

EVALUATION OF BEAN RESIDUES IN THE PRODUCTION OF AGGLOMERATED PANELS

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ABSTRACT

This work aimed to evaluate the physical-mechanical properties of *Pinus oocarpa* wood agglomerated panels produced with different levels (0 %, 25 %, 50 %, 75 % and 100 %) of wood replacement with bean residues. For this purpose, *Pinus oocarpa* wood and the agricultural residue were reduced into particles and their properties of apparent density, extractives, lignin and ash content of these raw materials were determined. Then, the particles were dried to a 3 % humidity and granulometrically selected to produce panels with a density of 0,60 g/cm³. These particles were bonded using 12 % urea-formaldehyde adhesive, pressed, following normative dimensions (250 mm x 250 mm x 15 mm (width, length, and thickness)), and kept in a climate-controlled environment (20 °C ± 2 °C and 65 % ± 5 % RH) until the physical and mechanical tests were carried out. The research results indicated that the particles from bean residues in comparison with *Pinus oocarpa* wood, presented low density, lignin and holocellulose values, and higher extractives data. Furthermore, regarding the characterization of the panels, there was a trend towards uniformity in the apparent density values, an increase in the properties of compact ratio, water absorption and thickness swelling, and a decrease in their mechanical properties associated with the increase in the by-product addition to the panels. Therefore, new studies are necessary, seeking a larger study and greater knowledge of the addition effects of bean residues in particulate panels, aiming the dissemination of this sustainable process on large scale.

Keywords: Agglomerates, agricultural residues, *Pinus oocarpa*, sustainability, urea-formaldehyde.

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INTRODUCTION

Agglomerated sheet panels are obtained by reducing wood or lignocellulosic materials into particles, which, after being dried and bonded employing synthetic adhesive, are formed through the action of heat and pressure ABNT NBR 14810-1 (2013).

Such products stand out among wood-based goods and are considered the most consumed materials worldwide in this field. In this sense, panel industries are characterized by a constant search for innovation and technology, which favors the development of new and sustainable production processes, mainly aimed at popularizing this material. Wood species, such as the *Pinus oocarpa*, present medium hardness, high strength and other desirable physical-mechanical properties, mainly for the furniture industry, however, and even though it is not the most expensive raw material, it is responsible for approximately 59 % of the panel's costs and one of the ways of greater accessibility to the public is through their replacement by cheaper products (ABIPA 2020).

In this context and in view of the current great social demand for the diffusion of economic and ecological processes in the different branches of human activities, several agricultural residues have been evaluated regarding the influence of their addition in particulate panels, such as soybean (Borges *et al.* 2022), grape (Wong *et al.* 2020), cotton (Nguyen *et al.* 2020), corn (Prasetyo *et al.* 2020), sugarcane bagasse (Soares *et al.* 2017), hazelnut (Çöpür *et al.* 2007), coffee (Scatolino *et al.* 2017, Santos *et al.* 2022), rice (Ayrilmis *et al.* 2012), coconut (Narciso *et al.* 2020). Particles of wheat (Gomes *et al.* 2023), bamboo (Gomes *et al.* 2021, Miranda *et al.* 2022) and bean (Miranda *et al.* 2023) were also evaluated in matrices of other composite materials of gypsum, cement and polymer.

Bean residues emerge among the mentioned crops as they are highly produced in Brazil and worldwide; for example, the 2020/2021 Brazilian crop production projections reach 265,90 million tons of edible beans. From which its residues, pods, vines, stalks, leaves, roots, among others, were estimated at 146 million tons (CONAB 2020).

Studies found in literature argued that these residues generated from the agroindustry can be reused in improving the digestion of ruminants (Fuma *et al.* 2012, Ngwe *et al.* 2011). Though, research on the addition effect of bean residues on the physical and mechanical properties of reconstituted wood panels are still incipient and, needs to be further developed to verify the feasibility of using agricultural residues in this industrial sector. The use of these residues in wooden panels would meet the sustainability requirements of today's society in the panel industry, with the popularization of these products, and in the agricultural industry, with the reuse of underutilized waste.

Hence the objective of this project is the evaluation of the physical-mechanical properties of particulate panels with the replacement of *Pinus oocarpa* wood by bean crop residues.

MATERIAL AND METHODS

Experimental

The bean residues used in the experiment, stems and pods, came from the harvest remains of the bean *Phaseolus vulgaris* species. The material was obtained from the Pimentas farm (Lavras, Minas Gerais, Brazil) and collected after natural drying.

The *Pinus oocarpa* wood was obtained by cutting 100 cm logs with an average diameter of 35 cm from 25-year-old trees experimentally planted on the campus of the Federal University of Lavras (UFLA).

These two materials, the bean residues and *Pinus oocarpa* wood, were processed at the Wood Panel Experimental Unit (UEPAM) using a high-speed hammer mill and sieved for the production of agglomerated panels. The selected particles were those passing through the 40 mesh sieve and retained on the 60 mesh sieve

The resulting particles were then characterized "in natura" in apparent density - NBR 14810-2 (2018), total extractives - ABNT NBR 14853 (2010), acid-insoluble lignin - ABNT NBR 7989 (2010) and ash content - ABNT NBR 13999 (2017). Also, the holocellulose (H) content was calculated by difference. All tests were done in triplicate.

Specimen preparation

After the characterization, agglomerated panels were produced following five treatments (Table 1).

Table 1: Treatments to be analyzed in this study.

Treatments	<i>Pinus oocarpa</i>	Bean waste
	(%)	(%)
T1	100	0
T2	75	25
T3	50	50
T4	25	75
T5	0	100

For the production, the particles were dried to 3 % humidity in an oven and urea-formaldehyde adhesive (solids content of 70,04 %, pH 6,86, viscosity 1810 cP and gelatinization time of 53 s) was then sprayed in 12 % proportion to the dry mass through a colander until complete homogenization of the components. The mixture was then taken to a mat-forming box.

The formed mat was pre-pressed in a 30-t capacity hydraulic press, at room temperature and at 0,4 MPa pressure. Then, metal delimiters with a thickness of 15 mm were added and the mixture was hot-pressed at 160 °C and 4,0 MPa pressure for 10 minutes (ABNT NBR 14810-2 (2018)).

Two panels of each treatment were produced with a 0,60 g/cm³ nominal density, shaped into 250 mm x 250 mm x 15 mm (width, length, and thickness) dimensions and trimmed to normative sizes using a circular saw. The resulting samples were kept in a climate-controlled environment (20 °C ± 2 °C and 65 % ± 5 % RH) until the physical and mechanical tests were performed (ABNT NBR 14810-2 (2018)).

Physical tests

After being produced, the specimens underwent physical water absorption (WA) tests after 24 h of immersion, according to Equation 1 (ABNT NBR 14810-2 (2018)).

$$WA = 100 \frac{M_w - M_d}{M_d} \quad (1)$$

Where M_w is the mass of the sample after submission and M_d is the dry mass of the sample.

The swelling in thickness (TS) after 24 h submersion was also performed, according to Equation 2 (ABNT NBR 14810-2 (2018)).

$$TS = 100 \frac{T_w - T_d}{T_d} \quad (2)$$

Where T_d is the thickness of the dry sample and T_w is the thickness of the sample after submersion.

The apparent density (ρ_d) of the samples was also performed by the simple division between mass and volume of samples (ABNT NBR 14810-2 (2018)). From the density values, it was also possible to obtain the compaction rate of the panels (CR) (Equation 3).

$$CR = \frac{\rho d}{\rho_b(pb\%) + \rho_p(pp\%)} \quad (3)$$

Where ρd is the apparent density of the particle board (g/cm^3); ρ_b is the apparent density of bean residues (g/cm^3); $pb\%$ is the bean residue content; ρ_p is the apparent density of pine wood (g/cm^3); and $pp\%$ is the pine wood content.

Mechanical tests

Mechanical tests were also performed: static bending at three points, in order to obtain the values of modulus of elasticity (MOE) (Equation 4) and modulus of rupture (MOR) (Equation 5), and perpendicular traction in order to obtain internal bond (IB) by the simple division between rupture load in traction and area of the sample. These tests were carried out at a speed of 10 mm/min in a universal testing machine “Time Group” with a load capacity of 2 tons, equipped with a computerized system for data acquisition and variable control. (ABNT NBR 14810-2 (2018)).

$$MOE = \frac{D^3L}{4dbh^3} \quad (4)$$

$$MOR = \frac{3LbD}{2bh^2} \quad (5)$$

Where D is the distance between machine supports; L is the load variation before the proportionality limit in the generated “Force x displacement” graphs from static bending; d is the displacement variation corresponding to the force variation; Lb is the breaking load and b and h are the dimensions of the specimen cross section.

Statistical analysis

The experimental design used in the research was completely randomized with 5 treatments and 3 replications. A linear regression analysis was performed, for the properties that showed a significant effect with different levels of bean residues, in order to verify the relationship between the increase in by-products and the values variation of the evaluated properties of the panels. A Tukey statistical analysis at 5 % probability was also performed to analyze the relationship between the “*in natura*” properties of the residue and the reference wood.

A graphical abstract of the adopted experimental procedure can be found in Figure 1.

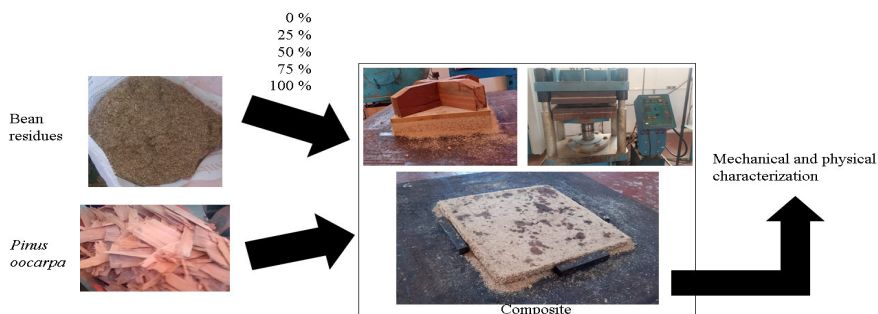


Figure 1: Graphical abstract of the adopted experimental procedure.

RESULTS AND DISCUSSIONS

Results from experiments

Table 2 shows the results obtained for the properties of “*in natura*” materials used in the research. First, it is observed that the characterization of *Pinus oocarpa* wood was similar to that found in relation to all parameters studied (Mendes *et al.* 2018, Narciso *et al.* 2020).

Table 2: Properties of lignocellulosic materials.

Material	Apparent density	Extractives	Lignin	Ashes	Holocellulose
	(g/cm ³)	(%)	(%)	(%)	(%)
<i>Pinus oocarpa</i>	0,48* (0,05) a	6,18 (0,72) a	29,28 (0,14) a	1,25 (0,03) b	63,29 (0,81) a
Bean waste	0,24 (0,02**) b	8,16 (1,60) a	8,13 (0,79) b	16,94 (0,43) a	56,55 (3,97) b

*Standard deviation of means.

**Means followed by the same letter in the line do not differ at 5 % probability by the Tukey test.

However, the density of the materials was low (< 0,50 g/cm³) according to the classification of the Technological Research Institute (IPT 1985), and statistically different from each other. The residue presented a lower density compared to the wood as a reference and to other industrial by-products, such as vine, which had a density of 0,62 g/cm³, according to Wong *et al.* (2020), but also higher than other residues such as the sugarcane bagasse, which exhibited an average data of 0,12 g/cm³ for this physical property (Soares *et al.* 2017). Bufalino *et al.* (2012) exhibited that, a low density is important regarding to the adaptation of lignocellulosic materials for the panels production, thus aiming to increase particles in the same volume of panels. However, this low property can influence negatively, for example, the panels thickness swelling and, therefore, other aspects such as the chemical composition of the raw materials must also be analyzed for correct pre-analysis of the theoretical influence of residues on plastic wood panels (Iwakiri and Trianoski 2020, Guimarães Júnior *et al.* 2016).

From this perspective, with regard to extractives, hydrophobic compounds of low molecular weight which are related to decreased permeability, hygroscopicity, pressing problems and adhesion reaction in the panels, the data obtained were statistically equal from the two constituents used as raw materials for particleboard and are within the recommended range of variation of 4 % -10 % of these components due to the different factors that lead to obtaining lignocellulosic materials. Thus, even with higher values than the wood, it is expected that bean residues do not cause negative impacts on the panels on this matter (Iwakiri and Trianoski 2020, Klock and Andrade 2013). Also, according to literature the extractives content of bean residues was lower than that of other species such as coffee, which had an average content of these chemical elements of 26,24 % (Scatolino *et al.* 2017), but higher than other by-products like coconut, whit 3,15 % of extractives according to Narciso *et al.* (2020).

Lignin, responsible for providing hydrophobicity, improving the aggregation quality, and, consequently, increasing the physical-mechanical properties of the panels, presented statistically different values between both materials. The lignin content found in the agricultural by-product was 8,13 %, lower than the wood, which had 29,28 % of lignin, and also lower than other residues already used as wood replacements in particulate panels, such as hazelnut, which had 35,10 % of lignin, according to Çöpür *et al.* (2007). Therefore, it is expected that the physical-mechanical properties will be negatively impacted, regarding the presence of lignin, by the addition of bean residues in the panels (Neutelings 2011).

On the other hand, ash content can affect the adhesion process and workability of panels; however, it does not significantly alter the fundamental characteristics of the panels. The values found in this research for

this component were 16,94 % for bean residues and 1,25 % for the wood. The significantly higher content of ash in agricultural by-products is common in other studies and is mainly due to differences in production and harvesting processes, such as planting location and different management conditions (Iwakiri and Trianoski 2020).

As for holocellulose, it was observed a significant reduction of this component in bean residues compared to *Pinus oocarpa* wood and also to other agricultural by-products, such as coconut, which obtained 68,75 % of this chemical in the research by Narciso *et al.* (2020). However, there was an increase in this content in relation to other residues, such as banana, which has 51,90 % of holocellulose in its chemical composition, according to Guimarães *et al.* (2014). According to Iwakiri and Trianoski (2020), normally, the use of lignocellulosic residues is limited in wood panels, since such materials have high levels of holocellulose which can affect the physical-mechanical properties of the panels due to their hygroscopicity, referring to free hydroxyl groups that can adhere to water. The trend found in the research was inverse, with the by-product presenting lower values of holocellulose than the wood, which may indicate a possible improvement of the panel's properties containing bean residues, in relation to the content of this component.

Results from bean panels

Figure 2 shows the physical characteristics of apparent density and compaction ratio found for agglomerated panels with different additions of bean residues.

It is observed that the apparent density was below the proposed nominal density of 0,60 g/cm³ due to laboratory conditions in relation to the industrial process (Martins *et al.* 2018); however, all panels, according to CS 236-66 (1968) and ANSI A208.1-99 (1999) standards were classified as low density (< 0,60 g/cm³ and < 0,64 g/cm³, respectively) and, in general, were not statistically different from each other, according to the analysis of variance test ($\alpha=0,05$). This small range of data also resulted in a low value for the linear regression coefficient (0,1741). However, it is observed that the density of the panel presented small decreases as more bean particles are added, an expected fact, since the density of the bean is lower than the reference wood (Table 2). This fact can provide gains in the logistical process (Iwakiri and Trianoski 2020).

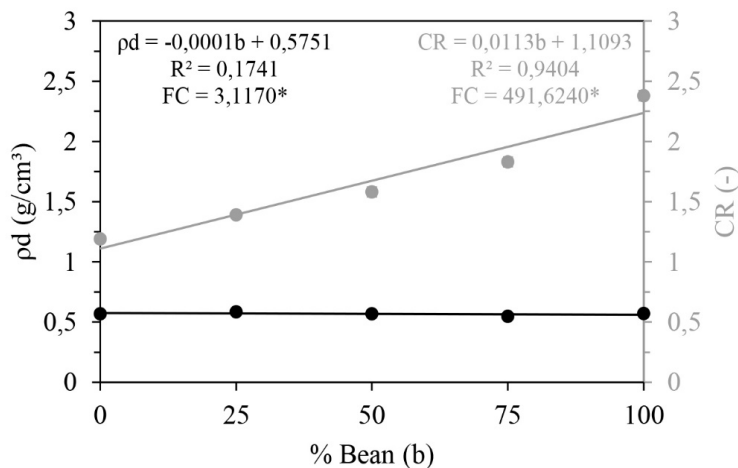


Figure 2: Density and compaction ratio of particulate panels.

*Significant regression analysis at 5 % significance.

Regarding the compaction ratio, on the other hand, the addition of bean residues resulted in an increase of this property, proportional to the increase in the presence of these by-products in the panels. This trend was also described in other studies and also can be explained by the fact that the density values of agricultural residues are significantly lower compared to the wood (Scatolino *et al.* 2017, Guimarães Júnior *et al.* 2016).

Maloney (1993) recommended values between 1,3-1,6 for this property. Replacing these values in the regression generated in Figure 2, it is observed that the values for meeting such reference are between 16,8 % and 43,2 % of bean insertion in the agglomerated panels. However, the author stipulated such values for particleboard panels produced with wood and not lignocellulosic waste, and, therefore, this range may be different

for panels similar to those described in this project.

On the other hand, the properties of water absorption and thickness swelling (Figure 3) also showed a general tendency to increase due to the increase in the addition of agricultural by-products. The data obtained by the panels with the addition of waste did not show a significant difference between them and were higher than the values found for the reference panels and also for products made from the raw material of other agricultural residues, such as hazelnut (Çöpür *et al.* 2007), rice (Ayrilmis *et al.* 2012) and cotton (Nguyen *et al.* 2020).

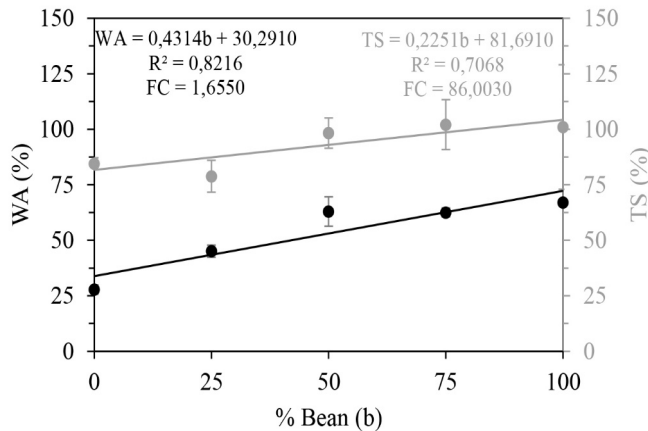


Figure 3: Water absorption and thickness swelling of particulate panels.

This upward trend is explained in the literature essentially by the large presence of holocellulose in the waste, these structures are highly reactive with water, by the low presence of lignin, hydrophobic structure, and also by the high compaction ratio of the panels (Figure 2) (Iwakiri and Trianoski 2020). Regarding normative limits, no panel met CS 236-66 (1968) standard of TS property (maximum 35 %).

The modulus of elasticity (MOE) and modulus of rupture (MOR) values, derived from the static bending, are shown in Figure 4. Worth noting that both properties were significantly affected by the addition of bean residues. The values varied between 1,43 MPa - 6,55 MPa for the MOR and 190,87 MPa - 741,29 MPa for the MOE and were lower than those found in panels with the addition of other agricultural residues, like corn (Prasetyo *et al.* 2020). This reduction in the mechanical properties of stiffness and strength in the panels containing residues, may be associated with the low values of lignin found in the particles of this agricultural element (Iwakiri and Trianoski 2020, Neutelings 2011).

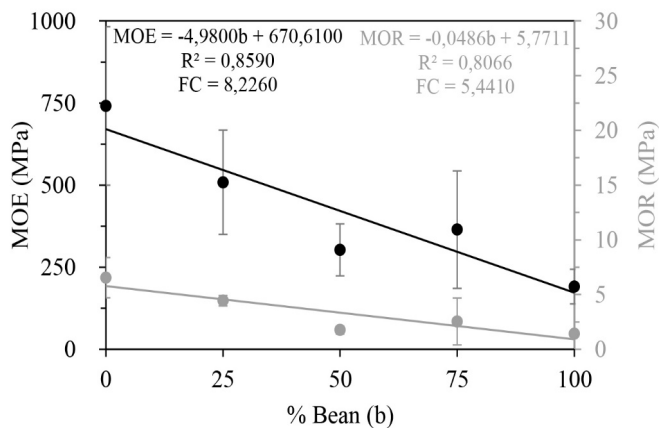


Figure 4: Values obtained for MOE and MOR of the particulate panels.

IB values (Figure 5), on the other hand, ranged between 0,06 MPa - 0,25 MPa. Such values were lower than in other similar literature that used, such as vine residues (Wong *et al.* 2020), cotton (Nguyen *et al.* 2020),

or corn (Prasetyo *et al.* 2020) in wood panels. This trend may indicate that the adhesive used affected IB and several other properties of the panels. It is also argued that all panels with the addition of residues obtained significantly lower IB values than the reference sample, which may also be related to the low values of lignin found in the particles of the agricultural by-product (Iwakiri and Trianoski 2020, Neutelings 2011).

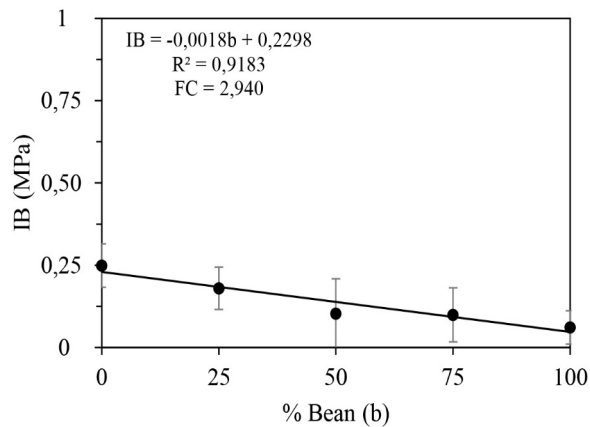


Figure 5: IB properties of particulate panels.

Regarding normative documents, ANSI A208.1-99 (1999) recommends that low-density particleboards must present minimum values for MOE, MOR, and IB of 550 MPa, 3 MPa and 0,14 MPa respectively. By replacing these values in the linear regressions generated in Figures 4 and 5, it is observed that the maximum value of bean residues to be added to the panel to comply with the standard is 24,22 % for the MOE, 57,02 % for the MOR, and 49,88 % for IB.

CONCLUSIONS

According to the results of the characterization of the particles “*in natura*”, from bean residues, compared to *Pinus oocarpa* wood, density values were lower and the lignin, holocellulose, and the extractives content presented higher values.

Regarding the characterization of the panels, there was a uniformity trend towards the apparent density that met the proposed standards. Furthermore, there was an increase in the compaction ratio, water absorption, and thickness swelling properties, besides a reduction in the mechanical properties concomitant with the increase in the addition of the by-product in the composites.

In this way, the research presented important results aiming at the propagation of this sustainable process, mainly in the furniture industries, aiming to reduce the high demand of native trees for commonly underused residues.

However, more studies are needed to gain a better understanding of the effects of adding bean residues to particle boards. In these new studies, pretreatments could be used on the particles to reduce their affinity for water.

AUTHORSHIP CONTRIBUTIONS

E. H. D. N. M.: Conceptualization, investigation, methodology, data curation, formal analysis, writing - original draft, writing - review & editing. **D. A. C. G.:** Conceptualization, investigation, methodology, data curation, formal analysis, writing - original draft, writing - review & editing. **A. C. C. F.:** Conceptualization, investigation, writing - review & editing. **D. C. V. V.:** Conceptualization, investigation, writing - review & editing. **C. A. D. S.:** Conceptualization, investigation, writing - review & editing. **L. M. M.:** Conceptualization, Investigation, Writing - review & editing. **J. B. G. J.:** Conceptualization, investigation, writing - review & editing.

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