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Properties of Wood Particleboards Containing Giant Reed (*Arundo donax* L.) Particles

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Abstract: Agriculture is responsible for generating large amounts of waste that are not adequately managed in terms of their environmental treatment and economic administration. This work uses giant reed, which was traditionally used as a construction material in eastern areas of Spain. Nowadays, it is no longer used, which has led to its rapid, autonomous, uncontrolled proliferation on river banks, making it a serious environmental hazard because this plant causes significant blockages of bridges and other infrastructure when uprooted by the strong currents that occur as rivers flood. The aim of this work is to develop wood and giant reed particleboards, which help to counter the high dependence on wood in industrial manufacturing by using an easily renewable resource. It will thereby be possible to achieve two general objectives: controlling the growth of a weed and obtaining a product (particleboards) from a waste material. Particleboards containing 9% urea formaldehyde composed of different proportions of sawmill wood and giant reed (0, 50, 70 and 100%) have been manufactured by applying two different pressures (2.1 and 2.6 MPa) and a temperature of 120 °C for 4 min in a hot plate press. Density, thickness swelling (TS) and water absorption (WA) after immersion in water, modulus of elasticity (MOE), modulus of rupture (MOR), internal bonding strength (IB) and screw holding strength (SH) have been tested according to european norms (EN) for wood boards. With the addition of 70% reed particles, the density, MOR and TS decrease and the MOE, IB and SH increase; therefore, adding giant reed particles to wood boards can improve their properties, bringing about considerable industrial and environmental benefits.

Keywords: plant waste; particleboards; physical; mechanical and thermal properties

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1. Introduction

Wood is the most widely used lignocellulosic material in pulp manufacture, the furniture industry, the construction industry and as fuel. Every year, a surface area of 11 million hectares of forest is lost globally due to the production of wood for industrial and fuel purposes, in addition to the deforestation caused by the expansion of pastures, crops and urban development [1]; it is therefore an environmental problem.

According to the European "EUwood" study [2], wood consumption for energy generation is expected to increase from a solid volume of 346 million m^3 in 2010 to 573 million m^3 in 2020, and it could reach as much as 752 million m^3 by 2030. These results are based on an assumed reduction of the share of wood in energy from renewable sources from 50% in 2008 to 40% in 2020. By 2025, the deficit of wood is expected to be 200 million m^3, which will increase to 300 million by 2030. Due to a decreasing availability of wood, the use of particleboards is constantly growing in the furniture industry. They are also known as a form of hardboard and fibreboard called MDF (Medium Density Fibreboard), which are obtained from wood chips and a binder.

Over the last decade, there has been a deterioration in the mechanical properties of commercial particleboards in countries where forest resources are scarce. The main reason for this decline in quality is the increased use of recycled materials obtained from old furniture rather than using shredded natural wood. The use of recycled materials has been favoured, on the one hand, by the high cost of natural wood, and, on the other hand, by the fact that their use can help alleviate the shortage of raw material for the particleboard industry, thus helping to reduce the environmental impact of furniture production by reducing pressure on forests. National governments and the EU have promoted recycling at all stages. Therefore, the search for substitutes for natural wood, such as non-woody plants and the use of an organic binder, is currently of interest. Lignocellulosic materials from waste generated in agricultural activities could be used as a substitute for natural wood, but to achieve this, it is necessary to demonstrate that their fibres are suitable for manufacturing boards.

In order to reduce the consumption of natural wood, studies have been conducted regarding the production of particleboards using wood particles combined with different plant residues and using urea formaldehyde (UF) as an adhesive resin. The following materials have been used for this: sunflower stalks [3,4], peanut hull [5,6], walnut shell [7], walnut and almond shells [8], hazelnut shell [9], walnut and hazelnut shells [10], coffee parchment [11], cocoa industrial waste [12], rice straw [13], sycamore leaves [14], castor husk [15], tobacco stalk [16], apple and plum pruning [17] and grass clippings [18].

Reeds are the largest type of grass growing in Mediterranean regions, a wild plant to which no genotype selection or genetic improvement has been made. Giant reed is a weed that grows annually, reaching average heights of 4 m and a mean thickness of 4 cm. It is a perennial plant that forms dense reed beds. Reed has been used in construction since ancient times in Mediterranean countries, but it is now in disuse. In cases where reeds grow on river banks, when the water level rises, they are uprooted and carried away on the current, forming large masses that block watercourses, causing flooding and sweeping away any structure that gets in their way; they are therefore an environmental problem.

There are also studies on the use of giant reed (*Arundo donax* L.) in particleboards with different adhesives such as urea formaldehyde [19], starch [20] and citric acid [21].

In this work, we study the possibilities of manufacturing hybrid wood and *Arundo donax* L. particleboards that could easily be produced in the wood board industry to counter the high dependence on wood imports by using an easily renewable resource such as the giant reed. The aim is to control a weed while at the same time obtaining a mixed board composed of wood and giant reed that could reduce the pressure on forest resources and create new job opportunities.

2. Materials and Methods

The materials used to manufacture boards were giant reed (*Arundo donax* L.) particles, pine wood particles from the particleboard industry and a binder consisting of 9% urea formaldehyde diluted in water and 0.4% ammonium sulphate with respect to the weight of the wood-reed particles.

The reed biomass came from clearing of the River Segura, in south-east Spain. The reeds were dried outdoors for 6 months. They were then cut and shredded in a blade mill.

The particle size distribution of pine wood and giant reed particles, classified according to sieve size, is shown in Table 1. The moisture content of both types of particles was 9%.

The methodology followed is the manufacture of particleboards composed of different proportions of wood and giant reed (0%, 50%, 70% and 100%). The mat was formed in a mould (600 mm × 400 mm) and was pressed and heated in a plate. Temperature and pressure time were 120 °C and 4 min, respectively. Pressure varied from 2.1 to 2.6 MPa. Temperatures ranging from 180 to 200 °C and pressures of around 3.5 MPa are used in the manufacture of commercial particleboards, so with the parameters selected for this work, we intended to use a manufacturing process involving lower energy consumption than the industrial process.

Table 1. Size distributions of pine wood and giant reed particles.

Sieve (mm)	Pine Wood Particles (%)	Giant Reed Particles (%)
4	36.4	24.9
2	26.3	30.1
1	27.1	20.4
0.5	5.3	14.4
0.25	2.0	6.5
0.125	2.2	2.1
0.063	0.4	1.5
<0.063	0.3	0.1

The boards consisted of a single layer with a thickness of approximately 6.5 mm. The eight types of particleboards manufactured in this study are shown in Table 2. Samples of the type-B board series are shown in Figure 1.

Table 2. Types of board manufactured.

Type of Board	Proportion of Pine Wood Particles (%)	Proportion of Giant Reed Particles (%)	Pressure (MPa)	Time (min)	Temperature (°C)	Number of Boards
A1	100	0	2.1	4	120	4
A2	50	50				
A3	30	70				
A4	0	100				
B1	100	0	2.6			
B2	50	50				
B3	30	70				
B4	0	100				

Figure 1. Photograph of the sample boards tested, measuring 50 × 50 mm.

The European standards for wood particleboards [22] were used to determine the properties. The properties of the boards measured according to the European standards were: density [23], thickness swelling (TS) and water absorption (WA) after 2 and 24 h immersed in water [24], internal bonding strength (IB) [25], modulus of elasticity (MOE) and modulus of rupture (MOR) [26] and screw holding strength (SH) [27]. The boards were evaluated according to the European standard [28]. The thermal conductivity was measured using the heat flow meter method [29].

Before testing, the samples were placed in a JP Selecta refrigerated cabinet (model Medilow-L, Barcelona, Spain) at a temperature of 20 °C and a relative humidity of 65% for 24 h.

Water content of the particleboards was obtained with an Imal laboratory moisture meter (model 200, Modena, Italy), whereas the immersion test was performed in a water tank heated to 20 ºC.

An Imal universal testing machine (Model IB600, Modena, Italy) was used to perform the mechanical tests and a heat flow meter (NETZSCH Instruments Inc., Burlington, MA, USA) was used for the thermal conductivity tests.

For the statistical analysis of variance (ANOVA) at a significance level of $\alpha < 0.05$, we used SPSS software for Windows v.26 (IBM, Chicago, IL, USA).

3. Results and Discussion

3.1. Physical Properties

Table 3 shows the density, thickness swelling and water absorption results according to the type of board.

Table 3. Physical properties of eight types of particleboards.

Type of Board	Density (kg/m^3)	TS 2 h (%)	TS 24 h (%)	WA 2 h (%)	WA 24 h (%)
A1	842.91 (5.93)	26.04 (0.57)	27.70 (0.95)	53.52 (4.80)	52.08 (0.81)
A2	695.27 (22.39)	13.51 (0.52)	15.95 (0.55)	57.55 (5.46)	63.59 (8.83)
A3	632.72 (23.54)	12.20 (0.41)	14.23 (0.23)	56.49 (1.52)	61.69 (3.75)
A4	631.41 (26.19)	12.36 (0.82)	34.46 (4.69)	14.88 (0.78)	46.34 (7.80)
B1	850.20 (44.54)	22.83 (2.07)	24.61 (2.56)	52.86 (5.23)	57.69 (5.17)
B2	743.26 (21.29)	16.44 (1.60)	18.03 (1.87)	54.54 (3.37)	61.28 (3.08)
B3	741.73 (37.47)	15.64 (1.29)	18.30 (1.98)	45.90 (6.67)	54.65 (7.84)
B4	738.16 (30.02)	12.12 (3.45)	23.29 (5.31)	16.25 (2.59)	41.35 (5.63)

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

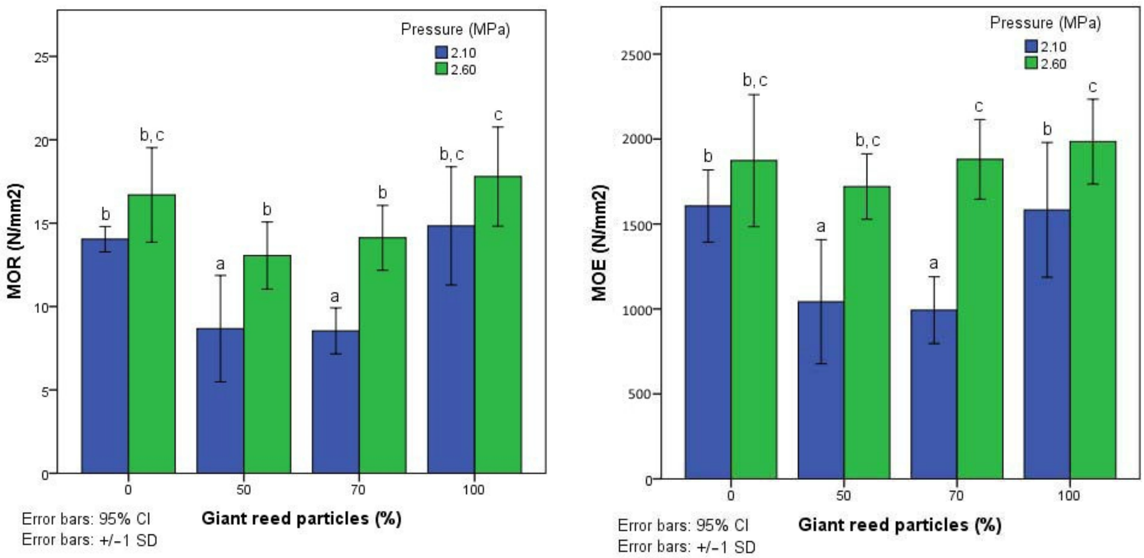
All the boards obtained can be considered to have a medium density. The highest density boards are type A1 and B1, with 100% wood particles from industry. Mixed boards with 70% reed particles (A3 and B3) produce the lowest density boards.

Type A2, A3, B2 and B3 mixed wood-giant reed boards produce lower % thickness swelling (TS) values than those of the other boards and similar water absorption (WA) values to those obtained with 100% wood particleboards. Two regions of the giant reed plant can be distinguished: the outer region or epidermis, which has a regular pattern of normal, small, densely-walled epidermal cells, intermixed with oval-shaped siliceous cells, and the inner region, formed by cells with large, thin walls [30]. The greatest water absorption takes place in the inner region of the reed particles, since the composition of the epidermis offers greater resistance to this phenomenon. This would therefore explain the low water absorption after 2 h offered by type A4 and B4 boards (100% reed particles).

The addition of giant reed particles improves the properties of 100% wood boards because it decreases the density and TS.

3.2. Mechanical Properties

Figure 2 shows the modulus of elasticity (MOE) and modulus of rupture (MOR) values obtained for the eight types of particleboard tested. The deviations from the values shown in Figure 2 are described in Supplementary Materials Table S1.

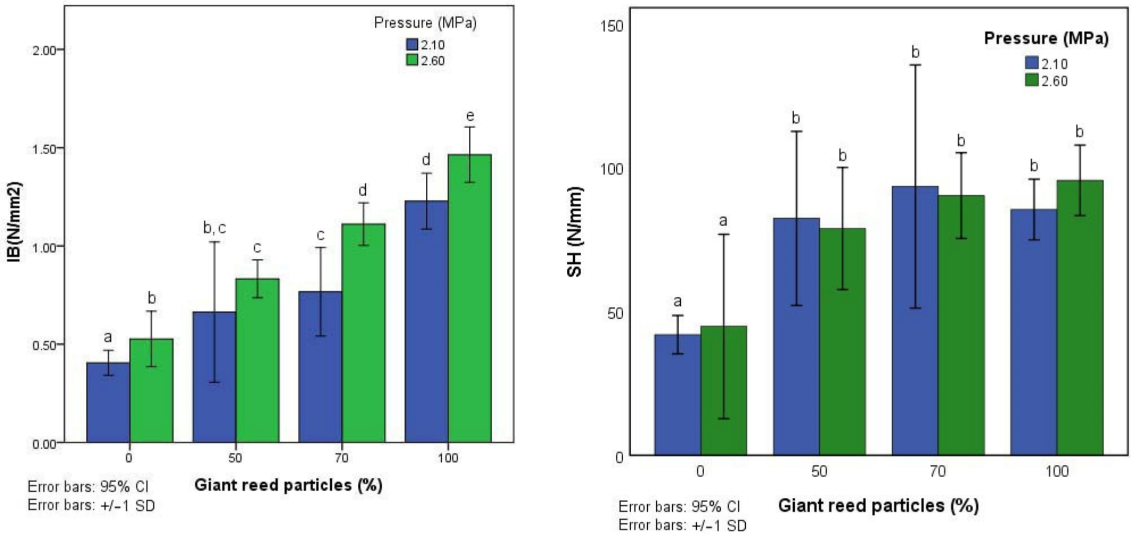


(**a**) (**b**)

Figure 2. Modulus of rupture (MOR) and Modulus of elasticity (MOE) values of the eight particleboards. Values with the same letter are not significantly different based on Duncan's multiple range test at the 0.05 level. (**a**) MOR values; (**b**) MOE values.

The best results for MOR and MOE were attained when the composition contains 100% giant reed particles, achieving the best performance when the pressure applied was 2.6 MPa. With a pressure of 2.1 MPa for the mixed wood-reed boards the MOR and MOE decrease, and with a pressure of 2.6 MPa, the MOR and MOE values obtained are similar to those of the 100% wood particle boards. With 70% reed particles and a pressure of 2.6 MPa (type B3 board), an MOR value of 14.1 N/mm^2 and MOE value of 1880 N/mm^2 were obtained.

This same trend can be observed in the results obtained for internal bonding strength (IB) and screw hold (SH), as shown in Figure 3, where the best mechanical parameters were achieved with type B4 boards. In mixed boards, the addition of giant reed particles was found to increase the IB and SH. With 70% reed particles and a pressure of 2.6 MPa, an IB of 1.11 N/mm^2 and an SH of 90.24 N/mm^2 was obtained. The deviations from the values shown in Figure 3 are described in Supplementary Materials Table S1.



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

Figure 3. IB and SH values of the eight particleboards. Values with the same letter are no significantly different based on Duncan's multiple range test at the 0.05. (**a**) IB values; (**b**) SH values.

As can be seen from the ANOVA in Table 4, all the physical properties except for MOE depended on the percentage of giant reed added. The density, MOR, MOE and thermal conductivity also depended on the pressure applied.

Table 4. ANOVA of the results of the tests.

Factor	Properties	Sum of Squares	d.f.	Half Quadratic	F	Sig.
% of reed added	Density (kg/m^3)	65,724.901	3	21,908.300	6.252	0.002
	TS 24 h (%)	1260.236	3	420.079	17.876	0.000
	WA 24 h (%)	2054.597	3	684.866	16.689	0.000
	MOR (N/mm^2)	162.434	3	54.145	5.832	0.002
	MOE (N/mm^2)	533,881.466	3	177,960.489	1.187	0.329
	IB (N/mm^2)	3.451	3	1.150	40.724	0.000
	SH (N/mm)	9422.803	3	3140.934	12.105	0.000
	Thermal C. (W/m·K)	0.002	3	0.001	12.108	0.000
Pressure applied	Density (kg/m^3)	34,161.109	1	34,161.109	8.196	0.007
	TS 24 h (%)	98.413	1	98.413	1.835	0.184
	WA 24 h (%)	20.619	1	20.619	0.220	0.642
	MOR (N/mm^2)	93.261	1	93.261	8.755	0.005
	MOE (N/mm^2)	2,517,539.649	1	2,517,539.649	28.529	0.000
	IB (N/mm^2)	0.344	1	0.344	3.108	0.086
	SH (N/mm)	105.462	1	105.462	0.212	0.648
	Thermal C. (W/m·K)	0.001	1	0.001	8.074	0.007

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

The minimum requirements established by the European standard [28] for general use in dry conditions (Grade P1) are an IB of 0.28 N/mm^2 and a MOR of 10.5 N/mm^2. For furniture manufacturing (Grade P2), the minimum values required are an IB of 0.40 N/mm^2, a MOE of 1800 N/mm^2 and an MOR of 11.0 N/mm^2. For non-structural boards for use in humid conditions, the minimum requirements are an IB of 0.45 N/mm^2, a MOE of 2050 N/mm^2, a MOR of 15 N/mm^2 and 17% for TS at 24 h.

The best mechanical results for mixed boards are achieved with 30% wood and 70% giant reed (board B3) at a pressure of 2.6 MPa. As shown in Table 5, board B2 could be classified as P1 and board B3 would achieve P2 classification.

Table 5. Mechanical and physical properties and classification of B2 and B3 boards according to the European regulations [28].

Type of Board	MOR (N/mm^2)	MOE (N/mm^2)	IB (N/mm^2)	TS 24 h (%)
B2	13.1	1.734	0.83	18.03
B3	14.1	1.880	1.11	18.30
Grade P1	10.5	-	0.28	-
Grade P2	11.0	1.800	0.40	-
Grade P3	15.0	2.050	0.45	17.00

Previous studies have manufactured particleboards made of walnut and almond shells [8] at 160 °C, which obtained the required properties for use in indoor conditions. Boards manufactured with a ratio of 6:94 grass clippings with eucalyptus [18] have achieved the mechanical properties required for interior fittings, including furniture and general use. Scatolino et al. [11] concluded that the mechanical properties of the boards were improved by adding 10% coffee parchment particles and applying a temperature of 160 °C. Other works established that in order to meet the standards required for MOR, the maximum proportion of walnut shell [7] that should be added was 20% and for peanut shell [5], it was 25%. Using castor husk as a raw material for the production of particleboards mixed with pine wood [15] and 8% UF and applying a pressure of 3.92 MPa and a temperature of 160 °C for 8 min, the mechanical strength of the particleboards generally decreased as the content of castor husk increased. Up to 50% castor husk can be added to pine wood to produce particleboards that are suitable for indoor applications. Good mechanical performance is obtained in this work with 70% reed particles, and the boards obtained with the application of a temperature of 120 °C and a pressure of 2.6 MPa for 4 min was found to achieve the mechanical performance requirements for indoor applications (including furniture) for use in dry conditions (Grade P2). Therefore, boards made of giant reed waste material have similar results of other studies of mixed boards while using a higher percentage of a lignocellulosic residue in a lower energy consumption process.

3.3. Thermal Conductivity

For the boards tested in this work, significant differences in thermal conductivity (Figure 4) were found between the types analysed, obtaining mean values between 0.0575 and 0.0804 W/m·K. They can therefore be considered as a good thermal insulating material, but it should be noted that B4 boards are the type with the best thermal properties. The addition of giant reed particles to the boards manufactured in this work provides similar thermal conductivity results to the boards using only wood particles. The deviations from the values shown in Figure 4 are described in Supplementary Materials Table S1.

Khedari et al. [31] performed a study using durian peel and coconut coir with 12% UF to manufacture particleboards, concluding that the boards had low thermal conductivity, ranging from 0.0540 to 0.1854 W/m·K; however, the mechanical properties obtained with these boards were quite low.

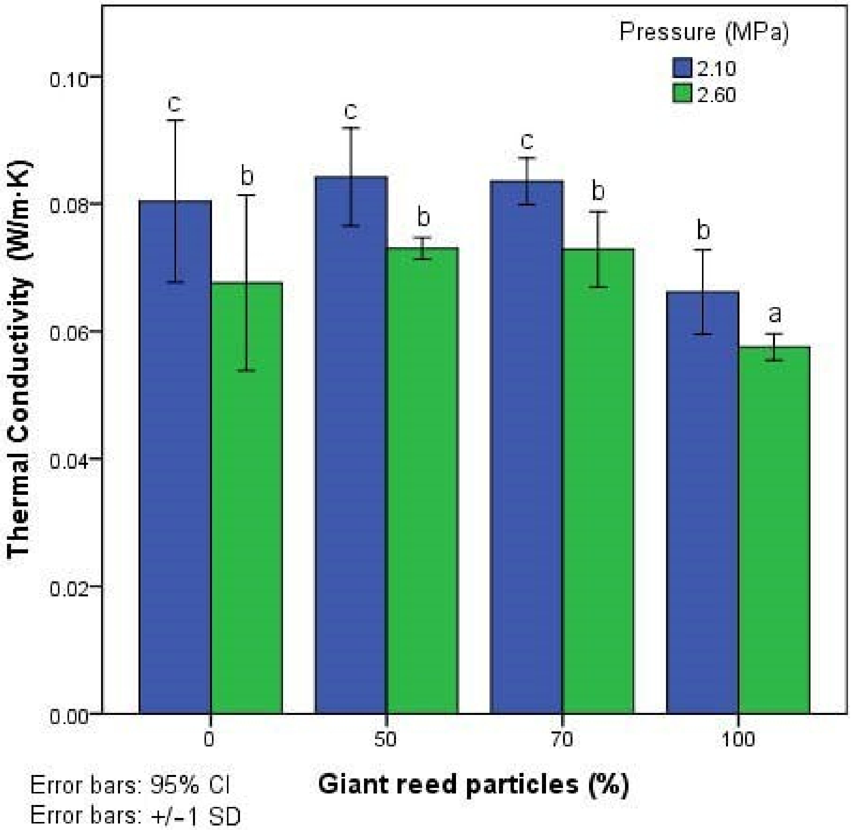


Figure 4. Thermal conductivity values of eight particleboards. Values with the same letter are no significantly different based on Duncan's multiple range test at the 0.05.

4. Conclusions

By adding reed particles to wood particleboards, the density is reduced and the TS, IB and SH are improved. Therefore, giant reed is a plant fibre that can be added to wood particles to enhance the properties of wood boards.

The best results are achieved for mixed wood and giant reed boards manufactured with 70% reed particles and applying a pressure of 2.6 MPa, obtaining boards with a Grade P2 classification (for the manufacture of furniture and interior décor in dry conditions). These boards also have good thermal properties, so they could be used for interior divisions in buildings without the need for coatings. Future research should seek appropriate dosages and the application of some kind of water-repellent product that would allow us to manufacture boards that achieve the properties required for outdoor use.

The use of giant reed particles in the manufacturing of mixed wood boards could be an interesting alternative because it contributes to the development of more sustainable materials, involving lower energy consumption than industrial wood boards.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/24/10469/s1, Table S1: Average results of mechanical and thermal properties.

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