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Properties of Binderless Insulating Boards Made from Canary Island Date Palm and Cork Particles

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Abstract: Agglomerated cork is a natural cork that has gone through a process of crushing and pressing using heat and binders. One of its applications is thermal insulator in construction. The design of these materials is becoming an essential part of building. The raw materials currently used to make insulators consume a large amount of energy, which has created the need to increase the use of renewable and ecological resources such as plant fibers to reduce the environmental problems generated. The objective of this study was to determine the different properties of experimental particleboard panels made from cork and Canary Island date palms without using any binder at minimum energy consumption. The produced cork–palm boards (density of 850 kg/m^3, reached a MOR 8.83 N/mm^2, MOE 794.5 N/mm^2, and IB 0.38 N/mm^2) are higher values than the traditional cork particleboards with UF made from cork. The thermal conductivity values obtained 0.069 to 0.096 W/m·K are higher than cork boards with UF. Ecological boards that can be used as rigid thermal insulators in the construction industry have been achieved to improve the mechanical properties of the traditional agglomerated cork.

Keywords: density; particleboard; *Quercus suber* L.; *Phoenix canariensis* hort. ex Chabaud

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1. Introduction

The growing concern to reduce energy consumption and increase energy efficiency in the construction industry has led to an increase in research aimed at improving the thermal envelope of buildings in order to limit the energy demand needed to achieve the desired thermal well-being. To do this, commercial, technical materials with good insulating properties and from plastic, like polyurethane foam, polystyrene, etc., and mineral origin, such as vermiculite, rock wool, fiberglass, etc., which have a high energy consumption during their production are not biodegradable, are generally used. In order to reduce the environmental impact generated by their manufacturing, new renewable and ecological resources, such as plant fibers, are being sought to be used as natural insulation materials for construction since, in addition to fulfilling their thermal function, they have many other characteristics that make them a great alternative for fighting CO_2 emissions. Nowadays, the most common lignocellulosic-based fibers used in construction are wood and cork, but there are many proposals for valorizing plant waste.

Cork is the bark of the cork oak (*Quercus suber* L.) that protects it against the extreme conditions of the Mediterranean climate, such as drought, high summer temperatures, and fires. Cork oak forests (*Quercus suber* L.) are one of the best examples of conservation and balanced development in the world. Cork oak can be found in areas of the western Mediterranean (Portugal, Spain, southern France, part of Italy, northern Africa) and China. Europe produces 80% of the world's cork, and Portugal is the world's largest producer [1]. Cork oak forests play a key role in ecological processes such as water retention, soil conservation and carbon storage [2]. The cork oak is a long-lived species with an outer bark, or cork, which is characterized by its elasticity, impermeability, and good thermal insulation. Cork extraction is a sustainable process because it does not damage the tree, and after extraction, new bark grows back. This process occurs every 9 to 14 years, depending on the area, until the tree is approximately 200 years old [3].

Cork is a material with a density between 100 kg/m^3 and 140 kg/m^3, and it is widely used for different applications, namely in products for the thermal insulation of walls, refrigerators and rockets, acoustic insulation in submarines and recording studios, joints in wind instruments and combustion engines, and as an energy-absorbing medium in floors, shoes, and packaging [4].

Cork-based insulating materials offer numerous advantages but also have limitations because it is a porous material that can absorb moisture, which reduces its insulating capacity and increases the risk of mold growth [5].

A compound with densities of 250 to 350 kg/m^3 is obtained by joining cork particles with different binders (urea formaldehyde, polyurethane, melamine, rubber, etc.), giving rise to products such as agglomerated cork stoppers, floor coverings, joints, etc. Densified cork panels with densities greater than 750 kg/m^3 are used for floor coverings, wall and ceiling coverings, false ceilings, door and screen panels, skirting boards, and sandwich panels and furniture. The physical and chemical characteristics of the binders determine the resistance of the agglomerate and its applications [4]. In agglomerated cork boards, there is a clear influence of the size of the granule on the density and mechanical properties, which increase with smaller sizes [6].

Expanded cork agglomerates are obtained without adhesives. Self-union is obtained by the degradation of the extractive and structural components of cork. The agglomeration is carried out in a steam autoclave with temperatures of 300–350 °C and 40 kPa for approximately 20 min. These agglomerates have low flexural and tensile strength and are not resistant to friction and wear due to weak intergranular adhesion [7].

The physical-mechanical and thermal properties of bio-based cork composites have been investigated, indicating that they are a viable alternative for developing more sustainable composite materials for automotive interiors, bottle caps, and a wide range of applications [8]. Increasingly, novel strategies and technologies are being studied to develop lightweight textiles with thermal insulation properties [9].

Sandwich structures with an agglomerated cork core have highly specific properties, such as good energy dissipation capacity, which means that cork can also be used for impact applications. The presence of agglomerated cork allows for better impact resistance and high energy absorption compared with other synthetic or mineral materials [10–12]. Cork has been studied as a central material in sandwich structures for aeronautical and aerospace applications [13] and as insulation for buildings.

Furthermore, cork is also used in multicomponent systems for insulation with different layers: adhesive, insulator, mechanical fixings, base layer, mesh, and finishing layer. The insulator is the component that has the function of increasing thermal resistance, practically eliminating thermal bridges. Multicomponent systems based on cork as an insulating material (natural cork or expanded cork), due to their lower thermal diffusivity, provide greater thermal delays than other insulating materials, with satisfactory overall performance, such as extruded polystyrene and mineral wool [14], which is the commonly applied system, being a more sustainable material [15]. Recently, many advances have been made that have led to new cork-based compounds, with ecological adhesives, synthetic adhesives, cement, and gypsum [16].

The palm tree was used in some traditional constructions, replacing wood in those places where wood was scarce. In the southeast of Spain, palm trees are widely used in the urban landscape, as in most countries surrounding the Mediterranean Sea. The Canary Islands palm (*Phoenix canariensis* hort. ex Chabaud) is a very fast-growing species, and its management produces an average annual dry mass of 49.34 kg/tree [17]; this biomass has traditionally been discarded in landfills. There are studies on insulating boards with different palm tree residues [18–20], indicating that they can be used for insulation in buildings.

The aim of this study was to manufacture a new cork and Canary palm particleboard through a novel pressing cycle process with the lowest energy consumption while ensuring it is binderless, biodegradable, and ecological and to study its properties so it could be used as a construction material.

2. Materials and Methods

The materials used in this work were the trunk of the Canary Island palm tree with two particle sizes and 3 mm cork granules. The cork granules were acquired from a distribution company (VIPED, Elche, Spain), and the palm tree trunk was acquired from an urban landfill. The palm tree trunk was left to dry for 6 months in the open air and was subsequently crushed in a blade defibrillator, and two particle sizes (<0.25 mm and 0.25 to 1 mm) with an approximate humidity of 9% were selected in a vibrating sieve.

The manufacturing process of the particleboards was a cyclic pressing process and consisted of mixing Canary Island palm particles and cork granules at 50% by weight and in a 600 × 400 mm^2 mold. Subsequently, a temperature of 130 °C and a pressure of 2.6 MPa were applied in the hot plate press for 15 min, 15 + 15 min, and 15 + 15 + 15 min to obtain rigid panels of agglomerated particles. Afterward, the panels were allowed to cool in a vertical position. Particleboards were single-layer and had approximate dimensions of 600 × 400 × 10 mm^3. Six types of cork–palm panels were manufactured using two sizes of palm particles (<0.25 mm and 0.25 to 1 mm) and two pressing times (15 min, 15 + 15 min, and 15 + 15 + 15 min). The manufacturing process is shown in Figure 1. The process is innovative because water was sprayed onto the surface in an amount equal to 5% of the weight of the particles in each pressing cycle to promote the necessary reactions that require an aqueous medium for self-union [21].

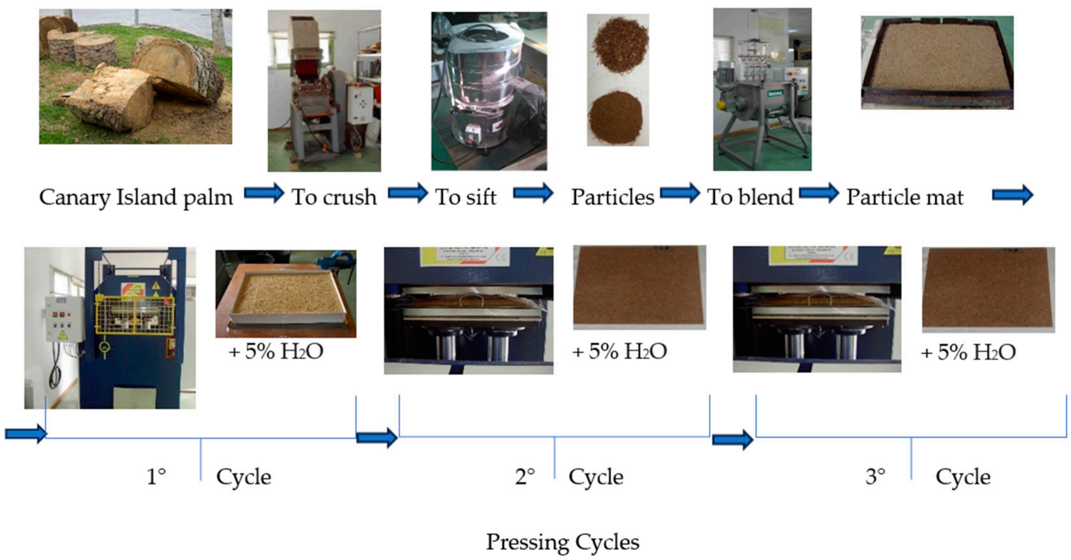


Figure 1. Diagram of the manufacturing process of palm-cork boards.

In order to be able to compare the results obtained, two types of boards (A_ref and B_ref) were produced as reference samples, maintaining the same characteristics as the new Canary Island–Cork particleboards but composed only of cork granules, following the traditional industrial process with a single pressing cycle, adding an 8% of urea formaldehyde (UF) as a binder but reducing the pressing time to 6 and 15 min. Four boards of each type were made (Table 1).

Table 1. Types of manufactured particleboards.

Type	Particle Size (mm)	% Cork	% Canary Island Palm	Binder	Temperature (°C)	Pressure (MPa)	Time (min)	No. of Boards
A1	<0.25	50	50	No	130	2.6	15	4
A2	<0.25	50	50	No	130	2.6	15 + 15	4
A3	<0.25	50	50	No	130	2.6	15 + 15 + 15	4
B1	0.25 to 1	50	50	No	130	2.6	15	4
B2	0.25 to 1	50	50	No	130	2.6	15 + 15	4
B3	0.25 to 1	50	50	No	130	2.6	15 + 15 + 15	4
A_ref	-	100	0	UF 8%	130	2.6	6	4
B_ref	-	100	0	UF 8%	130	2.6	15	4

The boards were cut on a circular saw to obtain specimens with the appropriate dimensions for each of the tests following the European Standards. The density [22], water absorption (WA), and thickness swelling (TS) after 2 and 24 h of immersion in water [23], the modulus of elasticity (MOE) and the modulus of rupture (MOR) [24], internal bonding strength (IB) [25] and thermal conductivity (λ) [26] have been measured.

The mechanical properties of the samples were evaluated on an Imal universal testing machine (Model IB600, Modena, Italy), which has a built-in calibrator and a precision balance. For mechanical tests, European Standards indicate that the load is applied at a constant speed throughout the test so that the maximum load is reached in (60 ± 30) s. The testing machine used is specific for particleboards and applies a speed of 5 mm/min in the bending test and 2 mm/min in the internal tensile test. Thermal conductivity tests of the samples (λ) were performed on a heat flow meter instrument (NETZSCH Instruments Inc., San Diego, CA, USA).

The analysis of sugars and starch was carried out by the company Eurofins using internal and enzymatic methods. The analyses of xylose, arabinose, and acetic acid were carried out using high-performance liquid chromatography with an Agilent column chromatograph with an HP processor. For liquid chromatography, 0.5 g of palm tree trunk samples and the exterior of the A3 palm cork board were used. They were diluted in 100 mL of distilled water at room temperature and left with a shaker for 48 h.

The statistical analysis of the test results was carried out using the SPSS v.22.0 software. The standard deviation was obtained from the mean values of the trials, the analysis of variance (ANOVA) was carried out to find out if the variables are related, and the Pearson correlation coefficient was carried out to observe if there was linear dependence between the preparation variables and the properties.

3. Results and Discussion

The different types of boards produced are depicted in Figure 2. The boards were cut on a circular saw to obtain specimens with the appropriate dimensions for each of the tests, obtaining from each board six specimens for the bending test, three specimens for the IB, TS, and WA tests, and one specimen for the thermal conductivity test.

The average values of the physical properties obtained in the tests are indicated in Table 2.

Cork–palm particleboards were successfully manufactured without binder with densities of 676–850 kg/m^3 and can be classified as medium-density boards. Boards made with cork and UF had a density value of 331 kg/m^3, which is much lower and similar to condensed cork boards. This is justified by the composition of the cork, which is made up of cells whose interior is filled with a gas similar to air. The ANOVA analysis (Table 3) indicates that the density depends on the type of board and the time in the press. The average values of the % thickness swelling (TS) after immersion in water for 2 h and 24 h show that at 24 h, higher values are achieved for the boards composed of cork–palm tree compared with the cork boards with UF, depending on the type of board. The average values of % water absorption (WA) indicate that all types of boards absorb a large amount of water, and their highest parameters at 24 h were 63.15% for cork–palm boards and 54.5% for UF cork boards.

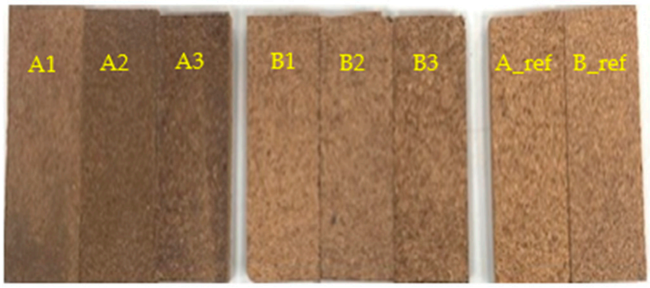


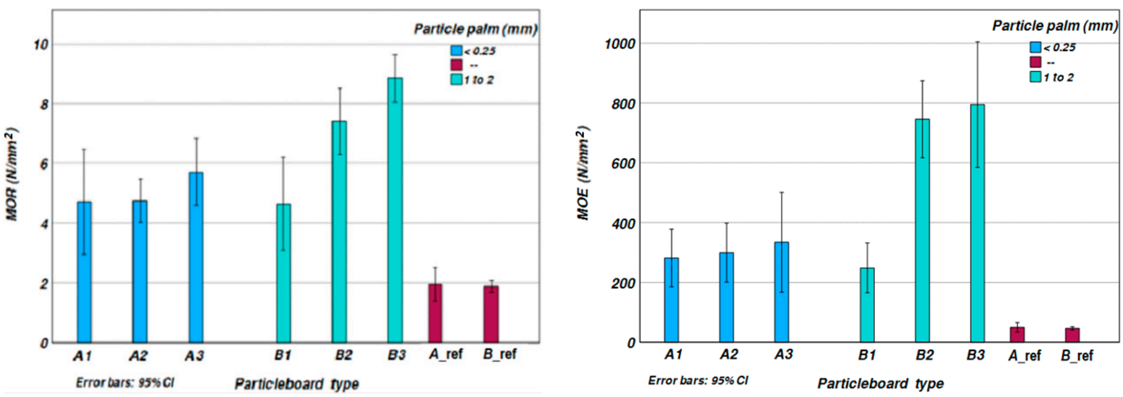
Figure 2. Specimens for the bending test of each type of board made.

Table 2. Average results of the physical properties of the boards.

Type of Board	Thickness (mm)	Density (kg/m^3)	TS 2 h (%)	TS 24 h (%)	WA 2 h (%)	WA 24 h (%)
A1	10.81 (0.11)	676.56 (9.52)	4.59 (1.45)	13.30 (2.58)	25.42 (8.06)	43.3 (7.06)
A2	10.71 (0.47)	718.66 (16.12)	7.82 (3.20)	14.00 (2.66)	31.44 (6.97)	49.96 (7.13)
A3	10.66 (0.94)	708.74 (24.39)	7.70 (3.39)	12.02 (1.99)	34.92 (7.09)	49.18 (10.32)
B1	10.63 (0.24)	698.37 (35.97)	13.87 (3.39)	19.71 (3.00)	47.20 (6.40)	63.15 (13.96)
B2	10.49 (0.15)	794.74 (52.24)	10.28 (2.53)	18.01 (3.40)	31.58 (7.49)	41.51 (10.93)
B3	9.98 (0.26)	850.13 (28.90)	2.77 (3.00)	13.04 (1.36)	18.27 (3.97)	24.64 (8.92)
A_ref	11.39 (0.47)	330.96 (10.54)	0.68 (0.35)	1.61 (0.13)	29.71 (5.74)	54.50 (10.95)
B_ref	11.03 (0.84)	331.36 (3.64)	0.69 (0.20)	1.62 (0.30)	27.90 (4.11)	45.64 (4.82)

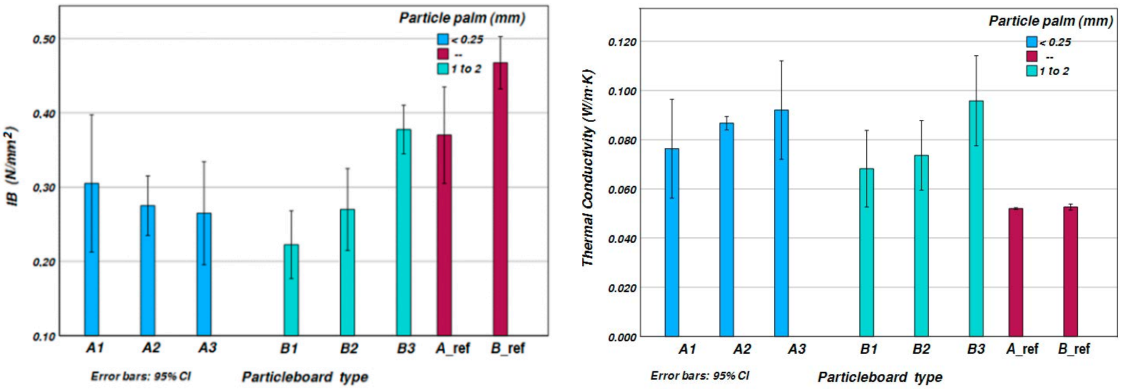
(..) Standard deviation.

The average values of the mechanical and thermal properties of the tested boards are indicated in Figures 3 and 4.



(a) (b)

Figure 3. (**a**) Average MOR results; (**b**) Average MOE results as a function of board type.



(**a**) (**b**)

Figure 4. (**a**) Average IB results; (**b**) Average thermal conductivity results as a function of board type.

Table 3. ANOVA results for manufacturing variables (type of board and pressing time).

		Sum of Squares	DF	Mean Square	F	Sig.
Type of board	Thickness	43.142	7	6.163	12.707	<0.001
	Density	1,446,845.1	7	206,692.1	242.17	<0.001
	TS 2 h	621.224	7	88.746	12.156	<0.001
	TS 24 h	1258.783	7	179.826	25.490	<0.001
	WA 2 h	2192.856	7	313.265	4.205	0.004
	WA 24 h	3496.046	7	499.435	4.749	0.002
	MOR	160.975	7	22.996	48.788	<0.001
	MOE	2,216,122.6	7	316,588.9	55.834	<0.001
	IB	0.179	7	0.026	19.505	<0.001
	(λ)	0.008	7	0.001	14.106	<0.001
Pressing time	Thickness	31.413	3	10.471	12.546	<0.001
	Density	961,465.5	3	320,488.5	17.739	<0.001
	TS 2 h	193.789	3	64.596	3.001	0.047
	TS 24 h	562.92	3	187.643	6.073	0.199
	WA 2 h	500.97	3	166.992	1.344	0.280
	WA 24 h	1208.76	3	402.921	2.345	0.094
	MOR	106.44	3	35.482	15.089	<0.001
	MOE	1,264,661.6	3	421,553.8	10.853	<0.001
	IB	0.030	3	0.010	1.528	0.229
	λ	0.006	3	0.002	17.000	<0.001

Figure 3a,b shows the results of the bending test obtained from the different types of boards. The MOR and MOE values of the cork–palm boards are much higher than the UF cork boards, having a MOR of 8.83 N/mm^2 and MOE of 795 N/mm^2; the IB has a slightly higher value for the UF cork boards. The boards with the best mechanical properties are palm–cork boards with particles of 0.25 to 1 mm that have been pressed three times for 15 min. The MOR and MOE values depend on the type of board and the time in press, as seen in Table 3.

The IB values of cork boards with UF are higher than palm cork boards, and according to the ANOVA (Table 3), it depends on the type of board and does not depend on the time in the hot plate press. As can be seen in Figure 4a, cork boards with a UF had an IB of 0.46 N/mm^2, and the maximum IB of palm–cork boards was 0.38 N/mm^2 obtained with board type B3.

The results of the thermal conductivity tests are shown in Figure 4b, offering for the new board manufactured average values of 0.068 W/m·K to 0.096 W/m·K, so they can be used as thermal insulators. The statistical analysis (Table 4) indicates that λ depends on the type of board and the time in the press. The results obtained are consistent since when the density increases, the thermal conductivity increases. Lower density achieves better thermal performance, which could be justified by the higher air content inside the board.

Table 4. Pearson correlation coefficient values obtained with respect to the manufacturing variables.

		Density	TS 2 h	TS 24 h	WA 2 h	WA 24 h	MOR	MOE	IB	λ
Type	Pearson Correlation	−0.378 *	−0.444 *	−0.017	−0.112	−0.017	−0.254	−0.102	−0.507 **	−0.507 **
	Sig.	0.033	0.011	0.928	0.541	0.928	0.161	0.578	0.003	0.003
	N	32	32	32	32	32	32	32	32	32
Time	Pearson Correlation	0.747 **	0.163	−0.337	−0.337	−0.444 *	0.773 **	0.696 **	−0.193	0.799 **
	Sig.	<0.001	0.374	0.059	0.059	0.011	<0.001	<0.001	0.289	<0.001
	N	32	32	32	32	32	32	32	32	32

**. The correlation is significant at the 0.01 level (two-sided). *. The correlation is significant at the 0.05 level (two-sided).

The best resistant palm–cork board was type B3; they had the highest mechanical properties and lowest TS and WA, although they had high density and thermal conductivity.

The new composite manufactured had better mechanical performance than the conventional agglomerated cork board. This aspect can be beneficial when managing the panel as thermal insulation in buildings.

To analyze whether there was a linear relationship between the manufacturing variables and the properties of the designed particleboards, the Pearson correlation was studied, as indicated in Table 4.

The type of board had a linear relationship between density, IB and λ. With a smaller Canary palm particle size, higher density, IB, and thermal conductivity were obtained. Pressing time was directly proportional to density, WA, MOR, MOE, and λ. Increasing the number of pressing cycles increased the density, MOR, MOE, and λ and decreased WA.

The best insulating boards designed were the B1 type, the ones manufactured with Canary Island palm particles of size 0.25 to 1 mm with a single pressing cycle (15 min).

Table 5 displays the average value of thermal conductivity achieved by panels manufactured using other types of plant fibers used as insulating construction materials. The thermal conductivity value was similar to that obtained for plant fibers with a density in the range of the densities obtained in this study and somewhat higher than that of kenaf and cotton, although these latter materials do not have any mechanical resistance, so they can only be used as filler or covered by other more resistant materials. Using polyurethane and UF as adhesives on cork particleboard results in boards with better-insulating properties, but they are non-biodegradable synthetic products.

Table 5. Thermal conductivity of different materials.

Name	Density (kg/m^3)	Thermal Conductivity (W/m K)	Source
Cotton	150–300	0.059 to 0.074	[27]
Kenaf	150–250	0.051 to 0.058	[28]
Sugar cane	350–500	0.079 to 0.098	[29]
Palm rachis	797–841	0.053 to 0.061	[30]
Cork + polyurethane	170	0.037	[5]
Cork–Canary Island Palm	676–850	0.068 to 0.096	This study
Cork + UF	321	0.052	This study

The explanation of the mechanism of self-bonding in binderless particleboards has been discussed in several reviews but has not been clarified due to the different chemical components of the plant products. A suggested mechanism of self-bonding is the reaction of some sugars that, with pressure and heat in an acidic aqueous medium, could have been transformed into furfural, which would then solidify into a thermostable resin [31]. Other authors propose that the union of the particles is due to the glass transition of cellulose, hemicellulose, and lignin [32,33]. With palm panels manufactured at 120 °C and 11% total moisture content, they indicated that some carbohydrates reached the glass transition temperature and helped in self-adhesion [34].

The chemical analysis in Table 6 shows that acetic acid can be an indicator of the reaction of sugars through the Wohl degradation process, obtaining arabinose since the sugars and acetic acid are consumed when the board is formed. The xylose increases as the board is formed and may be released by the heat in the press.

Table 6. Chemical analysis of some components.

Specimen	Total Sugars (%)	Xylose (%)	Arabinose (%)	Acetic Acid (%)	Starch g/100 g
Canary Island date palm trunk	1.19	-	-	3.96	<0.5
Canary Island date palm and cork	< 0.1	0.35	0.48	1.29	-

According to the tests carried out, the self-bonding mechanism could be due to the fact that xylose and arabinose have aldehyde groups that can produce thermostable adhesives. It is also observed that the starch has gelled and may contribute to the self-binding of the cork and palm particles. In the process of forming the palm cork boards, 10% water was added in each pressing cycle, and the palm tree contains acetic acid and sugars that are consumed when the board is formed, so furfural may have been produced. Then, the self-union of the palm cork particles may be due to a set of reactions of its components.

4. Conclusions

Based on the findings of this study, using cork and Canary Island date palm as raw material could have a potential to be utilized for manufacture of binderless experimental particleboard panels with acceptable mechanical and physical properties, as considered in this investigation.

The manufactured panels had enhanced mechanical characteristics in addition to their thermal properties than those of conventional agglomerated cork board. Such characteristics of the panels can be beneficial when these products are used where good insulation and structural performance are desired.

The density, MOR, MOE, and thermal conductivity of cork-based panels showed a linear increase as the number of pressing cycles increased.

It appears that panels made from both cork and palm particles can be considered an efficient and sustainable product to be used for thermal insulation units for different interior applications. They could be used for false ceilings and cladding without the need for other support structures as well.

Using the trunk of the Canary Island palm tree and cork for value-added particleboard panel production could be beneficial for the environment, reducing air pollution and the amount of waste within the scope of sustainability.

Although there are buildings that are more than 200 years old that use palm tree trunks as joists, to find out the durability of the cork–palm boards, durability and resistance tests against environmental and biological agents would have to be carried out.

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B.E.F.-G.; writing—review and editing, B.E.F.-G. and T.G.-O.; supervision, T.G.-O. All authors have read and agreed to the published version of the manuscript.

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References

1. Silvestre, J.D.; Pargana, N.; De Brito, J.; Pinheiro, M.D.; Durão, V. Insulation cork boards—Environmental life cycle assessment of an organic construction material. *Materials* **2016**, *9*, 394. [CrossRef]
2. Sierra-Pérez, J.; Boschmonart-Rives, J.; Gabarrell, X. Production and trade analysis in the Iberian cork sector: Economic characterization of a forest industry. *Resour. Conserv. Recycl.* **2015**, *98*, 55–66. [CrossRef]
3. Pereira, H. *Cork: Biology, Production and Uses*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2017; p. 336. ISBN 13: 978-0-444-52967-1.
4. Gil, L. Cork composites: A review. *Materials* **2009**, *2*, 776–789. [CrossRef]
5. Yay, Ö.; Hasanzadeh, M.; Diltemiz, S.F.; Kuşhan, M.C.; Gürgen, S. Thermal Insulation with Cork-Based Materials. In *Cork-Based Materials in Engineering: Design and Applications for Green and Sustainable Systems*; Springer Nature: Cham, Switzerland, 2024; pp. 3–15. [CrossRef]
6. Jardin, R.T.; Fernandes, F.A.O.; Pereira, A.B.; Alves de Sousa, R.J. Static and dynamic mechanical response of different cork agglomerates. *Mater. Des.* **2015**, *68*, 121–126. [CrossRef]
7. Knapic, S.; Oliveira, V.; Machado, J.S.; Pereira, H. Cork as a building material: A review. *Eur. J. Wood Prod.* **2016**, *74*, 775–791. [CrossRef]
8. Fernandes, E.M.; Correlo, V.M.; Mano, J.F.; Reis, R.L. Cork–polymer biocomposites: Mechanical, structural and thermal properties. *Mater. Des.* **2015**, *82*, 282–289. [CrossRef]
9. Carvalho, R.; Fernandes, M.; Fangueiro, R. The influence of cork on the thermal insulation properties of home textiles. *Procedia Eng.* **2017**, *200*, 252–259. [CrossRef]
10. Lakreb, N.; Şen, U.; Toussaint, E.; Amziane, S.; Djakab, E.; Pereira, H. Physical properties and thermal conductivity of cork-based sandwich panels for building insulation. *Constr. Build. Mater.* **2023**, *368*, 130420.
11. Sarasini, F.; Tirillò, J.; Lampani, L.; Sasso, M.; Mancini, E.; Burgstaller, C.; Calzolari, A. Static and dynamic characterization of agglomerated cork and related sandwich structures. *Compos. Struct.* **2019**, *212*, 439–451. [CrossRef]
12. Boria, S.; Raponi, E.; Sarasini, F.; Tirillò, J.; Lampani, L. Green sandwich structures under impact: Experimental vs numerical analysis. *Procedia Struct. Integrity* **2018**, *12*, 317–329. [CrossRef]
13. Reis, L.; Silva, A. Mechanical behavior of sandwich structures using natural cork agglomerates as core materials. *J. Sandw. Struct. Mater.* **2009**, *11*, 487–500. [CrossRef]
14. Simões, I.; Simões, N.; Tadeu, A. Thermal delay simulation in multilayer systems using analytical solutions. *Energy Build.* **2012**, *49*, 631–639. [CrossRef]
15. Malanho, S.; Veiga, R.; Farinha, C.B. Global performance of sustainable thermal insulating systems with cork for building facades. *Buildings* **2021**, *11*, 83. [CrossRef]
16. Gil, L. New Cork-Based Materials and Applications. *Materials* **2015**, *8*, 625–637. [CrossRef]
17. Sajdak, M.; Velázquez-Martí, B.; López-Cortés, I. Quantitative and qualitative characteristics of biomass derived from pruning *Phoenix canariensis hort*. ex Chabaud and *Phoenix dactilifera* L. *Renew. Energy* **2014**, *71*, 545–552. [CrossRef]
18. Ferrandez-Garcia, M.T.; Ferrandez-Garcia, A.; Garcia-Ortuño, T.; Ferrandez-Garcia, C.E.; Ferrandez-Villena, M. Influence of particle size on the properties of boards made from Washingtonia palm rachis with citric acid. *Sustainability* **2020**, *12*, 4841. [CrossRef]
19. Mawardi, I.; Aprilia, S.; Faisal, M.; Rizal, S. Characterization of thermal bio-insulation materials based on oil palm wood: The effect of hybridization and particle size. *Polymers* **2021**, *13*, 3287. [CrossRef]
20. Ali, M.; Alabdulkarem, A.; Nuhait, A.; Al-Salem, K.; Iannace, G.; Almuzaiqer, R. Characteristics of agro waste fibers as new thermal insulation and sound absorbing materials: Hybrid of date palm tree leaves and wheat straw fibers. *J. Nat. Fibers* **2022**, *19*, 6576–6594. [CrossRef]

21. Ferrandez-Garcia, B.E.; Garcia-Ortuño, T.; Ferrandez-Villena, M.; Ferrandez-Garcia, M.T. Evaluation of the Properties and Reaction-to-Fire Performance of Binderless Particleboards Made from Canary Island Palm Trunks. *Fire* **2024**, *7*, 193. [CrossRef]
22. *EN 323*; Wood-Based Panels. Determination of Density. European Committee for Standardization: Brussels, Belgium, 1993.
23. *EN 317*; Particleboards and Fiberboards. Determination of Swelling in Thickness after Immersion in Water. European Committee for Standardization: Brussels, Belgium, 1993.
24. *EN 310*; Wood-Based Panels. Determination of Modulus of Elasticity in Bending and of Bending Strength. European Committee for Standardization: Brussels, Belgium, 1993.
25. *EN 319*; Particleboards and Fiberboards. Determination of Tensile Strength Perpendicular to the Plane of de Board. European Committee for Standardization: Brussels, Belgium, 1993.
26. *EN 12667*; Thermal Performance of Building Materials and Products: Determination of Thermal Resistance by Means of Guarded Hot Plate and Heat Flow Meter Methods: Products of High and Medium Thermal Resistance. Committee for Standardization: Brussels, Belgium, 2001.
27. Zhou, X.Y.; Zheng, F.; Li, H.G.; Lu, C.L. An environment-friendly thermal insulation material from cotton stalk fibers. *Energy Build.* **2010**, *42*, 1070–1074. [CrossRef]
28. Xu, J.; Sugawara, R.; Widyorini, R.; Han, G.; Kawai, S. Manufacture and properties of low-density binderless particleboard from kenaf core. *J. Wood Sci.* **2004**, *50*, 62–67. [CrossRef]
29. Liao, R.; Xu, J.; Umemura, K. Low density sugarcane bagasse particleboard bonded with citric acid and sucrose: Effect of board density and additive content. *BioResources* **2016**, *11*, 2174–2185.
30. Ferrández-García, C.E.; Ferrández-García, A.; Ferrández-Villena, M.; Hidalgo-Cordero, J.F.; García-Ortuño, T.; Ferrández-García, M.T. Physical and mechanical properties of particleboard made from palm tree prunings. *Forests* **1018**, *9*, 755. [CrossRef]
31. Peleteiro, S.; Rivas, S.; Alonso, J.L.; Santos, V.; Parajó, J.C. Furfural production using ionic liquids: A review. *Bioresour. Technol.* **2016**, *202*, 181–191. [CrossRef]
32. Anglès, M.N.; Reguant, J.; Montané, D.; Ferrando, F.; Salvadó, J. Binderless composites from pretreated residual softwood. *J. Appl. Polym. Sci.* **1999**, *73*, 2485–2491. [CrossRef]
33. Pintiaux, T.; Viet, D.; Vandenbossche, V.; Rigal, L.; Rouilly, A. Binderless Materials Obtained by Thermo-Compressive Processing of Lignocellulosic Fibers: A Comprehensive Review. *BioResources* **2015**, *10*, 1915–1963. [CrossRef]
34. Ferrández-García, A.; Ferrández-Villena, M.; Ferrández-García, C.E.; García-Ortuño, T.; Ferrández-García, M.T. Potential use of Phoenix canariensis biomass in binderless particleboards at low temperature and pressure. *BioResources* **2017**, *12*, 6698–6712. [CrossRef]

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