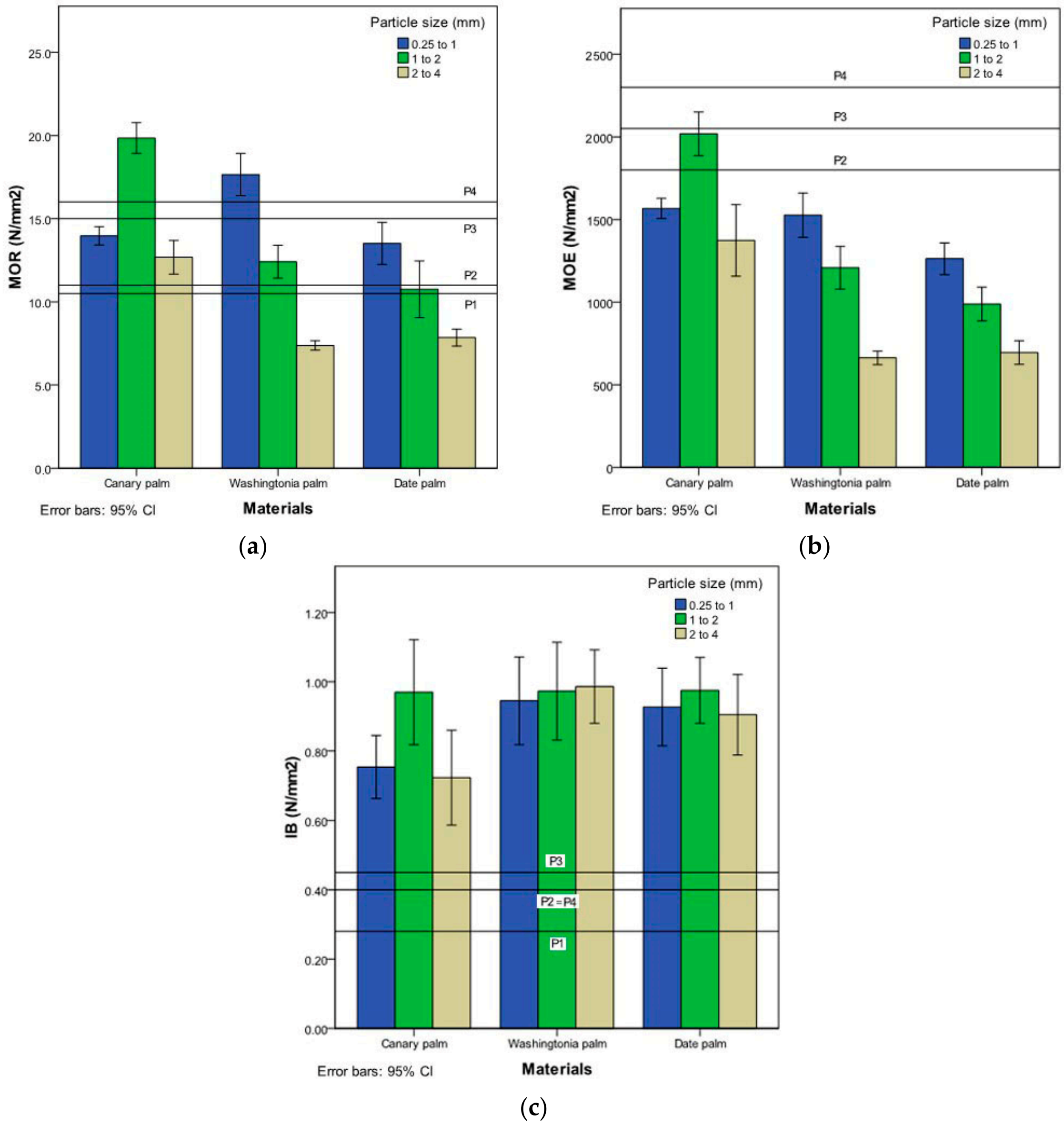


Figure 6. (**a**) MOR. (**b**) MOE (**c**) IB according to palm species and particle size and compared to the European standards (black horizontal lines) [46].

3.3. Thermal Conductivity

The average values of thermal conductivity ranged from 0.053 to 0.061 W/mK (Figure 7). No significant dependence was observed between the particle sizes or palm species with thermal conductivity (Figure 8).

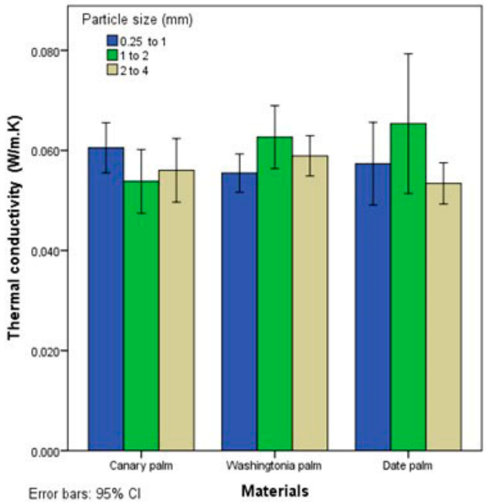


Figure 7. Average thermal conductivity results according to the palm species and particle size.

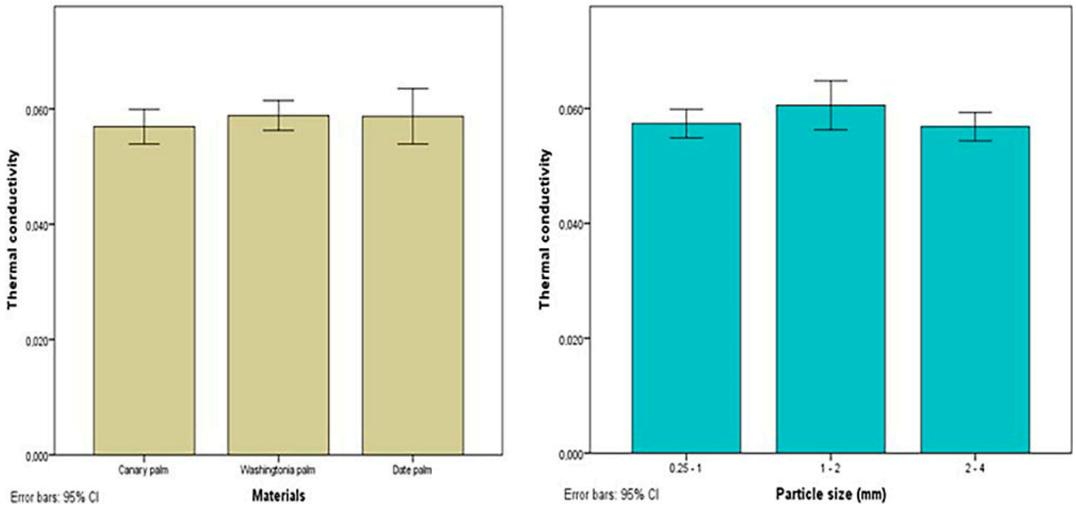


Figure 8. (**a**) Average thermal conductivity results according to the palm species. (**b**) Average thermal conductivity results according to the particle size.

4. Discussion

Several authors have obtained particleboards made of palm rachis with an adhesive following a similar manufacturing process (Table 4). Nemli et al. [8] manufactured boards from date palm using 33% of UF and applying 150 °C for 5 min in a hot press. They obtained boards with a density of 650 kg/m^3, a good MOR, and a low TS due to the high amount of adhesive used. The boards obtained by Ashori and Nourbakhsh [9] achieved a lower MOR and a higher density than the latter when using 9% of UF at 160 °C, but they accomplished better mechanical properties by increasing the amount of UF to 11%. Amirou et al. [13] studied the mechanical properties of boards from date palm manufactured at a higher temperature and pressing time (195 °C and 7.5 min), and 10% of PF. Their results showed a large increase in MOE, satisfactory values of MOR and IB, and a low TS value, probably due to the nature of the curing resin. Hegazy and Ahmed and Hegazi et al. [14,15] studied the influence of density on the strength of panels produced with date palm fibers at 140 °C for 10 min and 160 °C for 8 min with the same resin dose. Better strength (MOR, MOE and IB) was achieved in both cases with higher densities. In addition, the mechanical properties achieved were greater with the increase in the pressing temperature. In general, the results of the present study, which used a lower pressing temperature, pressing time, and amount of resin were in accordance with those described above.

Regarding the palm species, several studies have been made with canary palm. Ferrandez-Garcia et al. [22] obtained binderless boards with poor mechanical properties and a high TS value. Garcia-Ortuño et al. [19] substituted the UF with 10% of starch and longer pressing times. They obtained panels with a high density and with a good MOR and IB. These results are similar to the values obtained in the present work.

Ferrandez-Garcia et al. [18] made boards from the rachis of washingtonia palm using a pressing temperature of 120 °C for 6 min. They obtained better values of MOR and MOE, and similar but lower values of IB and TS than the present study just by lowering the temperature by 10 °C and increasing the pressing time by 1 min.

In general, using a higher processing temperature and a higher density resulted in the improved mechanical behavior of the particleboard, nevertheless, the best performance was obtained with pressing times between 5 and 7.5 min. The addition of higher amounts of UF was found to improve the mechanical properties and to reduce the TS, however, regulation limits must be taken into account due to the harmful effects of UF on human health. Particleboards with good mechanical properties were produced using pressing temperatures between 120 and 140 °C.

Table 4. Average properties of palm rachis particleboards by different authors.

Material: Rachis Palm	Temp (°C)	Time (min)	Adhesive (%)	Density (kg/m^3)	MOR (N/mm^2)	MOE (N/mm^2)	IB (N/mm^2)	TS 24 h (%)	Source
Date	150	5	33% UF	650	15.3–18.9	-	0.43–0.83	14.4	[8]
Date	160	5	9% UF	750	10.5	1333	0.38	30.1	[9]
Date	160	5	11% UF	750	16.6	1861	0.63	30.1	[9]
Date	195	7.5	10% PF	700	14.0	2780	0.66	14.9	[13]
Date	140	10	10% UF	650	6.7	950	0.67	84	[15]
Date	140	10	10% UF	750	8.2	1140	2.43	23.8	[15]
Date	160	8	10% UF	670	9.04	1443	0.43	-	[14]
Date	160	8	10% UF	790	13.3	2018	0.53	-	[14]
Canary	120	15	None	850	6.0	1022.32	0.39	55.22	[22]
Canary	110	240	10% Starch	1100	13.85	1702.67	0.63	28.98	[19]
Washing.	120	6	8% UF	866	16.73	1469.78	0.90	41.20	[18]
Canary	130	5	8% UF	842	15.93	1696.13	0.83	42.90	This study
Washing.	130	5	8% UF	813	12.48	1129.24	0.97	39.44	This study
Date	130	5	8% UF	797	10.71	982.06	0.94	33.02	This study

(UF) Urea–formaldehyde, (PF) Phenol–formaldehyde.

Industrial companies in Spain traditionally employ pine wood particles (*Pinus radiata* D. Dom) and other sawmill leftovers in the manufacturing of commercial particleboard. The standard process uses a higher pressing temperature and amount of UF [47,48], resulting in single-layer panels that have a similar MOR but higher MOE than those obtained in this study (Table 5). A different study [49] that used a hard wood such as eucalyptus (*Eucalyptus urophylla* S.T. Blake), manufactured particleboards that achieved a greater MOR but had a thickness of 17 mm.

Table 5. Average properties of commercial particleboards tested by different authors.

Material	Thick (mm)	Temp (°C)	UF (%)	Density (kg/m^3)	MOR (N/mm^2)	MOE (N/mm^2)	IB (N/mm^2)	Manufac-turer	Source
Pine wood	16	200	15%	660	13.7	1626	1.36	AA	[47]
Mix of pine, oak & beech wood	13	200	12%	665	11.7	2425	0.35	TL	[48]
75% pine wood & sawmill rests	13	200	12%	630	9.68	2094	0.30	EM	[48]
Eucalyptus	17	190	12%	838	33.0	-	0.45	-	[49]
Canary Palm	10.58	130	8%	842	15.93	1696.13	0.83	-	This study
Wash. Palm	10.57	130	8%	813	12.48	1129.24	0.97	-	This study
Date Palm	10.48	130	8%	797	10.71	982.06	0.94	-	This study

(AA) Aserraderos Aragón, S.A., (TL) Tableros Losan, S.A., (EM) Unión de Empresas Madereras, S.A.

Wood has always been considered a building material with good insulation properties. For comparison purposes, the thermal conductivity of some woods with a similar density to that of the particleboard in the present study is shown in Table 6. The experimental particleboard has lower thermal conductivity values than those made from wood.

Table 6. Average thermal conductivity values of wood with similar densities as rachis particleboards.

Material	Density (kg/m^3)	Thermal Conductivity λ (W/mK)	Source
Maple wood	750	0.349	[50]
Oak wood	850	0.209	[50]
Beech wood	800	0.143	[50]
Canary palm rachis	842	0.057	This study
Washingtonia palm rachis	813	0.059	This study
Date palm rachis	797	0.059	This study

In terms of thermal conductivity, the results suggested the possibility of using these particleboards as thermal insulation materials, since they had better thermal properties than commonly-used woods with similar densities.

In the literature, some authors have investigated the thermal conductivity of particleboards using fibers from the rachis of palm species. The results of such tests are in accordance with the values achieved in this study (Table 7). The board density and palm species did not have a relevant effect on their thermal insulating capacity. The composites shown in the table had the least insulation capacity, as cement and gypsum are not good insulators.

Table 7. Average thermal conductivity values of palm particleboards studied by different authors.

Board Type	Material: Rachis	Density (kg/m^3)	Thermal Conductivity λ (W/mK)	Source
Particleboard	Date palm	254	0.042	[12]
Particleboard	Date palm	273	0.084	[12]
Particleboard	Date palm	176	0.048	[51]
Particleboard	Date palm	270	0.070	[51]
Composite	Date palm/ (PF)	1240	0.160	[28]
Composite	Date palm/ (PF)	1320	0.200	[28]
Composite	20% Date palm/gypsum	736	0.174	[23]
Composite	50% Date palm/cement	1217	0.243	[26]
Particleboard	Washingtonia palm	860	0.084	[21]
Particleboard	Washingtonia palm	746	0.062	[18]
Particleboard	Canary palm	880	0.054	[22]
Particleboard	Canary palm	1030	0.079	[22]
Particleboard	Canary palm	842	0.057	This study
Particleboard	Washingtonia palm	813	0.059	This study
Particleboard	Date palm	797	0.059	This study

(PF) Phenol–formaldehyde.

The results showed that the physical and mechanical properties of particleboard in general were influenced by the palm species in addition to other parameters, such as the particle size, pressing temperature, pressure, pressing time, raw material, amount and type of adhesive used, particle moisture, and particleboard density. In the present study, the manufacturing variables were the palm species and the particle size. A statistical analysis was conducted in order to determine the dependence of the mechanical and physical properties of the experimental particleboards with respect to the variables of the study (Table 8).

Table 8. ANOVA of the results of the tests.

Factor	Properties	Sum of Squares	d.f.	Half Quadratic	F	Sig.
Particle size	Density (kg/m^3)	59,221.826	2	29,610.913	15.628	0.000
	MOR (N/mm^2)	437.186	2	218.593	25.186	0.000
	MOE (N/mm^2)	4,212,577.867	2	2,106,288.933	20.621	0.000
	IB (N/mm^2)	0.066	2	0.033	1.825	0.173
	TS 24 h (%)	187.647	2	93.823	1.607	0.212
	WA 24 h (%)	1103.284	2	551.642	4.946	0.011
Palm species	Density (kg/m^3)	12,789.499	2	639.749	2.185	0.124
	MOR (N/mm^2)	181.009	2	90.505	6.297	0.004
	MOE (N/mm^2)	3,737,773.838	2	1,868,886.919	16.584	0.000
	IB (N/mm^2)	0.161	2	0.080	5.031	0.011
	TS 24 h (%)	631.436	2	315.718	6.508	0.003
	WA 24 h (%)	119.859	2	59.929	0.449	0.641

d.f.: degrees of freedom. F: Fisher–Snedecor distribution. Sig.: significance.

With a significance of <0.05, the density, MOR, MOE, and WA depended on the particle size of the particleboard, whereas the MOR, MOE, IB, and TS depended on the palm species.

5. Conclusions

This study was focused on testing the mechanical, physical and thermal behavior of particleboard made of particles from the rachis of canary palm (*Phoenix canariensis* hort. ex Chabaud), date palm (*Phoenix dactylifera* L.) and washingtonia palm (*Washingtonia robusta* H. Wendl). Moreover, the influence of the particle size and the raw material (palm species) of the particleboard was also investigated.

It can be concluded that it is feasible to manufacture particleboard using palm rachis that will have similar properties to conventional wood particleboard using a low energy manufacturing process (short pressing time and low pressing temperature). This particleboard could replace the traditional raw materials used in construction, contributing to a reduction of the pressure on forest wood resources.

The particleboard made with canary palm rachis had better properties than the washingtonia and date palm rachis boards; therefore, it could be considered that it was the best raw material for the production of particleboard under the conditions tested in this study.

In terms of the particle size, the results showed that it affected some of the properties of the particleboard, namely the density, WA, MOR, and MOE. A particle size of 1 to 2 mm of canary palm and 0.25 to 1 mm of washingtonia and date palm achieved the best results. In general, smaller particles had better properties.

The TS, MOR, MOE and IB were found to be influenced by the palm species. Canary palm rachis particleboard of any particle size, and boards made of washingtonia and date palm with particle sizes of 0.25 to 1 mm, could be classified as P1 "General purpose boards for use in dry conditions". Canary palm rachis with particle sizes from 1 to 2 mm could be classified as type P2 "Boards for interior fitments (including furniture) for use in dry conditions".

The particleboard manufactured can be considered a good insulating material. The thermal conductivity did not depend on the particle size or the palm species.

The use of the pruning waste of palm trees to produce durable materials such as particleboard could be beneficial to the environment since it is a method of carbon fixation, helping to decrease atmospheric pollution and reducing the amount of waste that ends in dumping sites.

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