

Article

Evaluation of the Properties and Reaction-to-Fire Performance of Binderless Particleboards Made from Canary Island Palm Trunks

Berta Elena Ferrandez-Garcia , Teresa Garcia-Ortuño , Manuel Ferrandez-Villena 
and Maria Teresa Ferrandez-Garcia 

Centro de Investigación e Innovación Agroalimentaria y Agroambiental (CIAGRO-UMH), Miguel Hernandez University, 03300 Orihuela, Spain; m.ferrandez@umh.es (M.F.-V.); mt.ferrandez@umh.es (M.T.F.-G.)

* Correspondence: bferrandez@umh.es (B.E.F.-G.); tgarcia@umh.es (T.G.-O.)

Abstract: Repurposing agricultural and forestry by-products not only is beneficial for the environment but also follows the principles of the circular economy. In southeastern Spain, the Canary Island palm tree (*Phoenix canariensis* W.) is widely used in urban landscapes. Plantations affected by the red weevil, a pest, generate an abundance of plant waste that must be crushed and transferred to authorized landfills. The aim of this study was to manufacture boards using particles from trunks of the Canary Island palm tree without adding any binders in order to obtain an ecological and fire-resistant product. In order to manufacture the boards, three particle sizes (<0.25 , 0.25 – 1 , and 1 – 2 mm), a temperature of 110 °C, a pressure of 2.6 MPa, and a pressing time of 7 min were used. The boards were pressed in a hot plate press for 7 min up to four times (7 min, $7 + 7$ min, $7 + 7 + 7$ min, and $7 + 7 + 7 + 7$ min). The resulting boards showed good thermal performance, and the board's reaction-to-fire performance was classified as $Bd0$ (an F_s value of 70.3 mm). This study also showed that boards with a particle size smaller than 0.25 mm that underwent four pressing cycles of 7 min each in the press can be categorized as grade $P2$ according to the European Standards (MOR of 20 N/mm², MOE of 2589.8 N/mm², and IB of 0.74 N/mm²). Therefore, these manufactured particleboards could be used as a flame-retardant material for the interior enclosures of buildings (vertical and horizontal) without the need for coatings.



Citation: 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. <https://doi.org/10.3390/fire7060193>

Academic Editors: Yachao Wang, Long Yan and Xuebao Wang

Received: 13 May 2024

Revised: 2 June 2024

Accepted: 5 June 2024

Published: 8 June 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: panels; mechanical; physical; pressing cycle; thermal properties; reaction to fire

1. Introduction

The construction sector is the sixth most polluting industry worldwide, generating approximately 40% of the total CO₂ emissions [1]. Renovating and constructing green buildings while reducing contamination can be achieved in part through the use of low-environmental-impact materials, such as bio-based materials. According to the Food and Agriculture Organization of the United Nations (FAO)'s report on forestry and trade, wood-based boards have witnessed a significant increase in production, with 25% growth over the past five years. Their production exceeded 110 million cubic meters in 2022 [2].

The rising cost of wood, land scarcity, and supply shortages have driven research into non-wood alternatives. Apart from having many other environmental benefits, the by-products of agricultural activity can be utilized as raw material in the construction industry for the manufacture of goods such as particleboards. Agricultural waste constitutes an alternative source of income and a means of reducing expenses. From a technical perspective, non-wood plants possess a wide range of fiber qualities [3]. When properly managed, they can be developed into wood substitute materials while following the principles of the circular economy.

The residues of date palm trees are an interesting option as a substitute for wood in particleboards due to their renewable nature and abundant availability. Globally, there are approximately 120 million date palm trees [4], and each one generates approximately

47.57 kg of palm waste annually [5], including petioles, rachises, leaflets, fibrillae, bunches, pedicels, spathes, thorns, and trunks, most of which are gathered during seasonal pruning as a fundamental agricultural practice.

The Canary Island date palm (*Phoenix canariensis* W.) stands as one of the most iconic endemic plant species of the Canary Islands, where there are approximately 300,000 natural individuals [6]. In southeastern Spain, it is one of the most abundant species in the area due to its utilization in urban landscapes. These palm trees are also present in many countries around the Mediterranean Sea, Mexico, and the United States, but the exact number of individuals is unknown.

The red weevil (*Rhynchophorus ferrugineus* O.) is a pest that affects palm trees; it has caused the deaths of a very large number of these trees, leaving behind a significant amount of waste. During the mid-1980s, the red weevil invaded the Arabian Gulf nations, inflicting severe damage to palm trees [7]. The transportation of infected palms, as well as other gardening material, and the characteristics of the crop facilitated the rapid dissemination of this pest. The spread of the weevils affected over sixty countries from the Middle East and Africa to Europe. If timely curative measures are not taken, the presence of this pest typically results in the death of the palm tree. Nevertheless, implementing curative measures in the initial stage of an attack is often challenging due to the difficulty in detecting early-stage infestations [8].

In this way, the numerous plantations affected by the red weevil generate large amounts of plant waste that must be crushed and transferred to authorized landfills. The use of this waste can contribute to the adoption of sustainable solutions for the control and eradication of contaminated specimens and result in environmental improvements.

Numerous studies have focused on manufacturing particleboards from various types of palm tree waste [9–18]. Additionally, palm tree pruning waste has been investigated for its use as a reinforcement [19–21] and in the manufacture of various compounds [22,23]. These studies indicate that the outcomes vary based on the palm species and the plant part used (typically the leaves or trunk). Furthermore, the results show that the particle size and production parameters should be considered due to their importance, since they can greatly affect the physical and mechanical properties of the developed materials.

Most of the binders currently used by the timber industry are derived from fossil resources. They include formaldehyde-based resins, vinyl acetate resins, and isocyanate-based resins. These adhesives, which were developed within the petrochemical sector, exhibit outstanding performance, possess favorable properties, and are economically viable. Nevertheless, the utilization of these adhesives in the industry will eventually face limitations due to the depletion of fossil resource reserves. It has also been proven that formaldehyde-based resins are toxic and can cause serious health problems, such as cancer [24], so their use is increasingly restricted [25]. Due to these problems, there is a heightened interest in manufacturing formaldehyde-free boards, which has led to increased pressure on particleboard manufacturers to stop using these binders. On this basis, new studies on particleboards have been performed by utilizing natural resins and adhesives, such as proteins, lignins, tannins, glutens, starches, citric acid, and bark, to replace synthetic resins [10,26–33].

Currently, research on plant biomass aims to produce binderless particleboards through various pre-treatment methods, and the self-bonding capacity of natural fibers during the transition to the glassy state has been widely demonstrated [34]. Particleboards can be processed without the need for binders; this process is facilitated by the effects of water (molecule solubilization), the temperature, and the pressure, which enable particle agglomeration [35]. The cell walls of plant particles are primarily composed of a mixture of organic macromolecules, including pectins, cellulose, hemicelluloses, lignin, waxes, starch, proteins, and aromatic compounds, along with a minor portion of mineral molecules such as ash [36]. Therefore, cell walls can be regarded as biochemically complex compounds. Cellulose, hemicellulose, and pectin molecules are polysaccharides (carbohydrate polymers) that possess hydrophilic properties. Water-soluble compounds are typically pectins

and small soluble molecules. Depending on the botanical species and the specific part of the plant, the proportions of organic macromolecules change [37]. Furthermore, the size and shape of the particles greatly influence the properties of binderless boards [38] due to the higher number of contact points between the fibers and the more streamlined particle arrangement system, which significantly improve the self-bonding of the particles [3]. Hence, determining the size range of the particles is a crucial factor for enhancing the performance of binderless boards.

A significant concern regarding building materials derived from agricultural, forestry, and plant residues is the limited knowledge concerning their reaction-to-fire performance. While renewable building materials hold promise for substituting conventional materials such as cement, they must follow essential standards. Fire safety considerations must align with the EU Construction Products Regulation (CPR) [39]. Several studies have explored the fire resistance of particleboards composed of or incorporating agricultural residues such as flax [40], oil palm [41], kenaf [42], and rice straw [43]. However, there is a notable gap in the literature regarding the reaction-to-fire performance of palm tree particleboards.

Particleboards are used in furniture and coverings in construction. To improve their fire resistance properties, fire-retardant solutions are used. These compounds interfere with a particular stage of the combustion process and are based on silicon, chlorine, bromine, phosphorus, nitrogen, hydroxides, phosphates, carbonates, or sulfates [44]. Other studies have assessed the emission of smoke and toxic gases produced by the widespread use of epoxy resins and the use of different fire retardants that reduce these emissions [45,46]. There have also been studies on flame retardants with graphene to encapsulate the possible toxic gases released [47].

Taking into consideration the need for new construction materials that can offer environmental advantages, such as reducing air pollution and decreasing landfill wastes, the aim of this work was to manufacture particleboards using trunks of the Canary Island palm tree, without the use of binders, and evaluate the fire performance, mechanical properties, and physical properties of the boards. The goal was to obtain an ecological, biodegradable, fire-resistant product by following the principles of the circular economy.

2. Materials and Methods

2.1. Materials

The Canary Island date palm biomass was obtained from 5 palm trees affected by red palm weevils at the EPSO of the Miguel Hernández University of Elche. One example is illustrated in Figure 1. The 5 different trunks were cut, chopped, and dried outdoors for six months. They were subsequently crushed in a blade shredder and filtered out through a vibrating sieve, and three particle sizes were selected (<0.25, 0.25–1, and 1–2 mm). The particles initially had a relative moisture content of 55%, so they were allowed to air dry for an additional three months until a relative moisture content of 9% was reached with a density of $196 \pm 13 \text{ kg/m}^3$. The water sprayed onto the boards was procured from the public water supply network and had an average temperature of 20 °C.

2.2. Manufacturing Process of the Particleboards

Initially, the particle mat was formed using 1.50 kg of particles for each size (depending on the type of board) in an iron mold with dimensions of $600 \times 400 \text{ mm}$. Afterwards, water was sprayed onto the surface in an amount equaling 10% of the weight of the particles, and the mixture was homogenized by stirring it manually for 5 min. The mat was then placed into a hot plate press with a temperature of 110 °C and a pressure of 2.6 MPa for 7 min (particleboard type 1). The selection of the parameters was based on the results of previous studies [20]. Then, the panels were taken out from the hot press and left to cool in a horizontal position. For particleboard types 2, 3, and 4, the preparation process was repeated, with up to 4 pressing cycles of 7 min each. The particleboards were codified as follows: A1, <0.25 mm particle size and one pressing cycle of 7 min; A2, <0.25 mm particle size and two pressing cycles of 7 min; A3, <0.25 mm particle size and three pressing cycles

of 7 min; A4, <0.25 mm particle size and four pressing cycles of 7 min; B1, 0.25 to 1.00 mm particle size and one pressing cycle of 7 min; B2, 0.25 to 1.00 mm particle size and two pressing cycles of 7 min; B3, 0.25 to 1.00 mm particle size and three pressing cycles of 7 min; B4, 0.25 to 1.00 mm particle size and four pressing cycles of 7 min; C1, 1.00 to 2.00 mm particle size and one pressing cycle of 7 min; C2, 1.00 to 2.00 mm particle size and two pressing cycles of 7 min; C3, 1.00 to 2.00 mm particle size and three pressing cycles of 7 min; and C4, 1.00 to 2.00 mm particle size and four pressing cycles of 7 min.

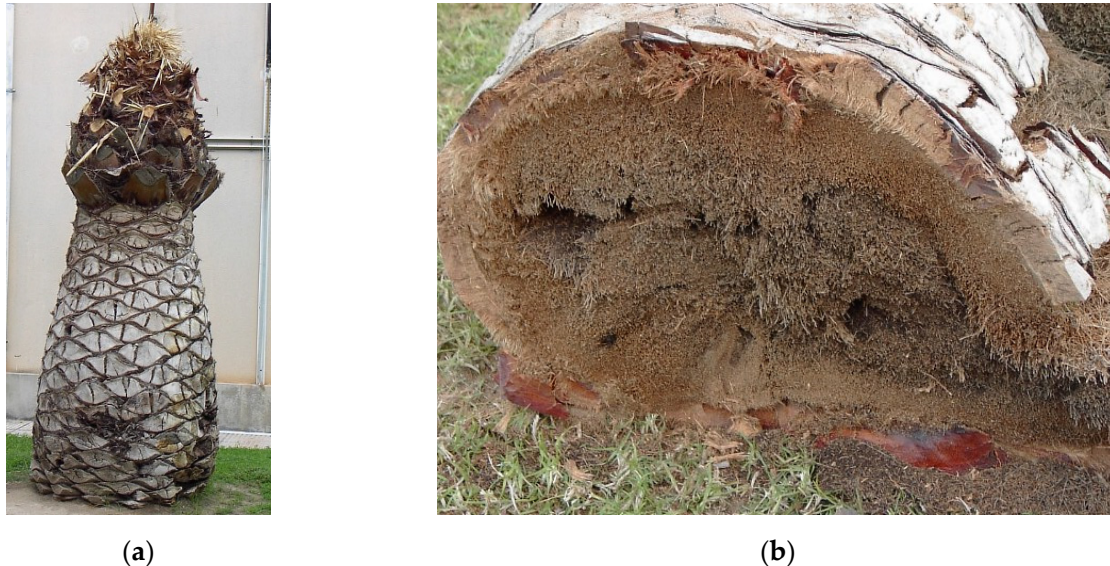


Figure 1. (a) Canary Island date palm infested with red palm weevils; (b) the infested trunk after being cut down.

The boards were made with a single layer and a thickness of approximately 7 mm. Four particleboards of each type were made. The characteristics of the manufactured boards are indicated in Table 1, and the boards with the 3 different particle sizes are shown in Figure 2.

Afterwards, the particleboards were cut into specimens in order to carry out the necessary tests for the characterization of the mechanical and physical properties of each of the 48 studied boards, with the dimensions indicated by the European Standards [48,49]. Subsequently, the specimens were conditioned in a JP Selecta conservation chamber (model Medilow-L, Barcelona, Spain) at a temperature of 20 °C for 24 h and a relative moisture content of 65%.

Table 1. Types of manufactured particleboards.

Type of Board	No. of Boards	Particle Size (mm)	Time (min)	Pressing Cycle	Temperature (°C)	Pressure (MPa)
A1	4	<0.25	7	1	110	2.6
A2	4	<0.25	7 + 7	2	110	2.6
A3	4	<0.25	7 + 7 + 7	3	110	2.6
A4	4	<0.25	7 + 7 + 7 + 7	4	110	2.6
B1	4	0.25 to 1.00	7	1	110	2.6
B2	4	0.25 to 1.00	7 + 7	2	110	2.6
B3	4	0.25 to 1.00	7 + 7 + 7	3	110	2.6
B4	4	0.25 to 1.00	7 + 7 + 7 + 7	4	110	2.6
C1	4	1.00 to 2.00	7	1	110	2.6
C2	4	1.00 to 2.00	7 + 7	2	110	2.6
C3	4	1.00 to 2.00	7 + 7 + 7	3	110	2.6
C4	4	1.00 to 2.00	7 + 7 + 7 + 7	4	110	2.6



Figure 2. Particleboards manufactured with 3 particle sizes (from left to right: type A, type B, and type C).

The properties of the particleboards were determined and evaluated while applying the current European Standards [50,51], including those for the density [52], the water absorption (WA) and thickness swelling (TS) after immersion in water for 2 and 24 h [53], the modulus of elasticity (MOE), the modulus of rupture (MOR) [54], the internal bonding strength (IB) [55], the thermal conductivity [55], and the reaction-to-fire performance using a single flame source [56–59].

To determine the moisture content of the boards in this study, an Imal laboratory moisture meter (model 200, from Modena, Italy) was utilized, while a heated tank with a water temperature of 20 °C was employed for the water immersion test.

The mechanical tests were conducted on an Imal universal testing machine (model IB600, Modena, Italy), and the thermal conductivity tests were performed on a heat-flow-measuring instrument (NETZSCH Instruments Inc., Burlington, MA, USA). The fire reaction tests were carried out on a flammability meter (model CEAST 1653, Turin, Italy).

Scanning electron microscopy (SEM) was used, and elemental analyses (qualitative and semiquantitative) were performed using energy-dispersive spectroscopy (EDS). Micrographs were taken from 0.5×0.5 cm fractured cross sections. An FEI brand Nova Nano SEM 200 field emission scanning electron microscope was used with the following characteristics:

- A resolution of 1 nm at 30 kV and 1.5 nm at 10 kV (under a vacuum);
- A throttle voltage of 200 V to 30 kV;
- A high-vacuum working mode for conductive samples and a low-vacuum working mode for semi- and non-conductive samples;
- An energy-dispersive X-ray microanalysis system (EDS or EDX), Oxford brand, model INCA X-Sight;
- SPSS v.28 software (IBM, Chicago, IL, USA) for performing a statistical analysis of variance (ANOVA) with a significance level of $\alpha < 0.05$ and Pearson correlations in order to measure the dependence of the manufacturing parameters.

3. Results and Discussion

3.1. Physical and Thermal Properties

The results for the density, thickness swelling, water absorption, and thermal conductivity of the manufactured boards are shown in Table 2.

Table 2. Average results of physical properties.

Type of Board	Density (kg/m ³)	TS 2 h (%)	TS 24 h (%)	WA 24 h (%)	WA 2 h (%)	Thermal Conductivity (W/m·K)
A1	882.32 (11.16)	45.65 (1.89)	58.78 (2.27)	63.57 (0.12)	84.10 (4.87)	0.075 (0.003)
A2	873.70 (28.63)	29.21 (2.28)	41.78 (1.27)	51.54 (4.70)	67.31 (0.64)	0.068 (0.004)
A3	1102.27 (26.07)	20.07 (1.94)	28.47 (2.49)	39.72 (1.27)	59.09 (1.29)	0.068 (0.003)
A4	1093.41 (61.32)	15.63 (3.61)	20.69 (0.62)	37.43 (13.75)	54.50 (8.69)	0.067 (0.004)
B1	840.98 (37.73)	19.13 (1.92)	38.73 (1.48)	61.57 (5.92)	94.48 (5.38)	0.070 (0.002)
B2	852.29 (68.66)	25.37 (10.30)	39.68 (9.61)	55.30 (10.69)	74.98 (7.75)	0.070 (0.001)
B3	935.46 (16.60)	16.02 (1.65)	29.05 (3.61)	37.52 (8.11)	75.46 (10.71)	0.060 (0.003)
B4	999.01 (53.90)	20.95 (10.42)	34.37 (20.90)	37.32 (7.91)	66.10 (11.19)	0.061 (0.002)
C1	750.94 (36.08)	16.70 (1.69)	21.60 (1.84)	63.96 (4.51)	89.20 (5.19)	0.064 (0.004)
C2	822.18 (62.91)	34.98 (6.24)	43.21 (4.89)	59.30 (13.72)	81.53 (3.88)	0.062 (0.004)
C3	1056.08 (40.64)	20.33 (4.53)	27.69 (6.41)	39.52 (7.78)	52.82 (7.73)	0.060 (0.003)
C4	1031.50 (37.97)	21.31 (3.32)	30.85 (1.43)	38.39 (5.73)	54.57 (2.49)	0.061 (0.002)

TS: thickness swelling; WA: water absorption; (): standard deviation.

The boards had a density between 750.94 kg/m³ and 1093.41 kg/m³, which was categorized as medium–high. This aligns with the densities obtained by other researchers for particleboards without binders [34]. A greater time in the hot plate press resulted in a higher density. Some of the average values did not reflect these results accurately due to the standard deviation, as certain data points may have skewed the mean value.

The panels subjected to a longer time in the press offered better results for thickness swelling (TS) and water absorption (WA). However, the parameters obtained did not allow these boards to be classified as P3 type (non-structural boards for use in dry environments) [49], since a limit of 17% TS after 24 h must be achieved.

The thermal conductivity of the boards ranged between 0.060 and 0.075 W/m·K. These were good results compared to those of commercial particleboards [47–49], with values between 0.180 and 0.070 W/m·K (depending on their density), and were similar to those of cork particleboards (0.065 W/m·K).

After performing an analysis of variance for the particle size and for the number of cycles (Table 3), it was observed that the density, TS, WA, and thermal conductivity (δ) depended on the number of pressing cycles and did not depend on the particle size. According to the Pearson correlation coefficient (PCC) values in Table 4, the density increased and the TS, WA, and δ decreased with a greater number of cycles.

Table 3. ANOVA results for manufacturing variables (particle size and cycle number).

Factor	Properties	Sum of Squares	d.f.	Half Quadratic	F	Sig.
Particle size	Density	48,068.923	2	24,034.4	1.979	0.152
	MOR	182.076	2	91.038	5.718	0.007
	MOE	890,667.25	2	445,333.627	1.176	0.319
	IB	0.935	2	0.467	27.595	0.000
	TS—2 h	150.696	2	75.348	0.913	0.410
	TS—24 h	118.200	2	59.100	0.390	0.680
	WA—2 h	8.275	2	4.137	0.023	0.977
	WA—24 h	1204.024	2	602.012	2.980	0.063
	Thermal conductivity (λ)	0.000	2	0.000	0.218	0.808
	Weight loss	0.056	2	0.028	11.754	<0.001
	Flame height	123.111	2	61.556	8.878	0.003
	Flame depth	5.422	2	2.711	0.664	0.529

Table 3. Cont.

Factor	Properties	Sum of Squares	d.f.	Half Quadratic	F	Sig.
No. of cycles	Density	354,021.437	3	118,007.146	28.088	0.000
	MOR	387.790	3	129.263	11.978	0.000
	MOE	10,260,552.869	3	3,420,184.290	25.220	0.000
	IB	0.325	3	0.108	3.202	0.034
	TS—2 h	794.738	3	264.913	3.933	0.016
	TS—24 h	1304.015	3	434.672	3.516	0.024
	WA—2 h	4398.009	3	1466.003	23.378	0.000
	WA—24 h	5259.819	3	1753.273	17.922	0.000
	Thermal conductivity (λ)	0.000	3	0.000	11.470	0.003
	Weight loss	0.012	1	0.012	2.314	0.148
	Flame height (Fs)	0.222	1	0.222	0.016	0.902
	Flame depth	14.942	1	14.942	4.620	0.047

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

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

Factor		Density	TS—24 h	WA—24 h	λ	MOR	MOE	IB	Fs
Particle size	PCC	−0.160	−0.100	−0.017	−0.190	−0.319 *	−0.089	−0.670 **	−0.728 **
	Sig.	0.317	0.534	0.917	0.555	0.042	0.582	0.000	<0.001
No. of cycles	PCC	0.780 **	−0.393 *	−0.747 **	−0.823 **	−0.376 *	0.784 **	0.404 **	0.031
	Sig.	0.000	0.011	0.000	0.001	0.015	0.000	0.009	0.902

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

3.2. Mechanical Properties

In accordance with the European Standards [50], the minimum requirements for the general use of particleboards with a thickness between 6 and 13 mm in dry environments are an MOR value of 10.5 N/mm² and an IB value of 0.28 N/mm² (grade P1). An MOR value of 11.0 N/mm², an MOE value of 1800 N/mm², and an IB value of 0.40 N/mm² are the minimum standards for the manufacture of furniture (grade P2). For a load (grade P3), the minimum values of MOR, MOE, and IB are 15.0 N/mm², 2.050 N/mm², and 0.45 N/mm², respectively.

The best mechanical performance (Figures 3–5) was achieved with the smallest particle size and four pressing cycles (A4-type board), which resulted in an MOR of 20.0 N/mm², an MOE of 2589.8 N/mm², and an IB of 0.74 N/mm².

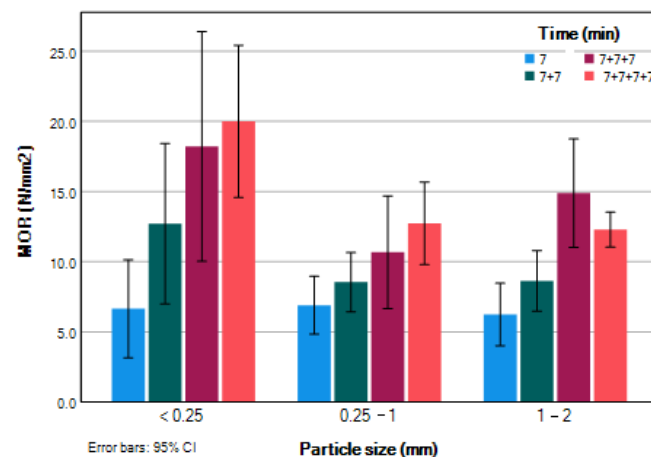


Figure 3. Modulus of rupture (MOR).

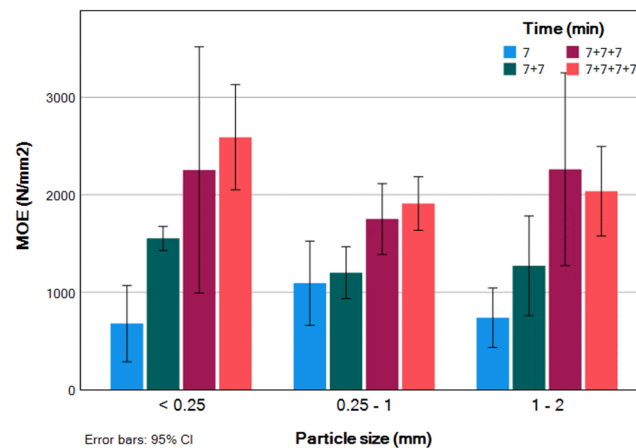


Figure 4. Modulus of elasticity (MOE).

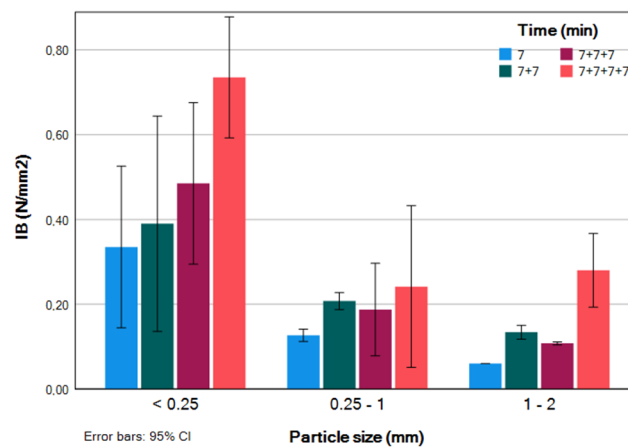


Figure 5. Internal bonding strength (IB).

Boards A3 and A4 could be classified as P2 as per the European Standards. They could not be categorized as P3, as they did not meet the necessary minimum 24 h TS value. Therefore, it would be recommended to apply a water-repellent product, similar to those used in the wood industry, to attain this classification. The boards with a particle size of 0.25 to 1 mm or 1 to 2 mm did not reach the necessary IB values.

According to analyses carried out by several researchers [13,35,60], one of the most important factors for the production of boards is the particle size. This is in line with the conclusion of this study that the best mechanical properties are attained with a smaller particle size.

Pintiaux et al. [34] indicated that, to manufacture vegetable fiberboards with other ecological binders (tannins, lignin, etc.), high temperatures are required (higher than 180 °C). However, in this work, the particleboards were manufactured from trunks of the Canary Island palm tree with temperatures of 110 °C, and this was acceptable as reflected in the specifications of the European Standards [48,49].

In a previous study [20], it was observed that the Canary Island date palm has large amounts of sugars, and it seems that the self-bonding mechanism is due to these sugars and the production of furfural. This indicates that the union of the particles is due to the furan resins obtained in the manufacturing process.

As can be seen in Table 5, in comparison to the results of previous studies on binderless palm tree trunk particleboards, the process of pressing cycles with lower temperatures and lower pressures yielded better results in terms of the mechanical properties of the resulting boards.

Table 5. Average values for palm tree trunk particleboards studied by different authors.

Material	Pressure (MPa)	Temp. (°C)	Time (min)	Density (kg/m ³)	TS—24 h (%)	MOR (N/mm ²)	MOE (N/mm ²)	IB (N/mm ²)	Source
Oil palm+10% UF	40	160	8	810	41.5	5.80	1149.6	1.16	[40]
Oil palm	12	180	20	800	20	13.37		0.71	[61]
Canary palm	2.6	120	30	838.5	27.56	13	1467.8	0.40	[20]
Canary palm	2.6	110	7 + 7 + 7 + 7	1093.4	20.69	20	2589.8	0.74	This study
Type P2					-	≥11	≥1800	≥0.40	[47]
Type P3					≤17	≥15	≥2050	≥0.45	[47]

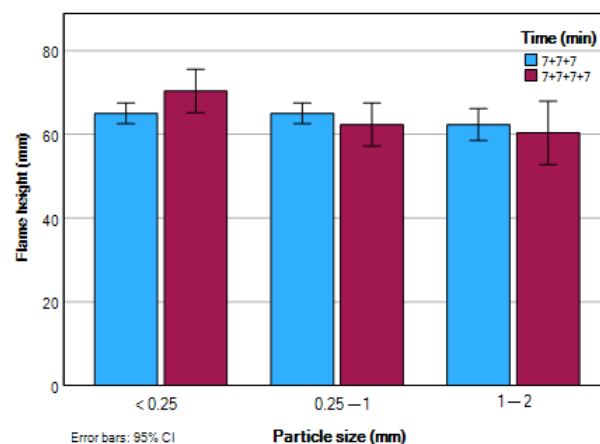
3.3. Reaction-to-Fire Performance

Three test specimens of the three-cycle and four-cycle boards were used to perform the reaction-to-fire test. As per the European Standards [57], the samples were conditioned to achieve a constant mass at a temperature of 23 ± 2 °C and a relative moisture content of $60 \pm 5\%$ RH before testing. Subsequently, the samples were vertically affixed to a frame and a flame was applied for 60 s at a 45° inclination, positioned 40 mm above the lower edge. Figure 6 shows some of the tested specimens.

**Figure 6.** Some specimens of Canary Island palm trunks used in the reaction-to-fire test.

Figure 6 shows that the burned area appeared to be superficial across all the tested specimens.

The results of the reaction-to-fire test are shown in Figures 7–9. The flame spread (Fs) is the measure of the flame height, and in all the specimens, it was from 60.3 to 70.4 mm.

**Figure 7.** Flame height (Fs) test results.

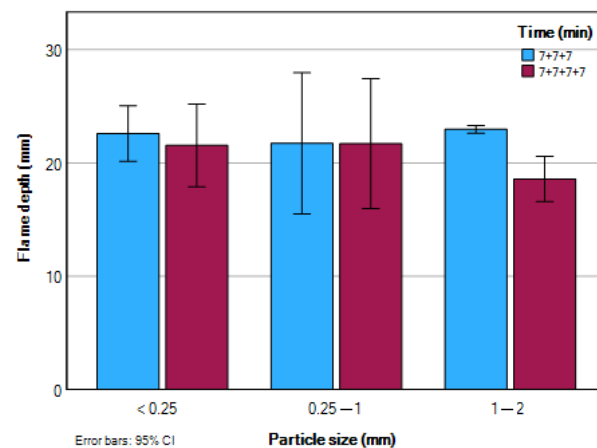


Figure 8. Flame depth test results.

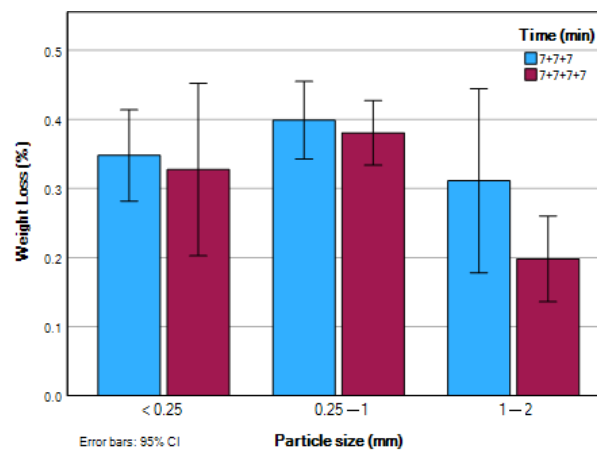


Figure 9. Weight loss of the specimens during the reaction-to-fire test.

Statistically, the analysis of variance (ANOVA; Table 3) indicated that the particle size influenced the weight loss and the flame spread (Fs) of the specimens, but the flame depth was influenced by the number of pressing cycles. Moreover, according to the bivariate Pearson's correlations (Table 4), the Fs decreased as the particle size increased; therefore, it did not have a direct relationship with weight loss. In addition, the values were within the admissible range. They corresponded to products obtained from a heterogeneous material, such as plants, and to the use of specimens from inside and outside the board for testing, as established by the European Standards [48].

Regarding the reaction-to-fire performance, the European Standards [58] establish that, when the Fs is less than 150 mm in 60 s, the boards are categorized as B. If there are also no burning drops or ignitions in any specimen, as was the case in this study, the boards are classified as d0. Therefore, the palm trunk particle boards without adhesives were classified as Bd0. To classify them as a higher class, flammability tests must be carried out.

Silicon-based chemical compounds are used as environmentally friendly fire retardants [62,63], and silica is recognized for its fire-retardant properties [42]; thus, the favorable behavior of the boards against fire could be attributed to the material's high silicon content. Silicon-based compounds form physically strong carbon/silica surface layers. These layers protect the substrate and serve as a barrier to prevent the migration of thermal degradation products to the surface [64,65].

By comparing the values obtained with those reported by other authors, as indicated in Table 6, we observed that the Canary palm boards had better properties against fire compared to other plant residues without any type of flame retardant, except vine prunings, which had large amounts of silica as well.

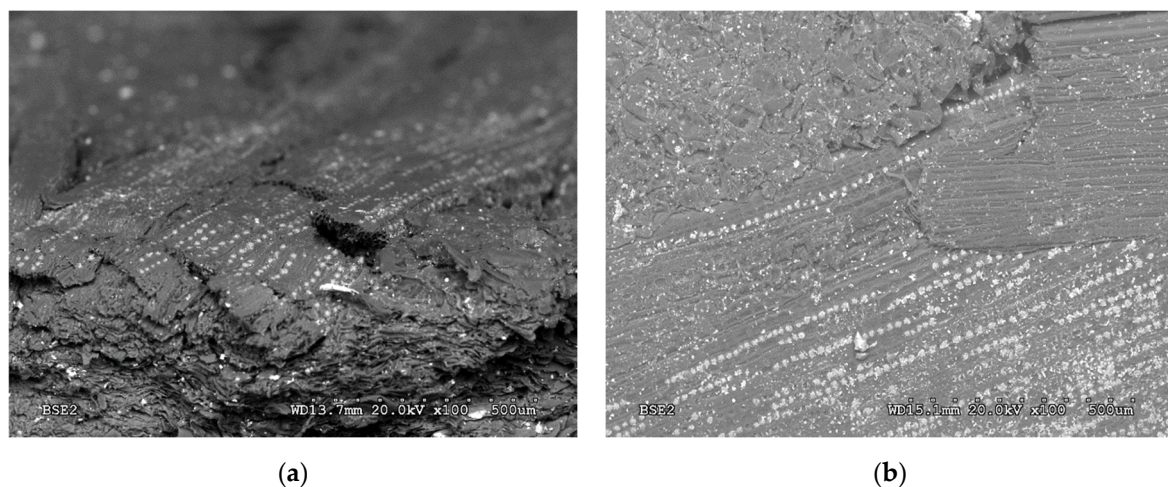
Table 6. Comparison of single-flame-source test results of particleboards in different studies.

Particleboard Material	Binder	Board Thickness (mm)	Flame Retardant	Flame Height (mm)	Source
Vine prunings	9% UF	7.5	-	41–67.78	[66]
Wood	10% UF	14	Phosphate-modified cellulose microfibrils	132	[67]
Cotton stalks	10% UF	14	Diammonium phosphate $(\text{NH}_4)_2\text{HPO}_4$ and boric acid	85.7	[68]
Corn stalks	10% UF	14	Diammonium phosphate $(\text{NH}_4)_2\text{HPO}_4$ and boric acid	88.4	[68]
Sawdust	10% UF	14	Diammonium phosphate $(\text{NH}_4)_2\text{HPO}_4$ and boric acid	91.1	[68]
Rice straw	10% UF	14	Diammonium phosphate $(\text{NH}_4)_2\text{HPO}_4$ and boric acid	92	[68]
Canary Island palm trunks	-	7	-	60.3–70.4	This study

The thickness and density of boards influence their time to ignition and weight loss: the lower the thickness, the shorter the time to ignition [69]. The boards in this work had a thickness of 7 mm, so it would be necessary to check whether the fire properties improve with thicker boards.

3.4. Evaluation of the Material Microstructure

In the micrograph of the longitudinal section of a Canary Island palm trunk (Figure 10a), the typical characteristics of vascular bundles were observed, consisting of fibers, vessels, and phloem embedded in the parenchymatic tissue. The SEM micrographs of the trunk samples indicated the presence of vascular bundles covered with large amounts of aligned siliceous phytoliths. This probably contributed to the lower thickness swelling in the boards made of Canary Island palm particles. In the EDS analysis, it was observed that the palm tree trunks had a high content of silicon phytoliths, and these silicon phytoliths were still arranged on the outside of the fibers in the boards manufactured with larger particles (Figure 10b). Therefore, these boards had better properties against fire. Figure 11 shows the characteristic shape of the Canary Island palm phytoliths.

**Figure 10.** (a) Canary Island palm trunk; (b) manufactured board with a particle size from 1 to 2 mm.

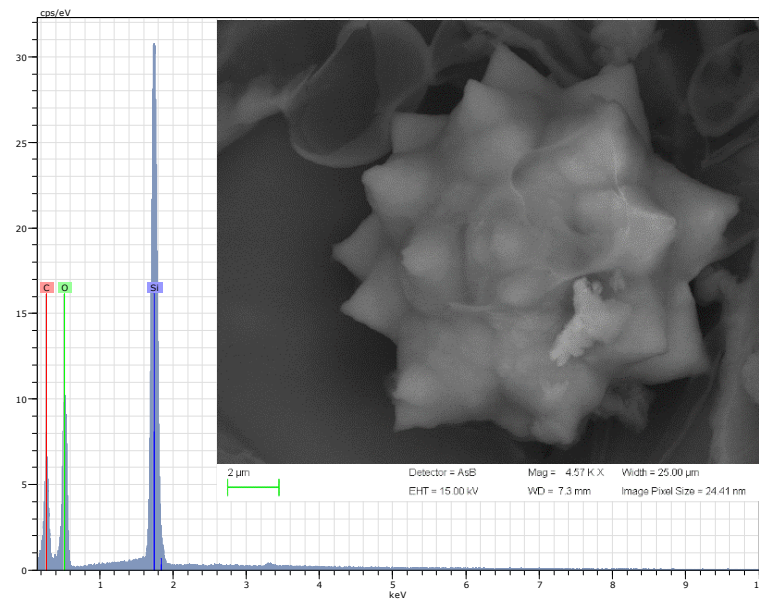


Figure 11. Phytolith from the trunk of a Canary Island palm tree.

4. Conclusions

In this study, binderless particleboards made from Canary Island palm trunks were successfully manufactured. The mechanical, physical, and thermal properties were analyzed, and the study concluded that, by using a manufacturing process with a low pressing temperature, particleboards can be manufactured from ecological materials. This variety of particleboard is a potential substitute for the traditional wood-based panels commonly utilized in construction, in addition to being environmentally friendly and following the principles of the circular economy.

The test results showed that the density, TS, WA, MOR, IB, thermal conductivity, and flame depth depended on the number of pressing cycles. The MOR, IB, Fs, and weight loss due to fire depended on the particle size used. To obtain more resistant boards, small particle sizes should be used; however, to make boards with better thermal and fire-resistant performance, larger particles and a lower number of pressing cycles should be considered. Therefore, in future research, two- and three-layer particleboards should be tested in order to combine both applications.

A3- and A4-type boards fall under the P2-grade classification (non-structural particleboards for indoor use) and exhibit favorable thermal performance. Hence, they could serve as interior enclosures for buildings, both vertically and horizontally, without requiring coatings. In future studies, consideration should be given to applying a water-repellent product or adjusting the dosages to enhance the properties of these boards for outdoor usage.

All the tested boards exhibited a good reaction-to-fire performance and were classified as Bd0, and those with a larger particle size had better properties. Moreover, the performance of the manufactured particleboards in this study was better than that of wood-based boards without fire retardants.

By using pressing cycles for the manufacture of boards, binderless boards with good properties were obtained. To improve this manufacturing process, it would be necessary to conduct additional tests by varying the time of each cycle, the temperature of the press, and the pressure. Moreover, subsequent aging and durability tests against environmental and biological factors should be performed.

The utilization of waste from Canary Island palm tree trunks to manufacture ecological and fire-retardant materials such as particleboards could offer environmental advantages by reducing air pollution and decreasing landfill waste accumulation.

Author Contributions: Conceptualization and methodology, T.G.-O. and M.T.F.-G.; research and experiments, B.E.F.-G. and M.F.-V.; resources, M.T.F.-G.; formal analysis, B.E.F.-G.; project administration, T.G.-O.; data curation, M.F.-V.; resources, M.T.F.-G.; writing—original draft preparation, 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.

Funding: This research was funded by the Second Vice Presidency and Ministry of Social Services, Equality and Housing of the Valencian Generalitat in Spain through the Plan IRTA, project HBIRT3-2023-1.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to thank the Second Vice Presidency and Ministry of Social Services, Equality and Housing of the Valencian Generalitat in Spain through the Plan IRTA, project HBIRT3-2023-1; Centro de Investigación e Innovación Agroalimentaria y Agroambiental (CIAGRO-UMH); and the University Miguel Hernandez for their support.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Sizirici, B.; Fseha, Y.; Cho, C.-S.; Yildiz, I.; Byon, Y.-J. A Review of Carbon Footprint Reduction in Construction Industry, from Design to Operation. *Materials* **2021**, *14*, 6094. [CrossRef] [PubMed]
2. Food and Agriculture Organization of the United Nations, FAO Stats. Available online: <http://www.fao.org/faostat/en/#data/FO> (accessed on 12 May 2024).
3. Chen, M.; Zheng, S.; Wu, J.; Xu, J. Study on preparation of high-performance binderless board from *Broussonetia papyrifera*. *J. Wood Sci.* **2023**, *69*, 17. [CrossRef]
4. Tahir, A.H.F.; Al-Obaidy, A.H.M.J.; Mohammed, F.H. Biochar from date palm waste, production, characteristics and use in the treatment of pollutants: A Review. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *737*, 012171. [CrossRef]
5. Almi, K.; Benchabane, A.; Lakel, S.; Krike, A. Potential utilization of date palm wood as composite reinforcement. *J. Reinf. Plast. Compos.* **2015**, *34*, 1231–1240. [CrossRef]
6. Sosa, P.A.; Saro, I.; Johnson, D.; Obon, C.; Alcaraz, F.; Rivera, D. Biodiversity and conservation of *Phoenix canariensis*: A review. *Biodivers. Conserv.* **2021**, *30*, 275–293. [CrossRef]
7. Murphy, S.T.; Briscoe, B.R. The red palm weevil as an alien invasive: Biology and the prospects for biological control as a component of IPM. *BioControl* **1999**, *20*, 35–46.
8. Ferry, M.; Gomez, S. The red palm weevil in the Mediterranean area. *Palms* **2002**, *46*, 172–178.
9. Garcia-Ortuño, T.; Ferrandez Garcia, M.T.; Andreu Rodriguez, J.; Ferrandez Garcia, C.E.; Ferrandez-Villena, M. Evaluating the properties of palm particle boards (*Washingtonia robusta* H. Wendl). In *Proceedings of the 6th Iberian Congress of Agroengineering, Evora, Portugal, 5–7 September 2011*; Sociedad Española de Agroingeniería: Valencia, Spain, 2011; pp. 126–130, ISBN 978-972-778-113-3, 5-7.
10. 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]
11. Ferrandez-Garcia, C.E.; Ferrandez-Garcia, A.; Ferrandez-Villena, M.; Hidalgo-Cordero, J.F.; Garcia-Ortuño, T.; Ferrandez-Garcia, M.T. Physical and mechanical properties of particleboard made from palm tree prunings. *Forests* **2018**, *9*, 755. [CrossRef]
12. Garcia-Ortuño, T.; Ferrandez-Garcia, M.T.; Andreu-Rodriguez, J.; Ferrandez-Garcia, C.E.; Ferrandez-Villena, M. Valorization of pruning residues: The use of *Phoenix canariensis* to elaborate eco-friendly particleboards. In *Proceedings of the Structures and Environmental Technologies. International Conference of Agricultural Engineering-CIGR-AgEng 2012, Valencia, Spain, 8–12 July 2012*; Federación de Gremios de Editores de España: Madrid, Spain, 2012; ISBN 978-84-615-9928-8.
13. Amirou, S.; Zerizer, A.; Pizzi, A.; Haddadou, I.; Zhou, X. Particleboards production from date palm biomass. *Eur. J. Wood Wood Prod.* **2013**, *71*, 717–723. [CrossRef]
14. Hegazy, S.; Ahmed, K.; Hizioglu, S. Oriented strand board production from water-treated date palm fronds. *BioResources* **2015**, *10*, 448–456. [CrossRef]
15. Hegazy, S.; Ahmed, K. Effect of date palm cultivar, particle size, panel density and hot water extraction on particleboards manufactured from date palm fronds. *Agriculture* **2015**, *5*, 267–285. [CrossRef]

16. Or, K.H.; Putra, A.; Selamat, M.Z. Oil palm empty fruit bunch fibers as sustainable acoustic material. In Proceedings of the Mechanical Engineering Research Day 2015 (MERD'15), Melaka, Malaysia, 31 March 2015; pp. 99–100.
17. Kerdthongmee, P.; Saleh, A.; Eadkhong, T.; Danworaphong, S. Investigating Sound Absorption of Oil Palm Trunk Panels Using One-microphone Impedance Tube. *BioResources* **2016**, *11*, 8409–8418. [\[CrossRef\]](#)
18. Kalaivani, R.; Ewe, L.S.; Chua, Y.L.; Ibrahim, Z. The Effects of Different Thickness of Oil Palm Trunk (Opt) Fiberboard on Acoustic Properties. *Sci. Int.* **2017**, *29*, 1105–1108.
19. Kriker, A.; Bali, B.; Debicki, G.; Bouziane, M.; Chabannet, M. Durability of date palm fibres and their use as reinforcement in hot dry climates. *Cem. Concr. Compos.* **2008**, *30*, 639–648. [\[CrossRef\]](#)
20. Ferrandez-Garcia, A.; Ferrandez-Villena, M.; Ferrandez-Garcia, C.E.; Garcia-Ortuño, T.; Ferrandez-Garcia, M.T. Potential use of *Phoenix canariensis* biomass in binderless particleboards at low temperature and pressure. *BioResources* **2017**, *12*, 6698–6712. [\[CrossRef\]](#)
21. Braiek, A.; Karkri, M.; Adili, A.; Ibos, L.; Nasrallah, S.B. Estimation of the thermophysical properties of date palm fibers/gypsum composite for use as insulating materials in building. *Energy Build.* **2017**, *140*, 268–279. [\[CrossRef\]](#)
22. Boumhaout, M.; Boukhattem, L.; Hamdi, H.; Benhamou, B.; Nouh, F.A. Thermomechanical characterization of a bio-composite building material: Mortar reinforced with date palm fibers mesh. *Constr. Build. Mater.* **2017**, *135*, 241–250. [\[CrossRef\]](#)
23. Bourmaud, A.; Dhakal, H.; Habrant, A.; Padovani, J.; Siniscalco, D.; Ramage, M.H.; Shah, D.U. Exploring the potential of waste leaf sheath date palm fibres for composite reinforcement through a structural and mechanical analysis. *Compos. A Appl. Sci. Manuf.* **2017**, *103*, 292–303. [\[CrossRef\]](#)
24. Cogliano, V.J.; Grosse, Y.; Baan, R.A.; Straif, K.; Secretan, M.B.; El Ghissassi, F.; Working Group for Volume 88. Formaldehyde, 2-Butoxyethanol and 1-Tert-Butoxypropan-2-ol. Meeting Report: Summary of IARC Monographs on Formaldehyde, 2-Butoxyethanol, and 1-tert-Butoxy-2-Propanol. *Environ. Health Perspect.* **2005**, *113*, 1205–1208. [\[CrossRef\]](#)
25. European Commission Homepage. Available online: https://single-market-economy.ec.europa.eu/news/chemicals-eu-restricts-exposure-carcinogenic-substance-formaldehyde-consumer-products-2023-07-14_en (accessed on 19 February 2024).
26. Imam, S.H.; Gordon, S.H.; Mao, L.; Chen, L. Environmentally friendly wood adhesive from a renewable plant polymer: Characteristics and optimization. *Polym. Degrad. Stab.* **2001**, *73*, 529–533. [\[CrossRef\]](#)
27. El-Wakil, N.A.; Abou-Zeid, R.E.; Fahmy, Y.; Mohamed, A.Y. Modified wheat gluten as a binder in particleboard made from reed. *J. Appl. Polym. Sci.* **2007**, *106*, 3592–3599. [\[CrossRef\]](#)
28. Ciannamea, E.M.; Stefani, P.M.; Ruseckaite, R.A. Medium-density particleboards from modified rice husks and soybean protein concentrate-based adhesives. *Bioresour. Technol.* **2010**, *101*, 818–825. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Moubarik, A.; Allal, A.; Pizzi, A.; Charrier, F.; Charrier, B. Preparation and mechanical characterization of particleboard made from maritime pine and glued with bio-adhesives based on cornstarch and tannins. *Maderas-Cienc. Tecnol.* **2010**, *12*, 189–197. [\[CrossRef\]](#)
30. Wang, Z.; Gu, Z.; Hong, Y.; Cheng, L.; Li, Z. Bonding strength and water resistance of starch-based wood adhesive improved by silica nanoparticles. *Carbohydr. Polym.* **2011**, *86*, 72–76. [\[CrossRef\]](#)
31. Ferrandez-Garcia, C.E.; Andreu-Rodríguez, J.; Ferrandez-Garcia, M.T.; Ferrandez-Villena, M.; Garcia-Ortuño, T. Panels made from giant reed bonded with non-modified starches. *BioResources* **2012**, *7*, 5904–5916. [\[CrossRef\]](#)
32. Ferrandez-Garcia, M.T.; Ferrandez-Garcia, C.E.; Garcia-Ortuño, T.; Ferrandez-Garcia, A.; Ferrandez-Villena, M. Experimental Evaluation of a New Giant Reed (*Arundo Donax* L.) Composite Using Citric Acid as a Natural Binder. *Agronomy* **2019**, *9*, 882. [\[CrossRef\]](#)
33. Matsumae, T.; Horito, M.; Kurushima, N.; Yazaki, Y. Development of bark-based adhesives for plywood: Utilization of flavonoid compounds from bark and wood. II. *J. Wood Sci.* **2019**, *65*, 9. [\[CrossRef\]](#)
34. 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. [\[CrossRef\]](#)
35. Chabriac, P.A.; Gourdon, E.; Glé, P.; Fabbri, A.; Lenormand, H. Agricultural by products for building construction and modeling to predict micro-structural parameters. *Constr. Build. Mater.* **2016**, *112*, 158–167. [\[CrossRef\]](#)
36. Lui, F.H.Y.; Kurokuchi, Y.; Narita, H.; Saito, Y.; Sato, M. The effects of chemical components and particle size on the mechanical properties of binderless boards made from oak (*Quercus* spp.) logs degraded by shiitake fungi (*Lentinula edodes*). *J. Wood Sci.* **2018**, *64*, 246–255. [\[CrossRef\]](#)
37. Terzopoulou, P.; Kamperidou, V. Chemical characterization of Wood and Bark biomass of the invasive species of Tree-of-heaven (*Ailanthus altissima* (Mill.) Swingle), focusing on its chemical composition horizontal variability assessment. *Mater. Sci. Eng.* **2021**, *17*, 469–477. [\[CrossRef\]](#)
38. Arufe, S.; Hellouin de Menibus, A.; Leblanc, N.; Lenormand, H. Physico-chemical characterisation of plant particles with potential to produce biobased building materials. *Ind. Crops Prod.* **2021**, *171*, 113901. [\[CrossRef\]](#)
39. European Council. *EU Construction Product Regulation No 305/2011*; CPR. COST Action FP1404; European Council: Brussels, Belgium, 2014.
40. Lazko, J.; Landercy, N.; Laoutid, F.; Dangreau, L.; Huguet, M.; Talon, O. Flame retardant treatments of insulating agro-materials from flax short fibres. *Polym. Degrad. Stab.* **2013**, *98*, 1043–1051. [\[CrossRef\]](#)

41. Selamat, M.E.; Hui, T.Y.; Hashim, R.; Sulaiman, O.; Kassim, M.H.M.; Stalin, N.J. Division of Bioresource, Paper and Coatings Technology, School of Industrial Technology, Universiti Sains Malaysia, 11800 USM Pulau Pinang, Malaysia. Properties of Particleboard Made from Oil Palm Trunks Added Magnesium Oxide as Fire Retardant. *J. Phys. Sci.* **2018**, *29*, 59–75. [\[CrossRef\]](#)
42. Lee, C.H.; Sapuan, S.M.; Hassan, M.R. A Review of the Flammability Factors of Kenaf and Allied Fibre Reinforced Polymer Composites. *Adv. Mater. Sci. Eng.* **2014**, *2014*, 514036. [\[CrossRef\]](#)
43. Ferrández-García, C.C.; García-Ortuño, T.; Ferrández-García, M.T.; Ferrández-Villena, M.; Ferrández-García, C.E. Fire-resistance, Physical, and Mechanical Characterization of Binderless Rice Straw Particleboards. *BioResources* **2017**, *12*, 8539–8549. [\[CrossRef\]](#)
44. Popescu, C.M.; Pfriem, A. Treatments and modification to improve the reaction to fire of wood and wood based products. An overview. *Fire Mater.* **2020**, *44*, 100–111. [\[CrossRef\]](#)
45. Wang, J.; Wei, Y.; Wang, Z.; He, X.; Wang, C.; Lin, H.; Deng, Y. MOFs-derived self-sacrificing template strategy to double-shelled metal oxides nanocages as hierarchical interfacial catalyst for suppressing smoke and toxic gases releases of epoxy resin. *Chem. Eng. J.* **2022**, *432*, 134328. [\[CrossRef\]](#)
46. Zhi, M.; Yang, X.; Fan, R.; Yue, S.; Zheng, L.; Liu, Q.; He, Y. A comprehensive review of reactive flame-retardant epoxy resin: Fundamentals, recent developments, and perspectives. *Polym. Degrad. Stab.* **2022**, *201*, 109976. [\[CrossRef\]](#)
47. Attia, N.F.; Elashery, S.E.; Zakria, A.M.; Eltaweil, A.S.; Oh, H. Recent advances in graphene sheets as new generation of flame retardant materials. *Mater. Sci. Eng. B.* **2021**, *274*, 115460. [\[CrossRef\]](#)
48. EN 312; Particleboards. Specifications. European Committee for Standardization: Brussels, Belgium, 2010.
49. EN 309; Particleboards. Definitions and Classification. European Committee for Standardization: Brussels, Belgium, 2005.
50. EN 13986:2004+A1; Wood-Based Panels for Use in Construction. Characteristics, Evaluation of Conformity and Marking. European Committee for Standardization: Brussels, Belgium, 2015.
51. EN 326-1; Wood-Based Panels. In Sampling, Cutting and Inspection. Part 1: Sampling and Cutting of Test Pieces and Expression of Test. European Committee for Standardization: Brussels, Belgium, 1994.
52. EN 323; Wood-Based Panels. Determination of Density. European Committee for Standardization: Brussels, Belgium, 1993.
53. EN 317; Particleboards and Fiberboards. Determination of Swelling in Thickness after Immersion in Water. European Committee for Standardization: Brussels, Belgium, 1993.
54. EN 310; Wood-Based Panels. Determination of Modulus of Elasticity in Bending and of Bending Strength. European Committee for Standardization: Brussels, Belgium, 1993.
55. EN 319; Particleboards and Fiberboards. Determination of Tensile Strength Perpendicular to the Plane of the Board. European Committee for Standardization: Brussels, Belgium, 1993.
56. 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. European Committee for Standardization: Brussels, Belgium, 2001.
57. EN ISO 11925-2; Reaction to Fire Tests—Ignitability of Products Subjected to Direct Impingement of Flame—Part 2: Single-Flame Source Test. European Committee for Standardization: Brussels, Belgium, 2020.
58. EN 13501-1; Fire Classification of Construction Products and Building Elements—Part 1: Classification Using Data from Reaction to Fire Tests. European Committee for Standardization: Brussels, Belgium, 2018.
59. EN 13823:2020+A1; Reaction to Fire Tests for Building Products. Building Products Excluding Floorings Exposed to the Thermal Attack by a Single Burning Item. European Committee for Standardization: Brussels, Belgium, 2022.
60. Ferrandez-Villena, M.; Ferrandez-Garcia, C.E.; Garcia-Ortuño, T.; Ferrandez-Garcia, A.; Ferrandez-Garcia, M.T. The Influence of Processing and Particle Size on Binderless Particleboards Made from *Arundo donax* L. Rhizome. *Polymers* **2020**, *12*, 696. [\[CrossRef\]](#) [\[PubMed\]](#)
61. Hashim, R.; Nadhari, W.N.A.W.; Sulaiman, O.; Hiziroglu, S.; Sato, M.; Kawamura, F.; Tanaka, R. Evaluations of some properties of exterior particleboard made from oil palm biomass. *J. Compos. Mater.* **2011**, *45*, 1659–1665. [\[CrossRef\]](#)
62. Liang, S.; Neisius, N.M.; Gaan, S. Recent developments in flame retardant polymeric coatings. *Prog. Org. Coat.* **2013**, *76*, 1642–1665. [\[CrossRef\]](#)
63. Giudice, C.A.; Pereyra, A.M. Silica nanoparticles in high silica/alkali molar ratio solutions as fire-retardant impregnants for woods. *Fire Mater.* **2010**, *34*, 177–187. [\[CrossRef\]](#)
64. Gardelle, B.; Duquesne, S.; Rerat, V.; Bourbigot, S. Thermal degradation and fire performance of intumescent silicone-based coatings. *Polym. Adv. Technol.* **2013**, *24*, 62–69. [\[CrossRef\]](#)
65. Kashiwagi, T.; Gilman, J.W.; Butler, K.M.; Harris, R.H.; Shields, J.R.; Asano, A. Flame retardant mechanism of silica gel/silica. *Fire Mater.* **2000**, *24*, 277–289. [\[CrossRef\]](#)
66. Ferrandez-Villena, M.; Ferrandez-Garcia, C.E.; Garcia-Ortuño, T.; Ferrandez-Garcia, A.; Ferrandez-Garcia, M.T. Analysis of the thermal insulation and fire-resistance capacity of particleboards made from vine (*Vitis vinifera* L.) prunings. *Polymers* **2020**, *12*, 1147. [\[CrossRef\]](#) [\[PubMed\]](#)
67. Benhamou, A.A.; Boussetta, A.; Kassab, Z.; Nadifiyine, M.; Sehaqui, H.; El Achaby, M.; Moubarik, A. Application of UF adhesives containing unmodified and phosphate-modified cellulose microfibers in the manufacturing of particleboard composites. *Ind. Crops Prod.* **2022**, *176*, 114318. [\[CrossRef\]](#)

-
68. El-Sayed, G.H.; Atallah, M.M.; Ahmad, M.I.M. Production of Fire-Resistant Particle Boards from some Agricultural Residues. *J. Soil Sci. Agric. Eng.* **2021**, *12*, 145–151. [[CrossRef](#)]
 69. Tureková, I.; Ivanovičová, M.; Harangózo, J.; Gašpercová, S.; Marková, I. Experimental Study of the Influence of Selected Factors on the Particle Board Ignition by Radiant Heat Flux. *Polymers* **2022**, *14*, 1648. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.