



Article

Influence of the Density in Binderless Particleboards Made from Sorghum

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Abstract: In order to fight climate change and decouple economic growth from material use, valorization of waste will be fundamental. Sorghum is one of the most important summer crops in the world. The non-edible parts of the plant, the stalks and leaves are left over and must be disposed of. This work proposes to use sorghum waste particles as a raw material to manufacture boards and analyze the influence of its density. Particles were sprayed with 10% wt of water and placed in a hot press at 2.1 MPa and 110 °C for 30 min. Eight types of panels were produced with densities ranging from 950 kg/m³ to 1250 kg/m³. The results indicated that the water absorption (WA), modulus of rupture (MOR), modulus of elasticity (MOE) and internal bonding strength (IB) depended on the density. With higher densities, the particleboards showed better physical and mechanical behavior. This study demonstrates that it is technically possible to manufacture adhesive-free particleboards from sorghum residues that comply with European standards and can be used as boards for general applications. The use of these particleboards could be beneficial in fighting climate change and in minimizing the use of natural wood.

Keywords: agricultural residues; plant waste; valorization; *Sorghum bicolor* L. Monech; fiberboard



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1. Introduction

In recent years, scientific research has shown that climate change is one of the most serious and complex threats to be faced on a global scale. The variation in the average temperature of the planet can affect ecosystems and natural communities, generating negative impacts on their life cycle. Greenhouse gases generated by human activities are causing global warming which leads to changes in the global climate, producing increasingly severe negative effects on the population, the environment and the economy [1,2].

The European Union (EU) is at the forefront of the international fight against climate change, applying ambitious measures to reduce its emissions to make the EU the first climate-neutral continent by 2050 [2].

Agricultural activity generates a large amount of biomass that is often not reused, such as stubbles, cereal straws and prunings from crops. Traditionally, the way to dispose of this waste is by burning it onsite. This is the common practice for economic and technical reasons in countries such as Spain, since the cost of this process is lower than other alternatives. However, burning agricultural residues also entails an environmental cost [3], since it constitutes an important source of direct greenhouse gas emissions, such as carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), and indirect ones such as carbon monoxide (CO), nitrogen oxide (NO_x) and sulfur oxide (SO_x). On the other hand, the burning of agricultural residues has an impact on the fauna and flora of the area, as well as causing problems for human health (respiratory conditions) and posing a risk for the spread of fires.

Between 1990 and 2020, forest area decreased from 32.5% to 30.8% of the total land area, representing a net loss of 178 million hectares due to the production of wood for

industrial and fuel purposes, and to deforestation caused by agricultural expansion, the last being the main driver of deforestation and forest degradation [4]. Wood is the most widely used lignocellulosic material worldwide for the manufacture of paper pulp, furniture, the construction industry and as fuel. However, in this industry, due to the lack of wood, the use of particleboard (chipboard) is continuously growing. Agricultural waste could replace wood as the raw material in particleboard production, making this industry more environmentally friendly [5].

Sorghum is one of the most important summer crops in the world after soya, corn and sunflower. The present global production is about 57 million tons of grain from 42.6 million hectares [6]. Besides its traditional use for food, animal fodder and the production of alcoholic beverages, sorghum is a source of starches and glucose for the pharmaceutical industry and for biofuel. After harvest, the non-edible parts of the plant, the stalks and leaves are left over and must be disposed of. One option to solve this problem is using this waste as raw material for producing wood-based composites [7].

In order to make these composites more environmentally friendly, investigations have been focused on obtaining particleboards without using any binder product: rice stalk [8,9], kenaf [10,11], cotton stalk [12], sugarcane [13], coconut shell [14], almond residues [15], date palm [16–18], oil palm [19–21], canary palm [22], bamboo [23] and olive tree leaves [24].

Sorghum was successfully used in the manufacturing of particleboards with urea formaldehyde (UF) [25,26], phenol formaldehyde (PF) [26], isocyanate [26], citric acid (CA) [27–29] and maleic acid (MA) [30]. However, when this residue was used without adhesives, it showed reduced mechanical properties [27].

For the reasons mentioned above, this work proposes to use sorghum straw waste particles as a raw material to manufacture boards, with the main goal of developing a value-added application for this residue. The objective was to obtain a totally ecological product without adhesives and to assess the influence of the density of the panels on its physical and mechanical characteristics.

2. Materials and Methods

2.1. Materials

The raw material used in this study was sorghum waste, comprising straw and leaves, and water from the municipal network.

The sorghum was obtained from a field in the city of Orihuela, Alicante (Spain). It was cleaned from impurities and left outside for air drying (Figure 1). The particles were obtained using a ring knife chipper and then they were screened using a sieving machine to obtain particles of less of 0.25 mm. Before manufacturing, the material had a moisture content approximately of 10% wt.



Figure 1. Sorghum waste used for manufacturing the experimental boards.

No binders or waxes were used in the process.

2.2. Methods

Boards were manufactured by following a dry process. After pressing, the finished particleboards were trimmed to avoid edge effects and then cut into various sizes for an evaluation of their properties according to the European standards established for wood particleboards [31]. Finally, the results of the panels were determined [32], evaluated [33] and assessed by statistical methods: analysis of variance (ANOVA) for a significance level of $\alpha < 0.05$ and the standard deviation for the mean values of the tests (SPSS v. 28.0 software (IBM, Chicago, IL, USA)).

2.2.1. Board Manufacture

The process started by forming a mat in a mold of 400×600 mm. Particles were then sprayed with 10% wt of water and placed in a hot press at 2.1 MPa and 110°C for 30 min.

In order to analyze the influence of the density of the boards, 8 target densities were set, from 900 to 1250 kg/m^3 , varying the amount of material of the boards while maintaining the thickness of the particleboards at 7 mm.

The mat formation was in a single layer. Four sample panels were made for each combination of parameters, as seen in Table 1. The finished panels were conditioned at 20°C and 65% relative air humidity for a week.

Table 1. Characteristics of the experimental panels.

Panel Type	Number	Density (kg/m^3)	Particle Size	Time (min)	Temp. ($^\circ\text{C}$)
900	4	900	<0.25	30	110
950	4	950			
1000	4	1000			
1050	4	1050			
1100	4	1100			
1150	4	1150			
1200	4	1200			
1250	4	1250			

2.2.2. Experimental Tests

The experimental tests consisted of measuring the physical properties of the panels, namely density [34], thickness swelling (TS) and water absorption (WA) after 2 and 24 h of immersion [35], and the mechanical properties: modulus of rupture (MOR), modulus of elasticity (MOE) [36] and internal bonding strength (IB) [37].

Each panel was cut to obtain six samples for determining the density ($50\text{ mm} \times 50\text{ mm}$), three for the determining WA and TS ($70\text{ mm} \times 70\text{ mm}$), six for the measurements of MOR and MOE (different lengths, depending on the thickness, $\times 50\text{ mm}$ width) and three for the measurement of IB ($50\text{ mm} \times 50\text{ mm}$).

The moisture content of the material was measured in a laboratory moisture meter (model UM2000, Imal S.R.L., Modena, Italy) and the water immersion test was carried out in a heated tank.

The density and the mechanical properties were evaluated with a universal testing machine (model IB700, Imal, S.R.L., Modena, Italy) operating at a velocity of $5\text{ mm}\cdot\text{min}^{-1}$ for the bending test and $2\text{ mm}\cdot\text{min}^{-1}$ for internal bonding strength.

3. Results

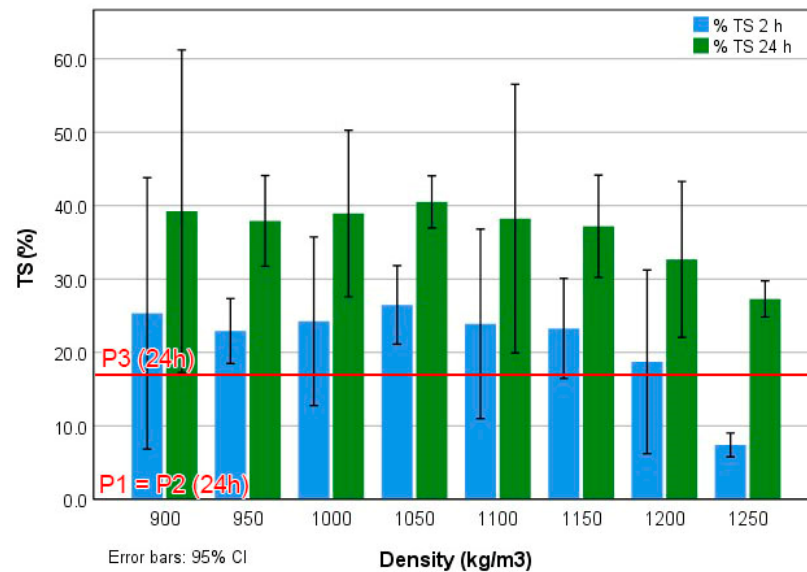
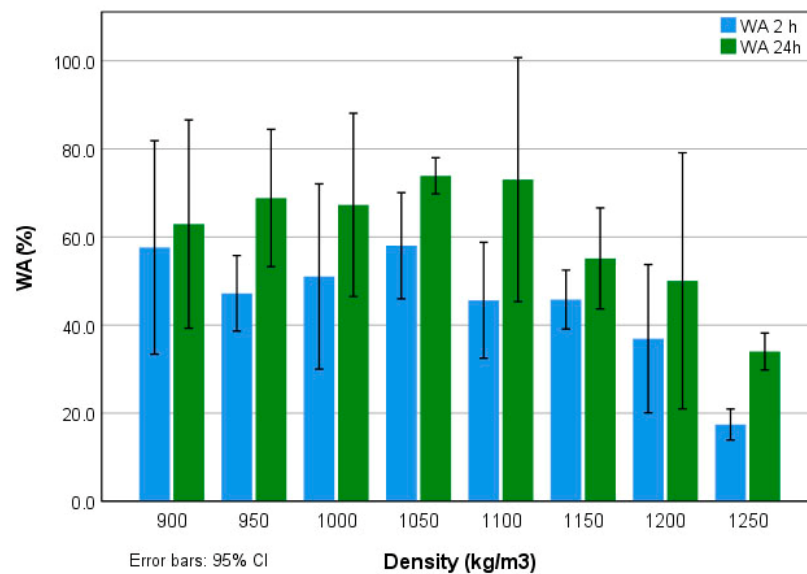
3.1. Physical Properties

In Table 2, the average density and standard deviation of the 8 types of particleboards manufactured are shown.

Table 2. Target and average density and standard deviation of the experimental panels.

Panel Type	900	950	1000	1050	1100	1150	1200	1250
Target density (kg/m ³)	900	950	1000	1050	1100	1150	1200	1250
Average density (kg/m ³)	912.9	976.3	1014.5	1069.3	1104.7	1146.9	1208.8	1250.8
Standard deviation	11.88	7.87	5.17	13.68	23.34	8.29	17.54	14.03

Figures 2 and 3 show the results of the TS and WA test after 2 and 24 h.

**Figure 2.** Thickness swelling (TS) after 2 and 24 h of the experimental panels and the minimum requirements of the European standards [33].**Figure 3.** Water absorption (WA) after 2 and 24 h of the experimental panels. European standards [33] do not apply to this property.

A large standard deviation of the values was found after 2 h and 24 h of immersion in water, probably due to the fact that some samples came from center of the particleboards while others were extracted from the outer part. However, it appears that particleboards with lower density had higher swelling results.

Similar to TH, a significant deviation in the WA results was observed for each type of panel. Starting from a target density of 1150 kg/m^3 , the particleboards absorbed less water. The boards with the lowest WA value were Type 1250 with a WA of 34.02%, whereas the boards that absorbed the highest amount of water were Type 1050 with a WA of 73.91%. Therefore, the WA results were influenced by the density.

Since the thickness of the particleboards had been fixed, boards with lower density had fewer particles. This produced air gaps inside the panels, which then were more easily filled with water. To increase the stability against water in the particleboard industry, different water-repellent substances are added. This could improve the results of the particleboards made from sorghum.

3.2. Mechanical Properties

Figures 4–6 shows the test results for MOR, MOE and IB respectively. The MOR values ranged between 5.4 N/mm^2 and 19.6 N/mm^2 . It can be observed that types with lower density had lower MOR values, while their performance improved as the density increased until reaching good results according to the European standards [33] from the Type 1050 particleboards and thereafter.

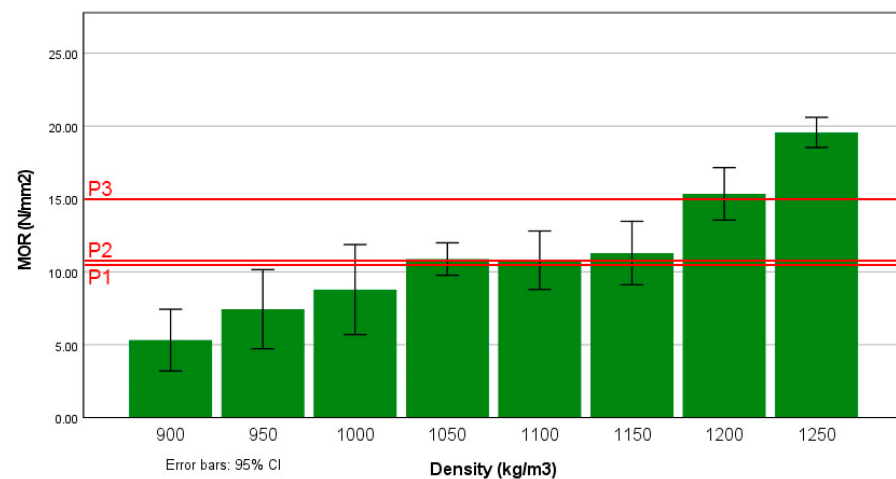


Figure 4. Modulus of rupture (MOR) results of the experimental panels and the minimum requirements of the European standards [33].

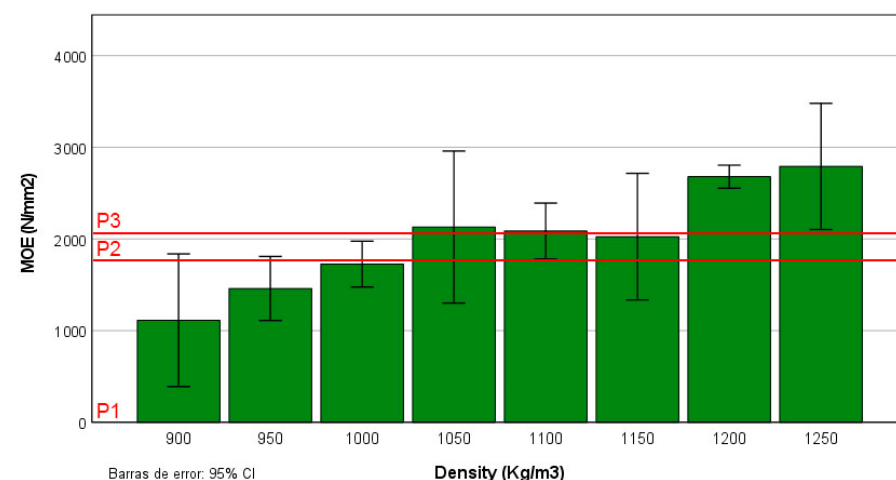


Figure 5. Modulus of elasticity (MOE) results of the experimental panels and the minimum requirements of the European standards [33].

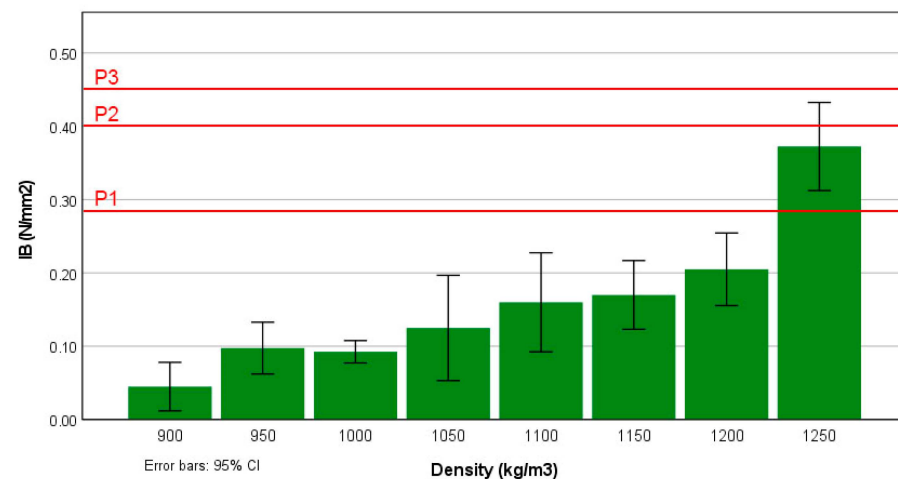


Figure 6. Internal bonding strength (IB) results of the experimental panels and the minimum requirement of the European standards [33].

The MOE test results had a large deviation for some of the types; however, a trend can be inferred from the figure. Type 900 had a MOR value of 1113 N/mm², whereas Type 1250 had a value of 2792 N/mm². According to the results, density had a great influence on the MOE results.

The great difference in the MOR and MOE values among the types of experimental particleboards can be justified again by the fact that the higher the density, the higher the number of particles in the particleboard. Therefore, boards with higher density had a lower total volume of air gaps, and hence, the amount of particles to resist stress was greater.

The IB values, as in the previous cases, increased with higher densities. Type 1250 boards reached average values of 0.37 N/mm²; in contrast, Type 900 boards had average values of 0.05 N/mm².

3.3. Statistical Analysis

To elucidate whether TS and WA depended on the density of the particleboards, an ANOVA was carried out and is shown in Table 3. The results indicated that WA was influenced by the density; however, contrary to all the other properties, TS did not have a significant dependence on the density.

Table 3. ANOVA of the results of the tests.

Factor	Properties	Sum of Squares	d.f.	Half Quadratic	F	p-Value
Density	TS 2 h (%)	1058.092	7	151.156	3.425	0.011
	TS 24 h (%)	538.283	7	76.898	1.338	0.276
	WA 2 h (%)	4791.327	7	684.475	7.870	0.000
	WA 24 h (%)	5194.868	7	742.124	4.986	0.001
	MOR (N/mm ²)	568.118	7	81.160	46.028	0.000
	MOE (N/mm ²)	9,070,832.001	7	1,295,833.143	10.688	0.000
	IB (N/mm ²)	0.281	7	0.040	39.564	0.000

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

3.4. Comparison with European Standards

A comparison between the properties obtained for the experimental particleboards and the required values specified in the European standards [33] with a thickness of 6 to 13 mm is shown in Table 4 in order to determine the boards' classification.

Table 4. Average properties of the experimental panels and the European standards' requirements [33].

Panel Type	MOR (N/mm ²)	MOE (N/mm ²)	IB (N/mm ²)	TS 24 h (%)
900	5.32	1113	0.05	39.25
950	7.44	1460	0.10	37.93
1000	8.79	1726	0.10	38.94
1050	10.88	2130	0.13	40.51
1100	10.80	2087	0.16	38.25
1150	11.29	2026	0.17	37.21
1200	15.35	2680	0.21	32.68
1250	19.57	2792	0.37	27.29
Type P1 [33]	10.50	-	0.28	-
Type P2 [33]	11.00	1800	0.40	-
Type P3 [33]	15.00	2050	0.45	17.00

Type 1050, 1100, 1150, 1200 and 1250 boards could be classified as P1 boards, which are specified for general use in a dry environment, according to their MOR values. However, only Type 1250 can meet the requirements, since its IB value is higher than 0.28 N/mm². This type of panel cannot be classified as P2 or P3 because it could not reach the necessary IB and TS values.

4. Discussion

The majority of the studies consulted [38] indicated that in order to manufacture boards without adhesives, temperatures higher than 180 °C are needed. Table 5 shows some other investigations that used lower pressing temperatures than 180 °C and achieved particleboards with good results.

Table 5. Properties obtained for binderless particleboards made from vegetable fibers.

Source	Material	Temp. (°C)	Time (min)	Density (kg/m ³)	TS 24 h (%)	MOR (N/mm ²)	MOE (N/mm ²)	IB (N/mm ²)
[39]	Giant reed rhizome	110	7 + 7	883	52.73	14.24	1904	0.75
[17]	Date palm	180	2	1200	150.00	8.40	928	0.13
[40]	Oil palm	180	20	800	20.00	13.57		0.71
[22]	Canary palm	120	30	850	27.56	13.00	1468	0.40
[9]	Rice straw	110	30 + 30	1140	53.75	15.09	2697	0.18
This work	Sorghum	110	30	1250	27.29	19.57	2792	0.37

Boards manufactured from sorghum consume less energy than those made from oil palm [40], canary palm [22] and rice straw [9], and had, in general, better results than those made from giant reed rhizome [39] and date palm [17]. The properties of the sorghum particleboards could be improved by changing the manufacturing parameters such as time or temperature, but further research is needed.

It can be concluded that with low pressing temperatures and short pressing times, it is feasible to manufacture sorghum particleboards with good properties in comparison with other materials that could be commercialized, since they comply with the specifications of the European standards [33].

In Table 6, a comparison of the characteristics and behavior of other particleboards made from sorghum can be observed.

From the results of these investigations, it can be concluded that, when using a binder in the same proportion, isocyanate resin is a better adhesive than UF and PF for improving the physical and mechanical properties of particleboards. It is also possible that increasing the pressing temperature results in better MOE value for all adhesives [26].

Investigating the effect of adding AC to manufacture sorghum particleboards [27], the authors used a binderless panel as control group that showed bad mechanical properties. However, this panel was manufactured without adding any water to the particles. These authors recommended drying the particles as a pretreatment, since it improved the results.

Table 6. Properties obtained for particleboards made from sorghum residues.

Source	Binder	Particle Size (mm)	Temp. (°C)	Press. (MPa)	Time (min)	Density (kg/m ³)	TS 24 h (%)	MOR (N/mm ²)	MOE (N/mm ²)	IB (N/mm ²)
[25]	UF (5%)	0.25–4.00	120	2.1–2.6	4	644–853	14–89	3.5–5.1	398–920	-
[26]	UF (10%)	0.57	120–130	2.45	8–10	690–790	20–65	4.9–9.3	1078–1863	0.03–0.15
[26]	PF (10%)	0.57	170–180	2.45	8–10	680–810	7–10	4.4–5.9	980–1176	0.15–0.23
[26]	Isocyanate (7%)	0.57	150–160	2.45	8–10	690–800	9–15	13.7–25.5	1863–3328	0.40–0.78
[27]	AC (0–30%)	0.90–5.90	200	6.5	10	800	10–170	4.0–22.0	900–3500	0.03–0.98
[28]	AC (20%)	0.90–5.90	140–220	6.5	2–15	800	10–85	10.0–22.0	2800–5200	0.40–0.90
[29]	AC + sucrose (0:100–100:0) (20%)	0.90–5.90	200	6.5	10	800	10–23	16.0–30.0	3900–7000	0.50–1.17
[30]	MA (20%)	4.00–20.00	200	6.5	10	800	7–8	12.0–13.0	2800–3300	0.22–0.25
This work	-	<0.25	110	2.1	30	913–1251	27–41	5.3–19.6	1113–2792	0.05–0.37

According to Kusumah et al. [28] sorghum bagasse-based particleboard using CA adhesive requires a temperature of 200 °C, but higher temperatures are considered inefficient. In their study, this pressing temperature was the most effective in terms of mechanical behavior, since at 220 °C, the properties decreased. They noted that this might be due to material degradation and lead to embrittlement of the surface layer. The authors also indicated that 10 min is an effective pressing time to obtain good bending properties, since their panels had a slight decrease in their mechanical behavior at 15 min due to degradation of the material and adhesive. In the present work, the panels were pressed for 30 min but no adhesive was used. It could be that the decrease in the properties was only related to the addition of CA.

Other research [29] investigated the addition of sucrose to the sorghum panels and concluded that it effectively reduced the brittleness of the particleboard bonded with CA. With a proportion of 10:90 CA/sucrose, the particleboards achieved the best results.

Sutiawan et al. [30] used MA instead of CA in the same proportion. Their results showed that while the TS improved, the mechanical values were not as high as with CA.

In all these studies, a similar range of density was used. However, in comparison with these authors, the present work showed that density had a great influence on the physical and mechanical behavior of the particleboards and that it is feasible to manufacture sorghum boards with good mechanical properties without any binder or adhesive.

5. Conclusions

It is feasible to manufacture adhesive-free particleboards from sorghum residues with reduced energy costs (low temperature and pressure), which achieved good mechanical properties.

Sorghum particleboards without adhesives manufactured with a density of 1250 kg/m³ meet the European standards and could be used in general applications.

The mechanical properties of the particleboards increased with higher densities, probably caused by boards with higher density having fewer air gaps; hence, the amount of particles to resist mechanical effort is higher.

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