Physical and Microstructural Properties of Coconut (*Cocos nucifera*) Particleboards Bound with Castor Oil-based Polyurethane Resin

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Particleboards find extensive application in both civil construction and the furniture industry. Nevertheless, concerns about the interaction of panels with humidity require the exploration of alternative sources to develop a product that meets the requirements for use. This work aims to produce single-layer particleboards with coconut fiber (*Cocos nucifera*) as substrate, bonded with 10% by mass castor oil-based polyurethane resin (CPUR). Two groups of mixtures were proposed, different from each other in the initial moisture content of the *Cocos nucifera* particles, ranging from 0 to 2% and from 4% to 6%. For this purpose, density (D), thickness swelling after 24 h (TS), moisture content (MC), and water absorption (WA) were evaluated. The Tukey mean contrast test, at a 5% significance level, was used to verify the influence of the initial moisture content of the particles on the physical properties of the particleboards. The microstructure of the composites was assessed through the utilization of scanning electron microscopy (SEM) technique. The results indicated better compaction of the *C. nucifera* particles, resulting in fewer voids, contributing to the densification of the panels and, with this, the reduction of water absorption by 15.1%.

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INTRODUCTION

Agglomeration of small wood fragments, such as chips, shavings, or flakes, using a binder of the mineral origin or synthetic resin, for the manufacture of sheets results in a product called particleboards (Bauer 2019). The Brazilian Association of Technical Standards is tasked with establishing standards governing the production and evaluation of medium-density particleboards (MDP). The American National Standards Institute (ANSI) performs a similar regulatory function, defining normative criteria in the face of the most diverse requests for use (ABNT 2013; ABNT 2018; ANSI 2022). Numerous studies have been conducted globally on particleboards. Figure 1 illustrates the increasing trend in the annual number of publications associated with the keyword 'particleboard,' as gathered from a survey conducted in the SpringerLink database. The data collection took place during the year 2024, therefore presenting partial values for this date. The base year of the survey was 1958.

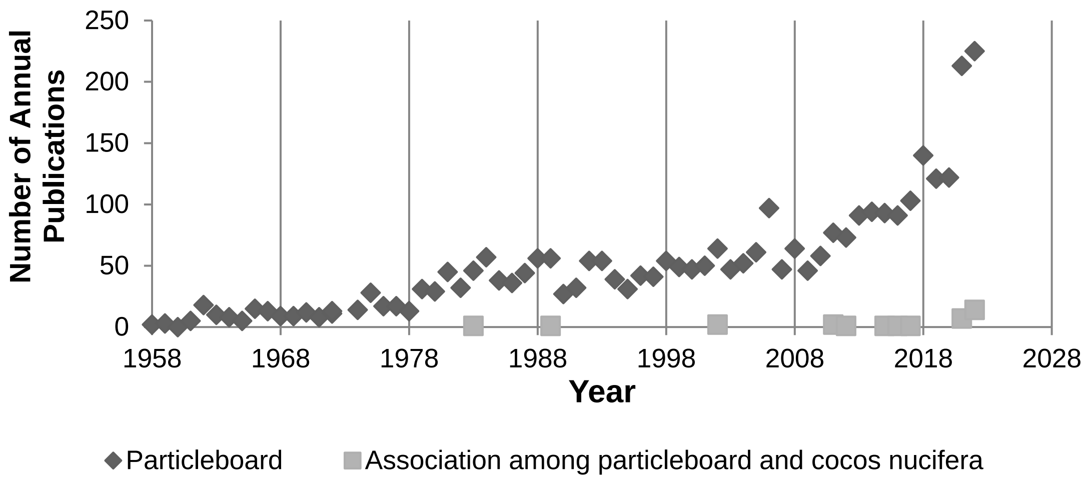

Fig. 1. Number of annual publications linked to the keyword particleboard and *Cocos nucifera via* SpringerLink database

Because of the diverse range of raw materials and production processes, particleboards have become the focal point of numerous scientific research endeavors. These studies aim to minimize losses, enhance the utilization of alternative non-wood raw materials, and contribute to the improvement of properties and efficiency in the production of these products (Farag *et al.* 2020; Hýsková *et al.* 2020; Nicolao *et al*. 2020; Martins *et al*. 2021; Si *et al*. 2022; Rodrigues *et al*. 2023a, 2023b). As reported by the literature (Fiorelli *et al.* 2019; Narciso *et al.* 2020; Owodunni *et al.* 2020; Bispo *et al.* 2022), *Cocos nucifera* stands out as a lignocellulosic material of alternative origin that has been studied very recently and used in the production of particleboard in a promising way. One of the main points that makes the plant studied is its chemical composition with a high amount of lignin.

The interaction between CPUR (polyurethane) and water is unfavorable; therefore, lower moisture contents are currently studied (Cazella *et al*. 2024). Consequently, two narrow intervals of *C. nucifera* moisture content were proposed to evaluate whether a significant disparity exists in the properties of the panels resulting from this fluctuation. This is pertinent given that the drying procedure is linked to substantial energy consumption.

This study aimed to manufacture particleboards from *Cocos nucifera* under two distinct moisture content ranges (0 to 2% and 4 to 6%), employing a bonding agent consisting of 10% by mass of castor oil-based polyurethane resin (CPUR). The impact of the raw material's moisture content on the physical and microstructural properties of the produced alternative panels as well as the significant difference was accessed in the present work.

EXPERIMENTAL

Two groups were proposed (G^1 and G^2), both produced with only *C. nucifera* husk particles (Nitran company, Potirendaba, Brazil). The size distribution of particles is shown in Fig. 2 below. Particles from group G^1 were oven-dried until they reached a moisture content (MC) within the range of 0 to 2%. For the G^2 group, the established MC range was between 4% and 6% (Bispo *et al.* 2021). For bonding the particles, CPUR (IMPERVEG company, Aguaí, Brazil) was used at a content of 10%, compared to the mass of dry particles (Campos *et al.* 2023). Three single-layer particleboards were produced for each group aiming to reduce one step in the production process described by Fiorelli (2019) with dimensions of 35 cm × 35 cm and thickness of 1.0 cm from pressing in a hydraulic press with a pressure of 5.7 MPa and a temperature of 100 °C for 10 min, (see Fig. 3) (Sugahara *et al.* 2019; Gilio *et al.* 2021; Oliveira *et al.* 2021). Before testing, particleboards were conditioned to equilibrate the moisture content.

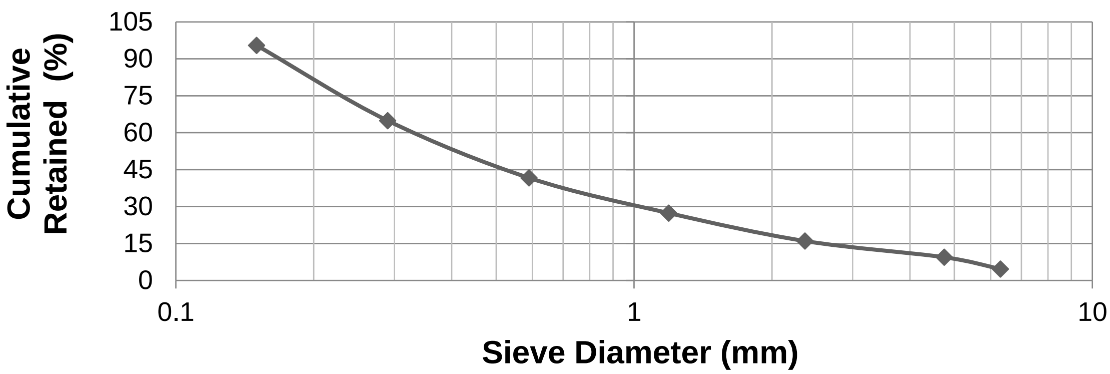

Fig. 2. Size distribution of *C. nucifera* husk

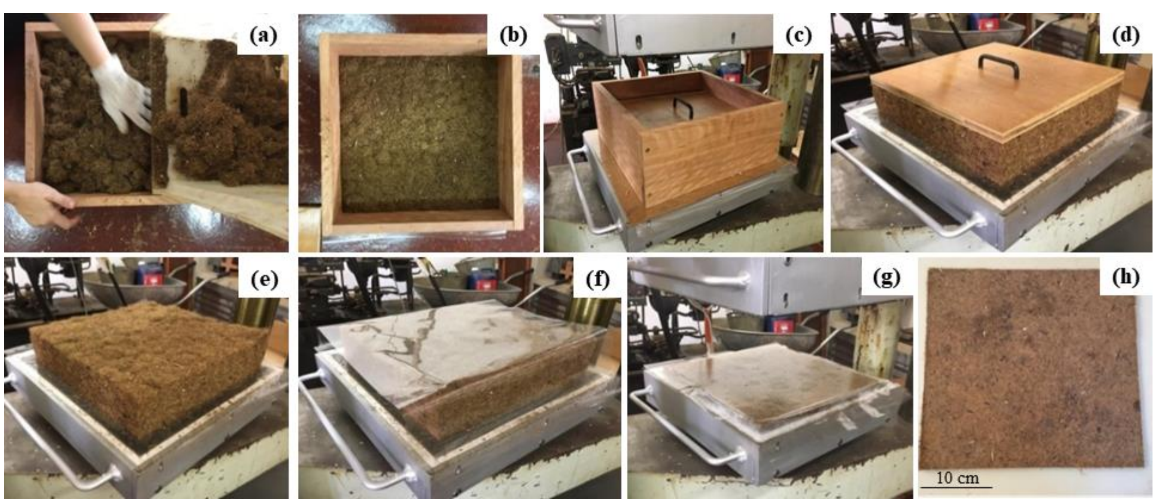

Fig. 3. Production process of *C. nucifera* and CPUR panels: **(a)** addition of raw material in the form, **(b)** particle mattress, **(c)** form and particle mattress in the hydraulic press, **(d)** removal of form, **(e)** removal of the lid, **(f)** addition of the plastic film, **(g)** particleboard right after pressing, and **(h)** particleboard produced

Twenty-four specimens with dimensions of 5.0 cm × 5.0 cm × 1.0 cm were extracted according to the normative cutting plan (ABNT 2018). Density, thickness swelling after 24 h (TS), moisture content, and water absorption (WA) tests were performed. Then the results were compared with the normative requirements (ABNT 2018; ANSI 2022). For morphological analysis, three specimens were prepared for each studied group, with dimensions of 1.0 cm × 1.0 cm × 0.5 cm. Subsequently, the breaking process was conducted using liquid nitrogen (Silva *et al.* 2018), followed by applying a thin layer of gold to the surface of the samples, a Quarum metalizer Q150TE model, was used. After that, scanning electron microscopy was used (SEM; EVO LS15 model, Zeiss), with Oxford Instruments EDS device (INCAx-act model, Abingdon, England).

RESULTS AND DISCUSSION

The density proposed for the panels was 0.65 g/cm³ based on the final volume of the particleboard and the mass of material used in production. The average effective density (D) values of the two groups exhibited a slight disparity (0.652 *versus* 0.623), yet they were deemed statistically equivalent to each other.

The physical properties of the panels, along with their respective coefficients of variation (CV), are presented in Table 1 for both proposed treatments, alongside the normative requirements (ABNT 2018; ANSI 2022).

Table 1. Results of D, TS, MC, and Water Absorption (WA) of the Panels Produced and the Minimum Regulatory Requirements

Proposed Groups / Standards	D (g/cm³)	CV (%)	TS (%)	CV (%)	MC (%)	CV (%)	WA (%)	CV (%)
G^1 #	0.652 A*	4.41	14.05 A*	19.68	8.71 B*	2.60	30.01 A*	11.94
G^2 #	0.623 A*	4.68	17.63 A*	15.78	10.48 A*	3.00	35.33 A*	14.13
ABNT (2018)	0.551 a 0.75	-	< 22	-	5 a 13	-	-	-
ANSI (2022)	0.64 a 0.8	-	-	-	< 10	-	-	-

* By the Tukey mean contrast test, with the aid of Minitab®18 software, at the 5% level of significance, A denotes the treatment associated with the highest mean value of the evaluated property and B the lowest, and equal letters (A and A) imply different treatments with statistically equivalent means.
[#] (G^1) - 0 to 2% moisture content / (G^2) - 4% to 6% moisture content

Among all the variables of a particleboard, the density stands out with great influence on its properties. The best way to improve the properties of a reconstituted wood panel is to increase the specific weight of the panel (Maloney 1977). The observed thickness swelling variation between the two groups could be attributed to the initial moisture content of the particles, which significantly influences the resin curing process as well as the industrial process. In this regard, the particles must be homogeneously dried at a moisture content of less than 3% (Iwakiri and Trianoski 2020). Researchers conducted studies on the production of medium-density particleboard using *C. nucifera* and three distinct types of natural adhesives. They maintained a *C. nucifera* moisture content of 5% (Owodunni *et al.* 2020). In terms of adhesive use, the advantages of using CPUR in relation to the three adhesives used by Owodunni (2020) are an expressive lower content of TS and WA. Alternatively, some authors suggested a moisture content of 3% for *C. nucifera* in particleboard production, with an acceptable variation interval of one percentage point (3% ± 1%) (Zhang and Hu 2014). Comparable studies have employed moisture contents of around 2% and 3% to produce *C. nucifera* particleboards with densities of 0.8 and 1.0 g/cm³ (Fiorelli *et al.* 2012). Figure 4 presents the relationship between the average density of the two studied groups and their physical properties of thickness swelling, moisture content, and water absorption.

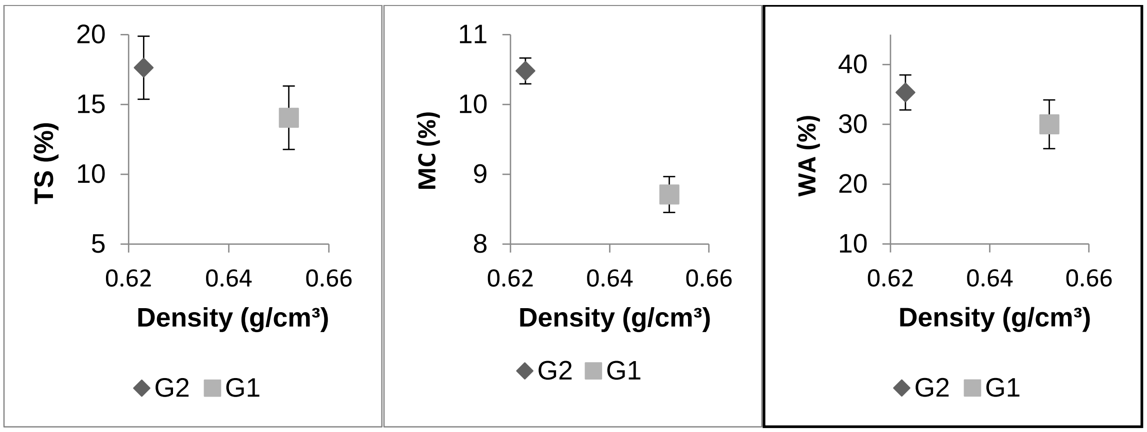

Fig. 4. Graphs of the average values of the physical properties as a function of the average density of the panels

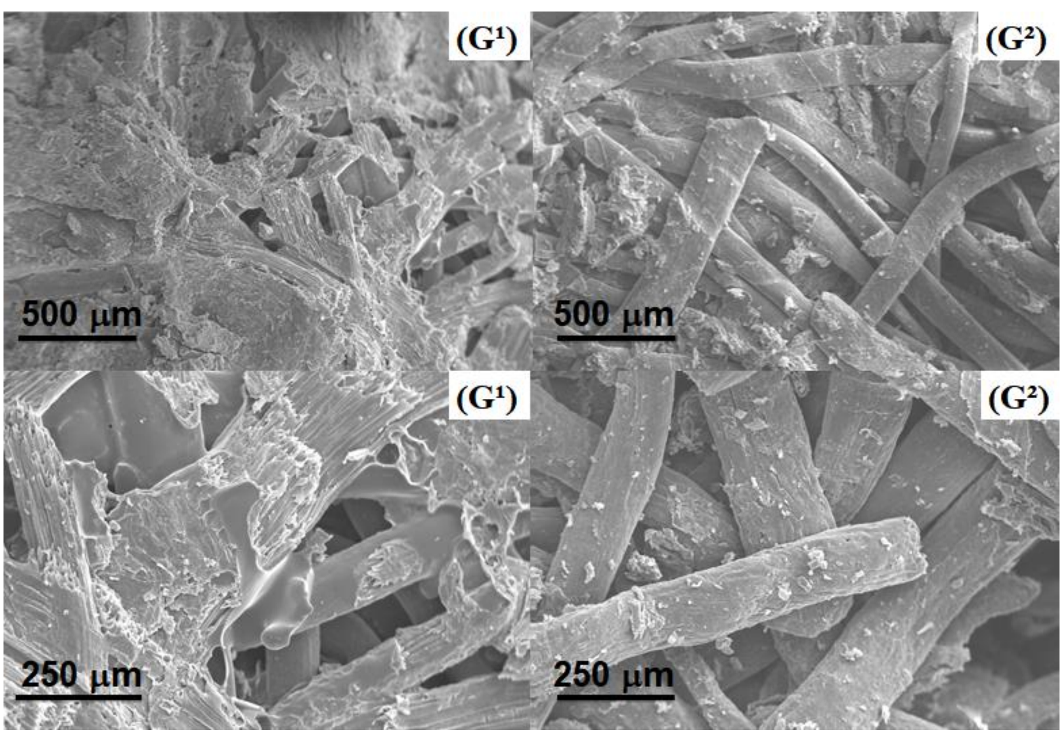

Fig. 5. SEM micrographs illustrating the interior of panels from G¹ and G². All the micrographs were obtained using secondary electrons (SE) mode and EHT 20.000 kV

The results of swelling in thickness and water absorption showed statistically equivalent averages at the 5% level of significance. This can be attributed to the large dispersion in the results of these properties. In contrast, the final moisture content of the panels showed a significant difference between the two evaluated groups, indicating that for this physical property, the initial moisture content of the particles influences the result. The SEM micrographs were captured to assess the microstructure of the two studied groups. Figure 5 showcases microscopy images of specimens extracted from the panels.

The enhanced compaction of *C. nucifera* within specimens from Group G¹, in comparison to Group G², is shown in Fig. 5. This behavior contributes to a reduction in voids and an elevation in panel density, as corroborated by the density results slight disparity in Table 1 (0.652 *versus* 0.623). It is well-established that higher panel density correlates with improved performance (Iwakiri and Trianoski 2020). There was no significant statistical difference between the two groups studied about the properties of TS and WA. Figure 6 exhibits the SEM micrographs depicting the fractured cross-section of *C. nucifera*, highlighting their fibrous morphology.

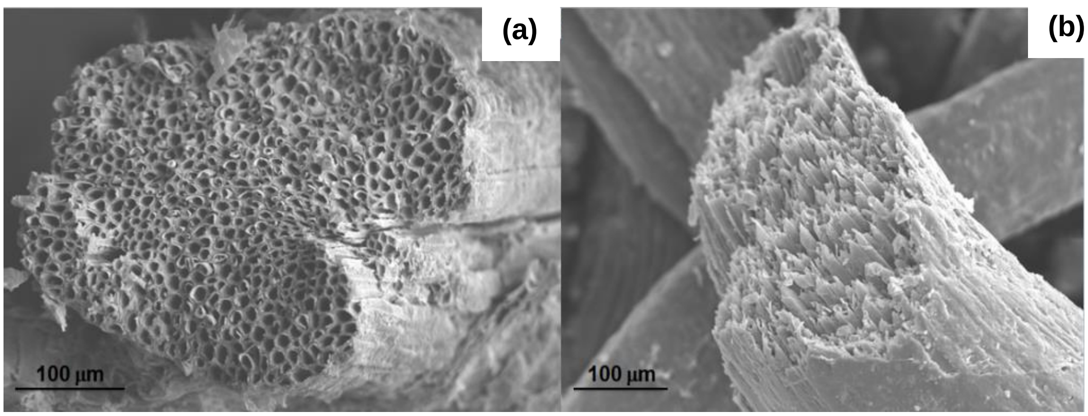

Fig. 6. SEM micrographs depicting the fractured cross-section of *Cocos nucifera* highlighting their fibrous morphology: **(a)** G¹ and **(b)** G²

Cocos nucifera, as a lignocellulosic material, possesses a markedly hydrophilic chemical composition, characterized by a substantial presence of hydroxyl groups (Narciso *et al.* 2020). Nevertheless, in comparison to wood, a frequently utilized material in panel production, and its raw materials, *Cocos nucifera* exhibits a higher lignin content (refer to Table 2), resulting in reduced water absorption and benefit in weather resistance (Satyanarayana *et al.* 1981).

Table 2. Chemical Characteristics of *Cocos nucifera*, Pine, and Eucalyptus Wood

Species or Common Name (Author)	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Holocellulose (%)
Green coconut	53.71	13.04	30.08	66.75
Sugarcane bagasse (Fiorelli *et al*. 2019)	52.24	26.92	13.32	79.16
Coconut coir	46.00 ± 0.5	16.00 ± 0.5	28.00 ± 0.5	62.00 ± 1.0
Date palm fiber	43.00 ± 0.5	25.00 ± 0.5	20.00 ± 0.5	68.00 ± 1.0
Date palm leaves (Alharbi *et al*. 2020)	26.00 ± 0.5	18.00 ± 0.5	16.00 ± 0.5	44.00 ± 1.0
Coconut husk	39.73 ± 1.01	29.02 ± 0.98	32.98 ± 1.69	68.75 ± 1.99
Pinus oocarpa (Narciso *et al.* 2020)	51.86 ± 0.37	23.61 ± 0.37	28.62 ± 0.22	75.47 ± 0.74
Coconut fiber	56.69	25.11	16.64	81.80
Pinus sp. (Fiorelli *et al.* 2014)	51.13	27.29	15.10	78.42
Pinus sp. (Bravo *et al*. 2017)	40.20	31.40	27.20	71.60
Eucalyptus globulus	50.00	24.00-27.00	20.50	74.00-77.00
Eucalyptus urograndis	48.60	-	26.70	-
Eucalyptus grandis (Evtuguin and Neto 2007)	46.60	-	25.70	-

Therefore, the quantity of free water during the production process surpasses that of wood panels, escalating further with an increase in the raw material's moisture content. This moisture reacts with the polyurethane resin, disrupting the curing process of the random matrix. One plausible reaction involves the isocyanate present in the polyurethane resin reacting with excess moisture to produce carbamic acid as an intermediate, subsequently transforming, through a chemical reaction, into an amide and carbon dioxide. This sequence of reactions can result in the formation of bubbles within the panel, exerting a detrimental impact on its properties.

CONCLUSIONS

In the present work, an innovative and practical approach was introduced for producing single-layer panels using polyurethane as the resin and *Cocos nucifera* as the substrate.

1. The results unequivocally demonstrate that the panels meet the minimum regulatory physical criteria (NRB and ANSI), as shown in Table 1, making them suitable for application in wet and dry environments and for non-structural application.
2. Both tested samples, regardless of the applied moisture interval (0 to 2% and 4 to 6%), exhibited satisfactory results of statistically comparable magnitude.
3. These findings underscore the feasibility of producing single-layer panels with particle moisture content between 4 to 6%, leading to reduced energy consumption compared to 0 to 2%, as well as enhanced environmental appeal.

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