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Evaluation of the Mechanical Properties of Polypropylene and Coir Fiber Composites: Contributions to the Circular Economy

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ABSTRACT

Materials developments has been constantly updated, observing the competitiveness for low cost, easy production and sustainability, the need arises to produce efficient, viable products that generate less environmental impact. Biobased composites can replace conventional materials, and those made using in natural fibers is a growing worldwide alternative. Coir fiber is a value-added material with satisfactory and superior mechanical properties compared to other natural fibers, in addition to its high availability. The aim of this study was to evaluate the mechanical properties of polypropylene and coir fiber composites and of sheets made with coir fiber alone, without the addition of binders. Composites with 20% and 40% fiber and different particle sizes were evaluated using tensile, flexural, hardness and impact resistance tests. The flexural modulus, water absorption and swelling of the sheets were evaluated. A correlation between the variables showed interdependence between fiber volume and melt flow index of 96%; breaking energy and moisture content showed a strong correlation of 83% and for the tensile, flexural and hardness tests, correlations of up to 94%. For the sheets, despite the limitation observed in relation to the pressure applied, the production process proved to be viable and with the possibility of improving their properties.

摘要

材料开发一直在不断更新，观察到低成本、易生产和可持续性的竞争力，需要生产出高效、可行的产品，减少对环境的影响. 生物基复合材料可以取代传统材料，而用天然纤维制成的复合材料是一种日益增长的全球替代品. Coir纤维是一种增值材料，与其他天然纤维相比，除了其高可用性外，还具有令人满意和优越的机械性能. 本研究旨在评估聚丙烯和椰纤维复合材料以及仅用椰纤维制成的片材的力学性能，而不添加粘合剂. 使用拉伸、弯曲、硬度和抗冲击试验对含有20%和40%纤维和不同粒径的复合材料进行了评估. 对片材的弯曲模量、吸水率和溶胀性进行了评估. 变量之间的相关性表明，纤维体积和熔体流动指数之间的相互依存关系为96%; 断裂能和含水量显示出83%的强相关性，拉伸、弯曲和硬度测试的相关性高达94%. 对于板材，尽管观察到施加压力的限制，但生产工艺被证明是可行的，并且有可能改善其性能.

KEYWORDS
Coir fiber; polypropylene; biobased composites; compressed boards; sustainable materials

关键词
薏苡纤维; 聚丙烯; 生物基复合材料; 压缩板; 可持续材料

Introduction

Material science is a field that requires constant updates. In addition to keeping pace with innovations in the search for materials with satisfactory mechanical properties for their various applications, there has also been a growing focus on competitiveness driven by low

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cost, ease of production, and sustainability. These factors have contributed to the integration of the concept of efficient materials (Lan et al. 2021). This approach also incorporates perspectives for future scenarios concerning new materials, with lighter structures, reduced energy demand for production, and concepts related to circular economy and ESG (Environmental, Social, and Governance) (Ostermann et al. 2023).

The need for materials with high stiffness and strength, combined with lower density and more sustainable production techniques, is also a key focus for sectors such as the automotive and construction industries. These sectors are not only striving to reduce their energy and resource demand but are also promoting a circular economy by incorporating waste into their production processes (Sagbansua and Balo 2017). Agro-industrial wastes such as coir fibers, sisal, jute, eucalyptus, among others, are an alternative for the development of more resistant, lighter materials with a lower environmental impact.

Despite the limited technologies and processes for producing such materials, there is a global increase in demand for fiber-reinforced materials, with an estimated growth of up to 500,000 tons produced by 2050 (Lefeuvre et al. 2017; Wang et al. 2023). Especially in Brazil, according to the Brazilian Institute of Geography and Statistics (IBGE), in 2021, the amount of coconut fruits produced in Brazil was more than 1.6 billion; this growing demand for coconut-derived products shows the possibility of using fibers, which, considered as waste from some industrial processes, can be a value-added material that contributes not only to the circular economy, but also proves to be competitive and with prospects of scalability across different industrial sectors (Ignacio & Miguel, 2021).

The role of reinforcement in a material is closely linked to the effectiveness of the chemical bonds between the matrix (the dominant material) and the reinforcement used, such as fibers. The use of natural fibers in conjunction with matrices is due to the presence of a natural polymer in the fibers – lignin – a complex, amorphous polyphenolic material with various chemical functionalities, which shows promise for composite applications (Thakur et al. 2014).

Each fiber has specific characteristics, with varying morphologies, densities, and lignin content, all of which influence the mechanical behavior of the polymers and, consequently, the composites. The coir fiber is known by its higher lignin content compared to other natural fibers. Properties such as elastic modulus, yield strength, and tensile strength can be used to compare material performance (Ahmad et al. 2023). Coir fibers contain approximately 40–50% lignin, a higher content than most other natural fibers, making them naturally stiffer and more suitable for applications where rigidity is important (Narendar and Priya Dasan 2014).

An important feature for the coir fiber, its high lignin content, allows the fabrication of binderless boards. Martins (2024) reported the production of binderless boards with the following conditions, similar to those reported in the CFC document. The results were an elasticity modulus of 2130 MPa and a flexural strength of 207 kgf/cm^2. The produced boards were tested for a brewery company as a support for beer cans on the top of wooden pallets.

Given that coir fiber may play a significant role in material production and that its properties must be assessed through various tests, this study aims to evaluate the mechanical properties of polypropylene and coir fiber composites. The specific objectives are to evaluate the influence of fiber volume on the mechanical properties of the composites, determine whether fiber particle size influences the final mechanical properties of the composites, and correlate the parameters measured during material processing with the final mechanical properties.

Another objective of this study is to assess the behavior of materials produced solely with coir fiber, thereby examining the fiber's capacity to form materials independently of being associated with a matrix. Based on the parameters defined by such tests, expand the possibilities of using coir fiber by the Brazilian industry, contributing to reducing the environmental impact of this waste and enhancing circular economy practices. The use of short fibers represents an excellent alternative to adding value and enhancing the productive chain for the coconut.

Materials and methods

The coir fiber used in this study was obtained pre-ground, which is the usual form in which fibers are purchased from a supplier located in Salvador, Bahia, Brazil (Sisall: www.sisall.com.br.). The fibers were sieved by range and tested with non-separated fibers and with a defined fiber size. From the three sieved fractions with particle sizes ranging from 0.125 mm, 0.250 mm and 0.355 mm in diameter, the frequency of the most abundant particle-size range was 0.125, with 80% and 10% for 0.250 and 10% for 0.355 mm. The fiber composition was cellulose, 33.3% and lignin 42.4% with a fiber length of 0.8 mm.

Heat value

The heat value test was performed to quantify the energy content per unit of mass, where higher calorific values indicate a higher energy content in the fiber. This evaluation is crucial for assessing the potential of fiber as a fuel for heat generation in industrial settings, such as in furnaces and boilers. The calorific value analyses were conducted using a Parr Model 6400 Automatic Calorimeter. Three 1 g samples were analyzed. The results were expressed in cal/g.

Coir fiber and polypropylene composites

For the granulometric analysis, 100 g of coir fiber were sieved using an electromagnetic sieve shaker, model AGMAGB, with sieves of different mesh sizes. The mass retained on each sieve was measured using an analytical balance.

Polypropylene (PP), brand SABIC®, specification 575P, was used as the matrix for the composite material, along with coir fiber and maleic anhydride grafted polypropylene (MAPP), brand Bondyram®, specification 1001, which acts as a coupling agent for fibers in polypropylene composites. MAPP has been widely studied and possesses considerable industrial potential due to its ability to promote interaction and miscibility between the different phases of the composites (Hu, Stevanovic, and Rodrigue 2014).

The sample compositions were varied by adjusting the fiber volume in the composite to 20% and 40%. PP was used as a control in mechanical tests. The amount of MAPP used was chosen based on previous studies (Passatore, Leão, and Rosa 2016). The sample composition is presented in Table 1.

The components of the samples were homogenized using a mixer, model MH-4, and the samples were extruded using a single-screw extruder, brand LGMT, model LGEX – SIV 0 V 060/36D, operating at a screw speed of 30 rpm and an average temperature of 170 °C along the screw. The filaments produced during the extrusion process were cut with a granulator brand SAGEC, model SG 70.

Before obtaining the test specimens (TP), the moisture parameters of each treatment were evaluated using a moisture analyzer, model MOC63u, and the melt flow index was obtained using a plastometer, brand JJH, according to the ASTM D1238–23 standards. For each treatment, 10 test specimens were produced for mechanical testing to be carried out later; that is, 10 TP for flexural tests, 10 TP for tensile tests, and 10 TP for impact tests. The materials underwent an injection molding process, using an injection-molding machine, brand SANDRETTO, and model 650/247, with a filling

Table 1. Composition of the samples.

Treatment	Polypropylene (%)	MAPP (%)	Coir Fiber (%)	Coir Fiber Particle size (x)
PP	100	0	0	
B1	78	2	20	x <0.355 mm
B2	78	2	20	No separation
B3	58	2	40	x <0.355 mm
B4	58	2	40	No separation

Figure 1. Composites pellets ready for injection molding and the samples used for testing.

pressure of 41 bar and an average temperature along the screw of 170 °C. The molds for each TP followed the dimensions defined by ASTM standards for mechanical testing.

For mechanical testing and obtaining the flexural and tensile stress variables, a universal testing machine, model Emic DL-3000, was used. The tests followed the ASTM D638–22 standards for tensile testing and ASTM D790–17 for flexural testing. For impact resistance testing, an impact pendulum tester, brand Tinius Olsen, model 892, was used following the ASTM D256 – 10 (Reapproved in 2018) standard.

For evaluating the Shore D hardness of the material, a durometer, brand Zwick, was used according to ASTM D2240 – 15 (Reapproved in 2021).

Figure 1 presents the composites pellets ready for injection molding and the samples used for testing. The results of tensile, flexural, impact, hardness, and melt flow tests were presented as a comparison of means and standard deviations. A linear correlation was made between B1, B2, B3, and B4 to assess the relationship between these treatments. All methods used for calculating the variables in the mechanical tests followed the previously cited ASTM standards. Data treatment and statistical analysis were carried out using R software version 4.3.1 (R Core Team 2023).

Coir fiber board

A coir fiber board was produced using a pilot press at Dexco S.A., located in Agudos, São Paulo, Brazil. The press has a maximum pressure of 102 bar (104.1 kgf/cm^2), and the fiber was pressed at 180 °C for 180 seconds. This board was used as a reference for the tests conducted at the laboratory scale. A report containing an evaluation of the board's properties, provided by the company, was forwarded to the RESIDUALL Laboratory for further analysis.

For the formation of boards (Figure 2) in the laboratory, samples were initially defined to observe their behavior regarding flexural modulus, water absorption, and swelling. A total of 6 treatments were conducted, with different densities and pressing times. The sample composition are shown in Table 2. The boards were pressed in a machine with hot and cold openings, hydraulic-pneumatic drive, model MH-8MT. After hot pressing, all samples were subjected to cold pressing for 5 minutes to finalize the board formation. For the mechanical tests, the boards were cut into test specimens measuring approximately 4 cm in width and 15 cm in length to obtain the flexural stress variables. The tests were performed using a universal testing machine, model EMIC DL-3000. The tests followed the ASTM D790–17 standards, and although this standard is intended for composite materials, it was used as a reference. The

Figure 2. Press used for the boards, with hot and cold plate. The binderless coir board.

Table 2. Board samples.

Sample	Temperature (°C)	Pressing Time (min)	Fiber Mass (g)	Mold Dimensions (cm)	Board Volume (cm^3)	Density (g/cm^3)
C1	180	10	100	17×17x0.1	28.9	3.46
C2	180	15	100	17×17x0.1	28.9	3.46
C3	180	10	140	17×17x0.47	135.83	1.03
C4	180	15	140	17×17x0.47	135.83	1.03
C5	180	10	110	17×17x0.47	135.83	0.81
C6	180	15	110	17×17x0.47	135.83	0.81
DT	180	3	-	-	-	0.97

DT – Board manufactured by Dexco SA.

results of the flexural tests were expressed through the comparison of means and standard deviations.

For the water absorption and swelling tests, test specimens (TP) of 7.6 cm in length and 2.5 cm in width were prepared. The specimens were weighed to obtain their initial mass. They were then immersed in deionized water for 2 hours to evaluate their final weight and determine the amount of water absorbed by the board, based on the increase in weight due to absorption. To evaluate swelling, the specimens' thickness was measured both initially and after 2 hours of immersion. The swelling and water absorption percentages were calculated using the following equations:

$$Water\ Absorption(\%) = \frac{(M2h - M0)}{M0} * 100$$

$$Swelling(\%) = \frac{(E2h - E0)}{E0} * 100$$

Where M2h is the mass in grams after 2 hours of immersion in water; M0 is the initial mass in grams; E2h is the thickness in centimeters after 2 hours of immersion in water; and E0 is the initial thickness in centimeters. Data processing and statistical analysis were performed using R software version 4.3.1 (R Core Team 2023).

Results

Heat value

The heat values of the coir fiber samples are presented in Table 3.

Mechanical tests of the composites

The average moisture content for each treatment was 4.45% for B1, 4.12% for B2, 5.45% for B3, and 3.39% for B4, while the moisture content for the coir fiber without particle separation was 13.39%. To evaluate viscosity, the melt flow index (MFI) was measured. The higher the MFI, the more material flows under the test conditions. This index indicates the material's processability and can influence the quality of parts during the injection molding process. The MFI values for each treatment are shown in Figure 3.

The modulus of elasticity, or tensile modulus, is related to the tensile strength limit: the higher the modulus, the stiffer the material and, consequently, the lower its ductility (the ability of a component to deform without cracking, breaking, or failing in other ways). The average tensile modulus values from the tensile tests were 1056.08 MPa for PP, 1453.91 MPa for B1, 1437.43 MPa for B2, 1637.44 MPa for B3, and 1914.84 MPa for B4, as shown in Figure 4.

The flexural test determines the resistance and behavior of materials when an applied force causes bending or curvature on their surface. The average flexural modulus values were 990.85 MPa for PP, 1665.83 MPa for B1, 1581.54 MPa for B2, 1641.32 MPa for B3, and 1975.02 MPa for B4, as shown in Figure 5.

The resistance of a material to impact loads is crucial depending on its application. This property is particularly relevant when the material must withstand specific loads, such as in vehicle components. In the impact test, the breaking energy was measured, yielding values of 6769.77 J/m^2 for PP, 4688.96 J/m^2 for B1, 5951.19 J/m^2 for B2, 4066.85 J/m^2 for B3, and 5462.19 J/m^2 for B4, as shown in Figure 6.

Another mechanical property that influences the performance of materials for specific applications is hardness. The Shore hardness test uses different scales to measure the hardness of various materials. The average values on the hardness scale, measured in hardness units (UD), were 62 UD for PP, 72 UD for B1, 70 UD for B2, 72 UD for B3, and 75 UD for B4, as shown in Figure 7.

In addition to the mechanical test results, a correlation matrix was created, which shows the correlation coefficients between factors, i.e., the degree of linear relationship between each pair of variables. The correlation matrix in Figure 19 shows the analysis of treatments B1, B2, B3, and B4. To assess the statistical significance between the variables, the p-value was calculated, with values below 0.05 considered statistically significant. The blank spaces in the graph of Figure 6 indicate relationships where the p-value was above the significance level.

Table 3. Heat value.

Heat Value (cal/g)			
Sample	Mass(g)		
1	0.9936	HHV	3956.58
		LHV	3952.72
		UHV	**3085.54**
2	1.0501	HHV	3982.97
		LHV	3679.11
		UHV	**3108.39**
3	1.0229	HHV	3956.75
		LHV	3652.89
		UHV	**3085.68**

HHV – Higher Heating Value, LHV – Lower Heating Value,UHV – Useful Heating Value.

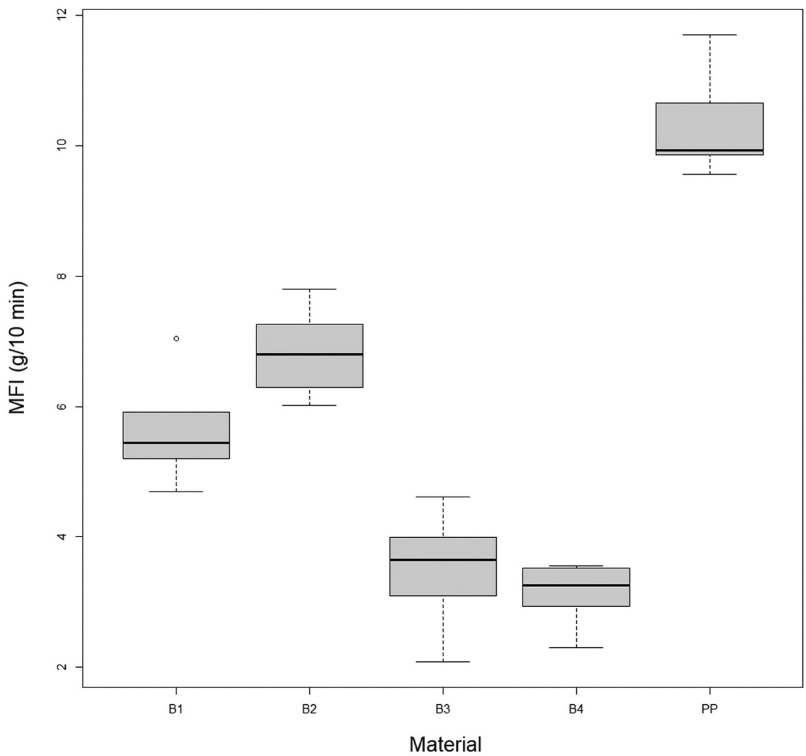

Figure 3. MFI for the different treatments.

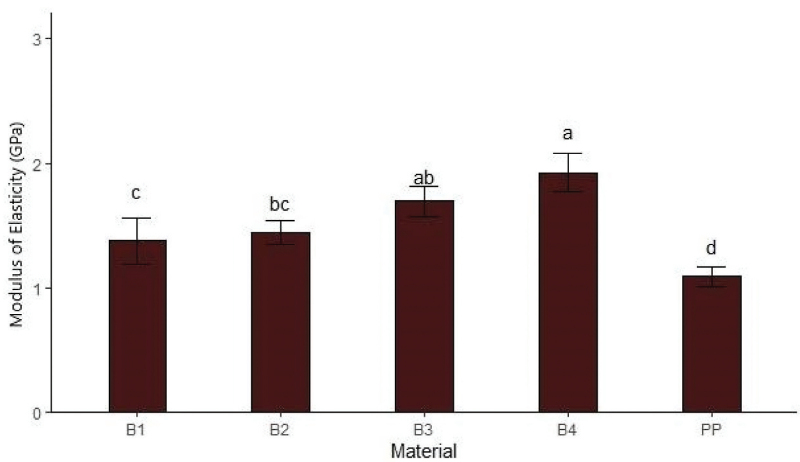

Figure 4. Elastic modulus for tensile tests.

Mechanical tests of coir fiber boards

A flexural test was conducted to evaluate the maximum stress the boards could withstand. The results for each treatment, including elastic modulus and flexural strength, are presented in Figures 9 and 10. The sample labeled "DT" represents the board manufactured by Dexco S.A.

Assessing the water absorption and swelling of the boards is essential for understanding how the material behaves in contact with water. The boards' ability to retain moisture, even after fiber pressing,

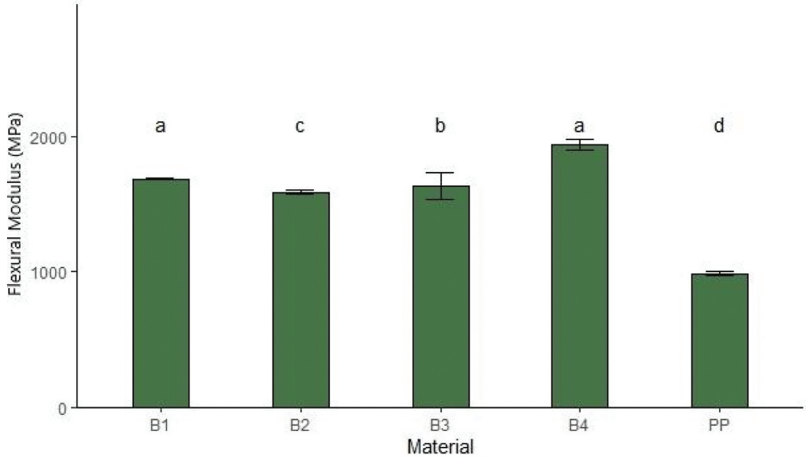

Figure 5. Flexural modulus.

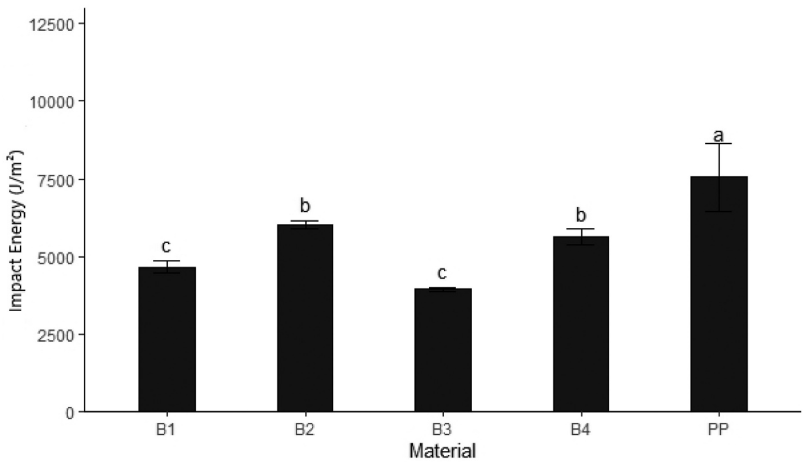

Figure 6. Impact break energy.

is critical, as water absorption can degrade their mechanical properties, reducing both strength and usability. Percentage values for water absorption and swelling of the boards are presented in Table 4.

Discussion

Heat value

The amount of energy contained in coir fiber was analyzed because of its potential for energy generation. It is important to prioritize processes that add greater value to the input and are economically and environmentally viable. From Table 3, the average useful heat value is 3093.20 cal/g or 12.94 MJ/kg for coir fiber.

Several authors have demonstrated higher energy potential by evaluating coir fiber in the form of briquettes (dense and compact blocks of material), reaching 19.47 MJ/kg (Esteves, Abud, and Barcellos 2015). Organic residues in general are assessed for their energy generation potential. For example, rice husk has a calorific value of 16.35 MJ/kg, while peach pit has 15.06 MJ/kg. Eucalyptus biomass residue

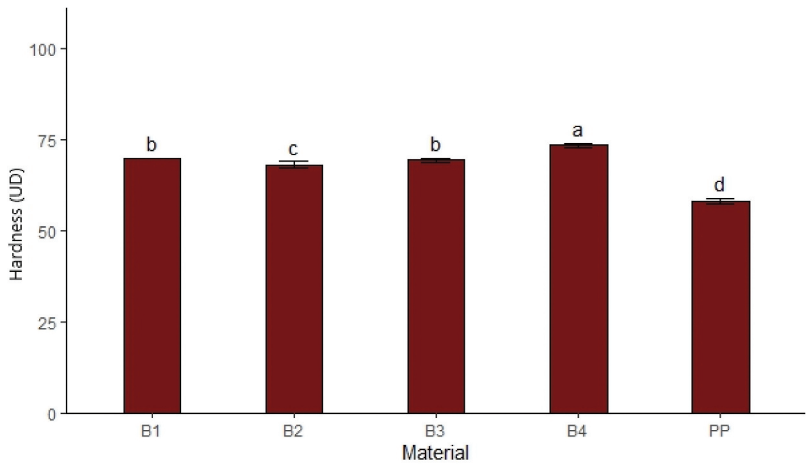

Figure 7. Shore D hardness test.

Table 4. Water absorption and swelling of the boards after 2 hours of immersion.

	Swelling (%)	Water Absorption (%)
C1	115	213
C2	94	179
C3	99	242
C4	75	220
C5	87	237
C6	64	247
DT	31	52

has a calorific value of 17.34 MJ/kg and is frequently used for steam and heat generation through combustion in industries.

It can be stated that coir fiber has energy generation potential; however, its energy potential is lower than other materials that already have a well-established waste utilization route. The choice of the best method for utilizing and applying coir fiber will depend on available resources, the possibility of substituting other materials, and the lack of utilization of the fiber through other commercial pathways.

Mechanical tests of the composites

Knowledge about the physical structure of fibers is of crucial importance in selecting a potential application. The length-to-diameter ratio can provide information that may predict the material's behavior and its strength; however, in many cases, this ratio is quite variable and depends on factors such as the morphology of the fruit, the age of the plant, fiber moisture content, among others (Leao and Rowell 2000).

It is known that coir fibers contain chemical groups (hydroxyls) that give them hydrophilic characteristics, meaning they have an affinity for water, whereas the vast majority of commercial polymers are hydrophobic. This difference in properties can result in poor adhesion between the fibers and the matrix, as poor dispersion of the particles can lead to a loss of reinforcement capacity in the material (Gama et al. 2022).

Melt Flow Index (MFI)

The PP showed a Melt Flow Index (MFI) of 10.34 g/10 min, the values for B1 and B2 (with 20% fiber) were 5.66 g/10 min and 6.83 g/10 min, respectively. For the treatments with 40% fiber, B3 and B4, the indices were 3.49 g/10 min and 3.11 g/10 min, respectively, as shown in Figure 3.

This change in material flow is strongly influenced by the fiber content in the composite. It was observed that for treatments with 20% fiber, the results were satisfactory in terms of flow, which decreased with the addition of a higher fiber volume (40%). In all cases, there was a reduction in flow compared to the pure PP material.

Despite a small difference between the average values of treatments B1 and B2 (with 20% fiber), no significant difference in MFI was found between these treatments in relation to the fiber dimensions. It can be concluded that the fiber volume in the material is a relevant factor regarding its flow, but the fiber size does not exert a strong influence in this case.

In general, materials with low MFI exhibit greater flow resistance, which can negatively affect injection molding. However, polymers with MFI values below 4 g/10 min can still be used in this processing technique, provided that the molding parameters are properly adjusted. Strategies such as the use of additives and fiber surface treatments have been reported by other authors as viable alternatives to improve fiber – matrix compatibility and, consequently, processability (Gama et al. 2022).

Tensile test

The modulus of elasticity was primarily influenced by the fiber volume used in the material, being higher in the treatments with 40% fiber, as shown in Figure 4. This significant increase in the rigidity of the composite material compared to PP reduces the material's ability to elastically deform without breaking.

During the test, a small neck forms in the specimen's gauge section, and it is at this point that the polymer chains align (the axes of the chains become parallel to the direction of elongation). At this stage, there is resistance to the continued deformation, and the elongation of the specimen proceeds by the propagation of the neck along the gauge length; the chain orientation phenomenon follows this neck extension (Callister and Rethwisch 2018).

This increase in rigidity and the consequent brittleness of the composites is a behavior commonly observed in polypropylene and coir fiber materials; the use of compatibilizers can also increase the adhesion at the fiber-matrix interface, thereby altering its final performance (Techawinyutham, Frick, and Siengchin 2016). Particle size did not cause significant variations between treatments.

The results found in the tensile tests show that the material made solely with coir fiber and polypropylene yields results equal to or superior to materials containing mineral additives. It is beneficial from both an environmental and economic perspective, as it reduces the use of chemical additives while maintaining a fraction of biodegradability in the final component (Passatore, Leão, and Rosa 2016).

Flexural test

The results of the flexural test also showed a significant difference between the PP and the coir fiber treatments due to the increased rigidity of the materials influenced by the fiber, as shown in Figure 5. A noticeable increase in rigidity was observed in treatment B4 (with 40% coir fiber and no particle separation). The increase in rigidity with higher fiber volume was also observed in previous studies (Obasi, Uchechi, and Udochukwu 2021; Passatore, Leão, and Rosa 2016).

In contrast to the results obtained in the tensile tests, it was observed that the variables assessed had less influence, meaning that regardless of the variation in fiber volume and particle size, the material performed similarly in the flexural test. Even though statistical differences were observed among the treatments, a similar range of flexural strength was seen in all cases. Still, the results of the flexural tests were superior to those found in the literature, where a blend of coir fiber, hemp, and epoxy resin was used, indicating that just the coir fiber, when incorporated with matrices, can produce a material with higher strength (Suriyaprakash et al. 2023).

Composites with discontinuous fibers and randomly oriented fibers typically exhibit a higher modulus of elasticity as the fiber volumetric fraction increases. The efficiency of the reinforcement in resisting applied forces is directly affected by the alignment of the fibers, which can be up to one-fifth of the efficiency in the longitudinal direction of a composite with aligned fibers, for example. This can explain the similar behavior observed in the different treatments (Callister and Rethwisch 2018).

Additionally, it was observed during the test that fiber pull-out was visible on the surface of the specimen, showing voids in the form of trapped gas, as previously reported in other studies. Short fibers may favor this pull-out, thereby reducing the flexural strength of these composites (Akhyar et al. 2024). The use of compatibilizers and fiber pre-treatment may improve the performance of these materials (Techawinyutham, Frick, and Siengchin 2016).

Impact test

The mechanical behavior of composites is related to the properties of the fibers and their interface-matrix bonding, and consequently, the way applied loads are transferred from the matrix to the fibers. The reduction in breakage energy between polypropylene (PP) and all composite materials may be associated with weak adhesion between the lignin particles and PP; lignin is less elastically deformed (Dias et al. 2016).

The particle dimensions influenced the amount of energy absorbed during the test. B1 and B3, with smaller particles, had lower breakage energy compared to materials B2 and B4, which had particles of varying sizes. In other words, smaller particles cause the material to resist less to impact forces. The aspect ratio (the ratio between width and thickness) directly affects the stress transfer to the matrix. Longer fibers, with a higher aspect ratio, allow for greater energy propagation through the material, which explains the higher energy absorption values observed for samples with longer fibers, as compared to those with shorter fibers of 0.355 mm, as seen in Figure 6 (Oliveira et al. 2020).

Shore D hardness test

A significant difference was observed only between the PP and the fiber-reinforced materials for all treatments, as shown in Figure 7. This measure of material hardness indicates that coir fiber composites are rigid compared to materials made solely from PP. This behavior has been observed in previous studies (Chagas et al. 2022; Kumar et al. 2021).

Correlation matrix

A strong negative correlation of 96% was observed between the MFI (Melt Flow Index) and the fiber volume in the material, as shown in Figure 8. This indicates that the material becomes less fluid as the fiber content increases. This reduction in fluidity is related to the shear of the PP chains and may result from oxidation occurring during processing (Passatore, Leão, and Rosa 2016). This characteristic is important during material fabrication, such as in extrusion and injection molding. Lower fluidity will affect the quality of the formed component, as it is directly linked to the homogeneity of the material being produced and, consequently, its final mechanical properties (Bledzki and Faruk 2005).

The chemical treatment of coir fibers has been evaluated from different perspectives, using either industrial or natural chemical substances, with the aim of improving the bonding between the matrix and reinforcement. This improvement directly impacts the processability of the material and its mechanical properties (Islam et al. 2010; Torres-Giner et al. 2018).

The Breaking Energy exhibited a negative correlation of 83% with the moisture content, meaning that the energy absorbed by the material was higher when the moisture content was lower. This could indicate that the moisture content in the sample affects the energy dissipation within the material

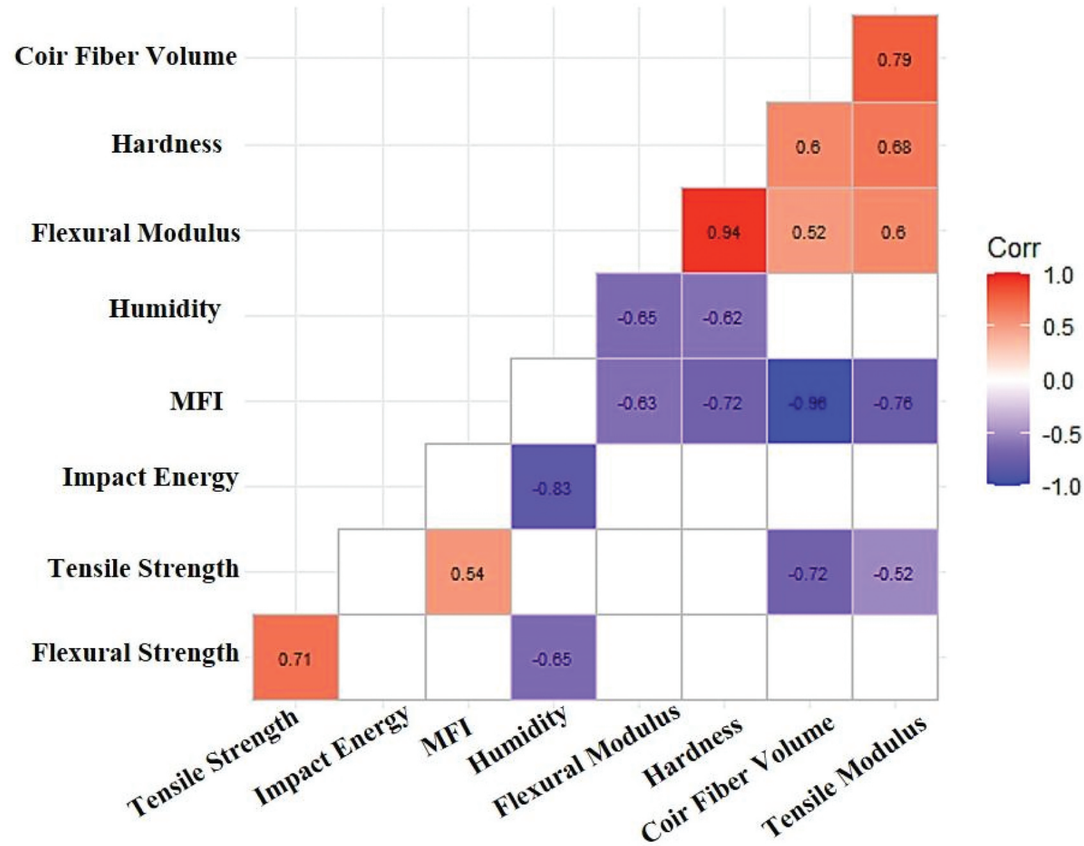

Figure 8. Pearson correlation matrix.

when subjected to the impact test. The interfacial adhesion is responsible for the efficiency of energy transfer between the matrix and reinforcement, and exposure to water reduces the effectiveness of this interfacial resistance (Lenda and Mridha 2011). For the Breaking Energy parameter, moisture content was the most influential factor, which is also linked to the fiber structure, specifically the microfibrils (cellulose chains that form the fiber cell wall). These microfibrils flow with increasing moisture and the hydrogen bonds that form them also begin to flow, thus reducing the fiber's strength (Richely et al. 2022). Over the long term, moisture in the material may promote microbiological action that degrades the fibers, making them less resistant to impact – an important characteristic when assessing the composite's behavior over time. One way to modify this property is by adding a drying step during processing.

The correlation between the bending modulus and hardness was positive at 94%, as expected, since both the modulus and the hardness scale indicate the material's rigidity. This increase in rigidity with the addition of fiber has been observed in other studies, showing that coir fiber composites exhibit mechanical properties such as higher hardness and bending strength (Jani et al. 2023).

Overall, the coir fiber volume was the most influential factor in the properties assessed during the tensile test of the composites. A positive correlation of 79% was observed with the tensile modulus, and a negative correlation of 72% with the tensile strength measure, confirming previous observations that as the fiber volume increases, the material becomes stiffer and consequently less elastic, making it more resistant to tensile forces until failure.

Mechanical testing of coir fiber boards

When evaluating the bending test results of the fiber boards, it is observed that it is not possible to define the parameter with the greatest influence on the resistance of the boards when evaluated at a laboratory scale. Neither the pressing time nor the density provided significant indicators for the final properties of the manufactured boards, as shown in Figures 9 and 10. Lower density is characteristic of thinner boards, which may have influenced the tensile strength and the maximum load applied during the tests. The difference between the board produced in the pilot press and those made at the laboratory scale is evident, indicating that the pressure used in the laboratory is insufficient for efficiently pressing the coir fiber.

When comparing the results with the technical document "Coir Based Building and Packaging Materials" (a manual developed by the Food and Agriculture Organization of the United Nations with guidelines on materials made solely from coir fiber), it is observed that the bending test results showed

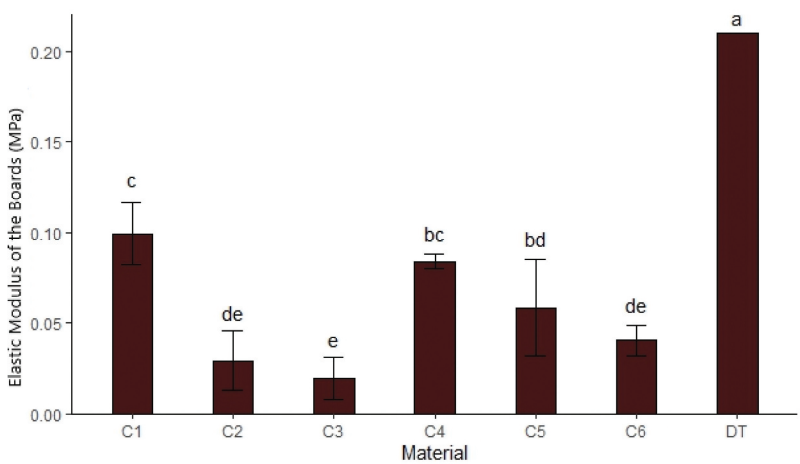

Figure 9. Elastic modulus of the boards.

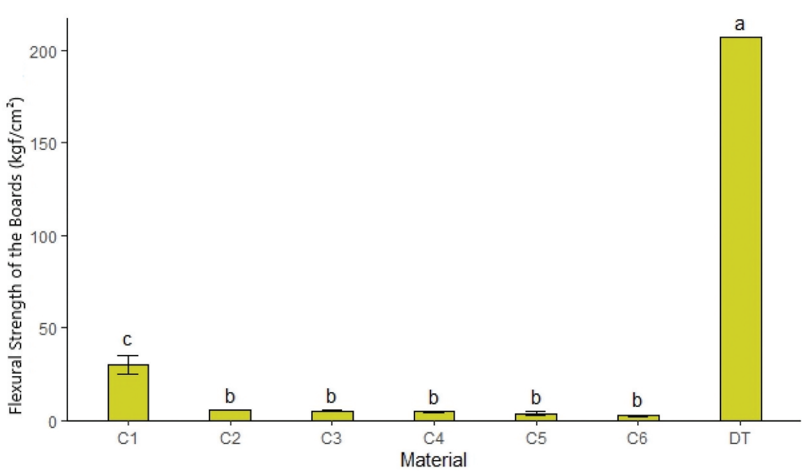

Figure 10. Flexural strength of the boards.

Table 5. Elastic modulus and maximum pressures used.

Boards	Maximum Pressure Applied (kgf/cm^2)	Maximum Elastic Modulus Obtained (MPa)	Maximum Flexural Strength Obtained (kgf/cm^2)
Laboratory Scale (*Residuall*)	20	0.9	30
Pilot Press (Dexco SA)	104.01	2130	207
Technical Document*Coir Based Building and Packaging Materials*	153	5000	509

superior performance to the current work, with higher bending modulus and strength values in the range of 5 GPa for the modulus and 50 MPa for strength. This could be directly related to the pressure variable, since all other parameters were similarly used. In the technical document, the pressure used was 150 bar (approximately 153 kgf/cm^2), while in the current work, it was 20 kgf/cm^2. Thus, in this study, the applied pressure was below 15% of the total applied in the pilot project (Snijder 2005). Table 5 shows the differences in the modulus of elasticity of the boards and the pressures used in each process, highlighting that this variable is relevant in the manufacturing of these materials.

Still, it is considered that the coir fiber boards showed potential for plasticization without the addition of an adhesive. In other words, practically, the fibers were transformed into boards solely due to the amount of lignin naturally present in the fibers. This is environmentally significant due to the biodegradability potential of the boards and the efficient utilization of coir waste.

In the water absorption test, the absorption rate at the laboratory scale was higher than 100%, meaning that all samples were saturated with water, as shown in Table 4. For the board manufactured at the pilot scale, the water absorption was 52%, demonstrating that the pressure was sufficient to densify the lignin, a lower absorption rate was achieved.

In the swelling test, it is observed that boards with lower density exhibited less expansion compared to boards with a higher volume of particles. This could be linked to the lower water absorption due to the lower fiber content, though in most cases, material saturation was also observed. The board manufactured in the pilot plant showed a swelling of 31%, indicating that pressure is the most significant factor in the board manufacturing process.

Saturated boards may experience significant loss of their final mechanical properties, making their ability to resist water an important factor in the boards' viability. Given the amount of pressure applied in the laboratory experiment, it can be inferred that the boards did not undergo an efficient pressing process. Therefore, this variable should be considered critically important.

Coir waste and the circular economy

The generation of coir waste has both direct and indirect environmental impacts. Disposal in landfills can cause these sites to face pressure due to the excessive volume of waste, reducing the landfill's lifespan. For example, in Brazil, approximately 81.8 million tons of organic waste were generated in 2022, with only 61% of this total being disposed of in an environmentally correct manner (Lino et al. 2023). Improper disposal or the high volume of organic waste in landfills is directly linked to the generation of gases resulting from the decomposition process, which often lacks any form of environmental control, as is the case in open dumps.

By reusing coir waste, it can be redirected into a new production process, no longer viewed as waste but rather as a raw material for the production and composition of new materials, for example. This shift from a linear system, which follows the premise of use and disposal, to a circular system that proposes new ways of producing by considering the circularity of materials and reducing the reliance on raw materials. Seeks to combine economic development with the sustainable, rational, and responsible use of natural resources. The Circular Economy refers to an industrial economy that is restorative by design and reflects nature by actively optimizing the systems in which it operates (Favre and Dubuisson 2014).

The strategy of reintegrating coir waste into a circular economy can be environmentally viable, as it reduces the amount of waste sent to landfills and avoids the exploitation of new natural resources. At the same time, the adoption of a circular production and consumption model can positively impact the local economy of coir producers, as well as the sustainability metrics of companies involved in the production process.

By reintegrating waste as raw materials into a new production chain, it is possible to utilize material that would otherwise be directly discarded. However, it is essential to understand all the links in this new chain to ensure that the environmental impact generated by the circular economy is minimized. This accounting of the impact's magnitude can be observed when comparing the potential uses of the waste, prioritizing business models that can extract the highest possible added value.

Conclusions

- Coir fiber composites exhibit satisfactory final mechanical characteristics when different fiber volumes are evaluated. The final component has good mechanical properties and can be environmentally viable, making these some of the advantages of this material.
- Due to its properties and the amount of lignin, coir fiber has the potential to be used in the manufacture of materials on its own, being able to be transformed into sheets without the addition of binders.
- The adoption of practices that utilize coir waste promotes the circular economy and the possibility for the entire production chain of the coir fruit to adopt sustainability commitments and generate positive environmental impacts.

Highlights

- Green coconut disposal is a global problem due to its high volume and long lasting decomposition.
- The use of its fibers can represent an important step toward the circular economy, since can reduce the stress in landfills.
- Binderless boards are sustainable alternative to reduce its carbon footprint in wood-based products, since use natural plastifiers.
- Thermoplastics matrices using coir as reinforcement agent presents a synergism, since allies high lignin content with natural fiber strength.
- The use of an important waste to produce a biobased composites open the ways for sustainable materials.

Disclosure statement

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