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SUSTAINABLE PRODUCTION AND MECHANICAL CHARACTERIZATION OF EXTRUDED WOOD-PLASTIC COMPOSITE MADE FROM HDPE AND BABASSU FIBER

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Abstract. Social development combined with economic progress and the preservation of natural resources forms the basis of the sustainability concept. In this sense, a productive model based on this strategy was established as an alternative to forest wood in the furniture industry by extruding wood-plastic composite (WPC) bars made of recycled HDPE and babassu coconut shell fibers. Temperature calibration of the extrusion set was conducted to verify the surface quality of the bars. The best surface aspect and lowest porosity were reached for higher extrusion temperatures and low speed, and these conditions were used for producing the samples for experimental tests on the material's resistance. The analysis of the stress-strain curves showed that natural wood alone behaves similarly to brittle materials in which there is little plastic deformation before rupture, whereas the additions of HDPE improved the total elongation and impact resistance substantially. The good mechanical properties validate the use of this material and the proposed production model, which promotes social integration in the babassu extracting economy chain in one of the poorest regions in Brazil.

Keywords: wood-plastic composite, sustainability, babassu fiber, extrusion, HDPE

1. INTRODUCTION

The 2030 Agenda, an international commitment signed by UN members, sets 17 goals for sustainable development to eradicate poverty and protect the planet. Sustainability stands out as a fundamental requirement for production, whether in cities, industries, or the countryside. According to Seliger et al. (2011), this concept is related to conserving natural resources and society's financial prosperity and well-being, concerns that form the tripod of sustainability commonly called the triple bottom line.

In this sense, production planning must be thought of from the beginning of the production chain to the end of the life cycle of the products, prioritizing circular flows in the economic chain to maximize the recycling and reuse of raw materials (Seliger, 2012). Also, the reuse of by-products from production processes becomes an essential element to minimize disposal into the environment. Thus, when a company establishes in its manufacturing processes the association of these factors in a profitable and integrated manner with local communities, it is possible to achieve socio-economic development and preserve the environment.

The production of wood plastic composites (WPC) approaches this scenario, using natural fibers widely available in the pulp and paper industry by-products mixed with traditional polymers. Fibers, which are renewable components, in addition to replacing petroleum-derived polymers in percentages by mass of 1 to 40% in these products, also substantially improve mechanical properties such as resistance to traction, bending, and impacts. This application received attention mainly from the 1970s onwards, with the development of technologies for preparing fibers, mixing, and manufacturing composites by lamination, extrusion, or other methods. Currently, annual production reaches 2.6 million tons (Kieling et al., 2019), and the main products are laminated boards used in wall and floor coverings, although various consumer goods have also been manufactured. In addition to good mechanical properties and aesthetic appeal, the products receive additives that ensure good resistance to chemical and biological weathering (oxidation, mold, termites) and low flammability.

Considering this context, this work evaluated the use of babassu coconut fiber as a cellulosic component in wood plastic composites. In addition to the traditional attractions of this technology, a major concern was its integration with the local community through the use of by-products from the traditional extractivism economy of the babassu coconut in the interior of Maranhão. Among the various applications of the palm tree and the different parts of the fruit, the extraction of nuts and the manufacture of edible oils occur by hand and are the main form of livelihood for more than 40000 families in the interior of the state (Porro, 2019), meaning a large number of by-products in the form of husks. According to Martins et al. (2011), despite corresponding to only 11% of the fruit's mass, the epicarp, if fully utilized, would allow an annual production of 1.5 million tons of fibers.

The main focus was to evaluate the application of these fibers in materials capable of replacing the wood used in the furniture industry in the cities of Maranhão, which often comes from felled forest areas. The intense deforestation in the native forests of this region in recent years is highlighted (Kalamandeen et al., 2018). Additionally, in line with sustainability, wood plastic composites were studied, considering the recycling of thermoplastics to obtain the polymer matrix. In this way, it contributes to ecological preservation and the competitiveness of the sector by promoting the reuse of a material that is often treated as waste, and for that reason, it can be obtained at lower prices.

The sustainability of this production model was already assessed in previous works (Siqueira et. al., 2021), the mechanical characteristic were more thoroughly studied now. For this, rectangular section profiles were extruded in high density polyethylene (HDPE) and in WPC, from which samples were cut to characterize the mechanical strength. Natural wood specimens were also evaluated. The extruder temperature was an important factor in the bars' quality, while the inhomogeneous distribution of the fibers was decisive for the fracture modes observed in the tests. Incorporating fibers improved the properties compared to the pure polymer, with some advantages over pure wood characteristics. These factors indicate the possibility of reusing babassu peels with recycled polymers as a strategy for the region's sustainable development in a business model that integrates regional tradition and preserves the environment.

2. MATERIALS AND METHODS

2.1. Extrusion of the wood plastic-plastic composite

The extrusion was carried out in a conventional worm screw extruder, shown in Figure 1, installed at the Department of Industrial Mechanical Engineering of the Federal Institute of Education, Science, and Technology of Maranhão (IFMA). The raw materials are added to the silo (1), pre-heated and mixed at controllable speed and temperature. The extruder (2) allows precise control of the motor (3) and puller (4) speed through frequency inverters and is divided into three zones whose temperatures can be adjusted independently on the panel (5). With valve control, the cooling system circulates the water in the extruder, die, and cooling channel (6).
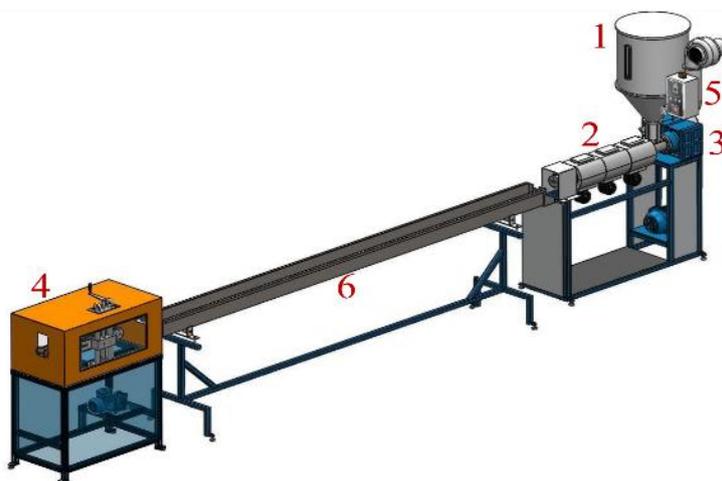

Figure 1. CAD model of the extrusion system and its main components.

The temperatures and speed of the extruder were evaluated at three levels with recycled HDPE pellets, obtained by crushing pallets from the food industry and provided by a local company. This material was dehumidified in an oven at 70 °C for 60 min. The data are presented in Tab. 1, and Figure 2 shows the appearance of the produced pieces. Thanks to the better finish and lower porosity obtained in test C, the conditions of this test were used for the extrusion of wood plastic. The babassu coconut shells were obtained from local producers and crushed in an industrial blender. The fibers were then dehumidified at 100 °C for 60 min and classified in a #80 mesh sieve. Its addition to HDPE was made in the silo, in 20% in fiber mass.

Table 1. Test extrusion parameters.

Trials	Temperature (°C)					Thread speed (rpm)
	Bin	Extruder			Matrix	
		Zone 1	Zone 2	Zone 3		
A	50	140	140	160	160	35
B	70	150	150	165	165	20
C	70	170	170	180	180	23

Figure 2. Extruded HDPE samples under different conditions of speed and temperature.

2.2. Mechanical Characterization

In order to compare the mechanical properties of wood, HDPE, and the composite formed by HDPE and babassu, tensile, compression, bending, and hardness tests were performed. Based on these tests, it is possible to evaluate the influence of babassu on the composite compared to pure HDPE and the performance of these two materials. The HDPE and WPC bars were cut and sanded with #80 to #1200 sandpaper to produce three specimens for each mechanical test. Additionally, Angelim wood was also used to compare strength characteristics, producing samples in the fiber direction.

The tensile tests were carried out on a Filizola bench model BME 10 kN, with specimens 1BA model of ISO 527 (2012) standard, shown in Figure 3(a), and a 1 mm/min deformation speed. The compression tests were carried out on a Shimadzu bench model AGS-X, with model A specimens of ISO 604 (2002) standard, shown in Figure 3(b), and at the same speed. Shore D hardness tests were performed according to ISO 7619 (2010) with a Woltest model MP-2 durometer, and a load of 5 kg applied for 10 min.
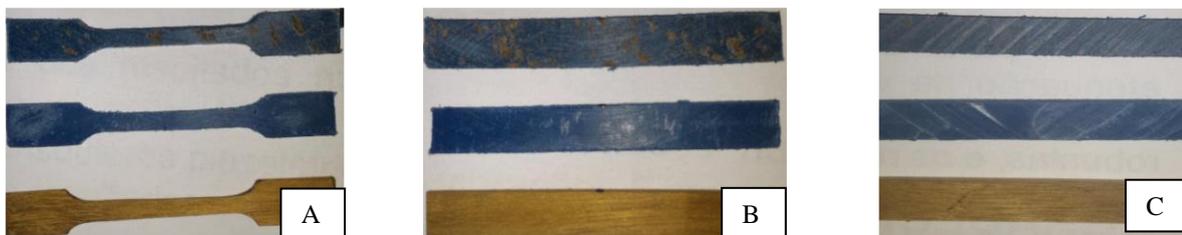

Figure 3. Test specimens from (a) tensile, (b) compression, and (c) hardness tests.

3. RESULTS AND DISCUSSIONS

3.1. Stress-Strain Tests

Figure 4.a) illustrates the variation of stress as a function of strain in the tensile tests of the materials analyzed. Figure 4.b) illustrates the maximum tensile strength (UTS) and the maximum strain obtained in the same tests. Figures 5.a) e 5.b) illustrate samples of fractured wood after the tensile test, with the region of the fracture being highlighted by the red circle. The wood samples showed the highest maximum tensile strength values, requiring an average of 44.38 ± 0.37 MPa to break the material.

On the other hand, this material presented the lowest deformation values, elongating about $22.16 \pm 1.23\%$ until its rupture. These data indicate wood as the most rigid of the three materials in terms of tensile strength since it supports the highest loads and suffers the smallest deformations, this rigidity being highly desirable in the structure of box beds.

The high structural homogeneity characteristic of Angelim is likely responsible for the low standard deviations observed in tensile tests compared to other materials. The highest values of maximum tensile strength can be explained by the fact that the tensile direction is parallel to that of the wood fibers, which is justified because this direction is subject to a greater bending moment in box bed structures.
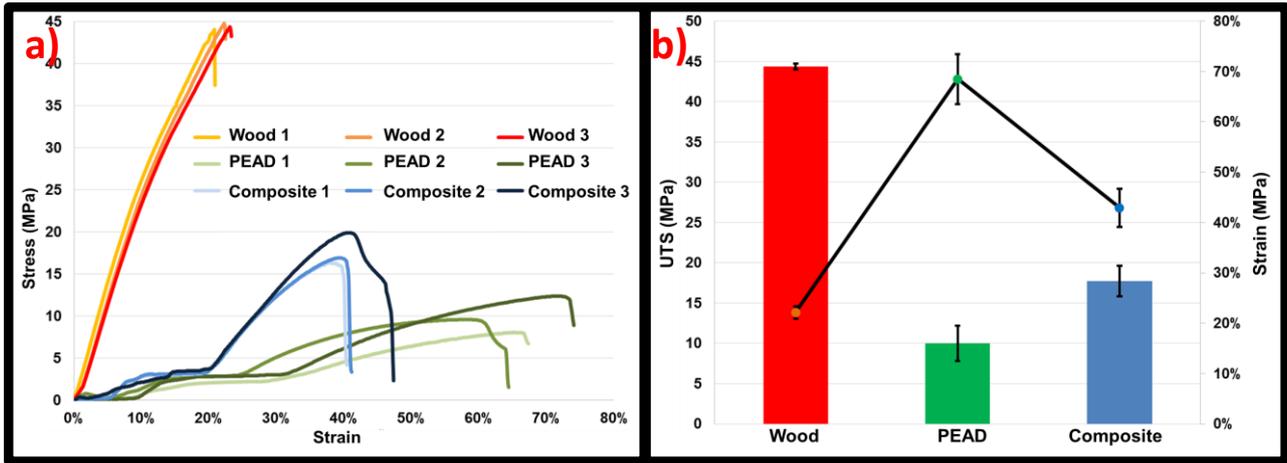
Figure 4. Stress-strain relation for the evaluated materials in tensile tests. a) Stress x Strain curves; b) Ultimate tensile strength (UTS) and maximum strain for the evaluated materials.

Figures 5.c) and 5.d) illustrate fractured HDPE samples after the traction test, with the fracture region highlighted by a red circle. The HDPE samples showed the lowest UTS values, requiring an average of 10.02 ± 2.17 MPa to break the material. This material presented the highest deformation values, stretching around 68.49 ± 4.94 % until its rupture.

The data allow us to conclude that HDPE has the lowest tensile stiffness among the three materials analyzed. The greater ductility of this material is due to the characteristic of the polymers in deforming elastoplastically easily due to having both covalent bonds (strong) and Van Der Walls forces (weak).

The change in color at the deformed ends of Figure 5.c also indicates the crazing mechanism during shear, a typical fracture mechanism for high-elasticity polymers that helps in energy dissipation, thus hindering crack propagation and increasing the ductility the material. The high standard deviation compared to the other materials tested is because the HDPE tested has high porosity. These bubbles are stress concentrators and preferential sites for the formation of cracks, as illustrated in Figure 5.d. This random distribution of bubbles and their sizes makes it difficult to obtain good mechanical repeatability among several tested samples.
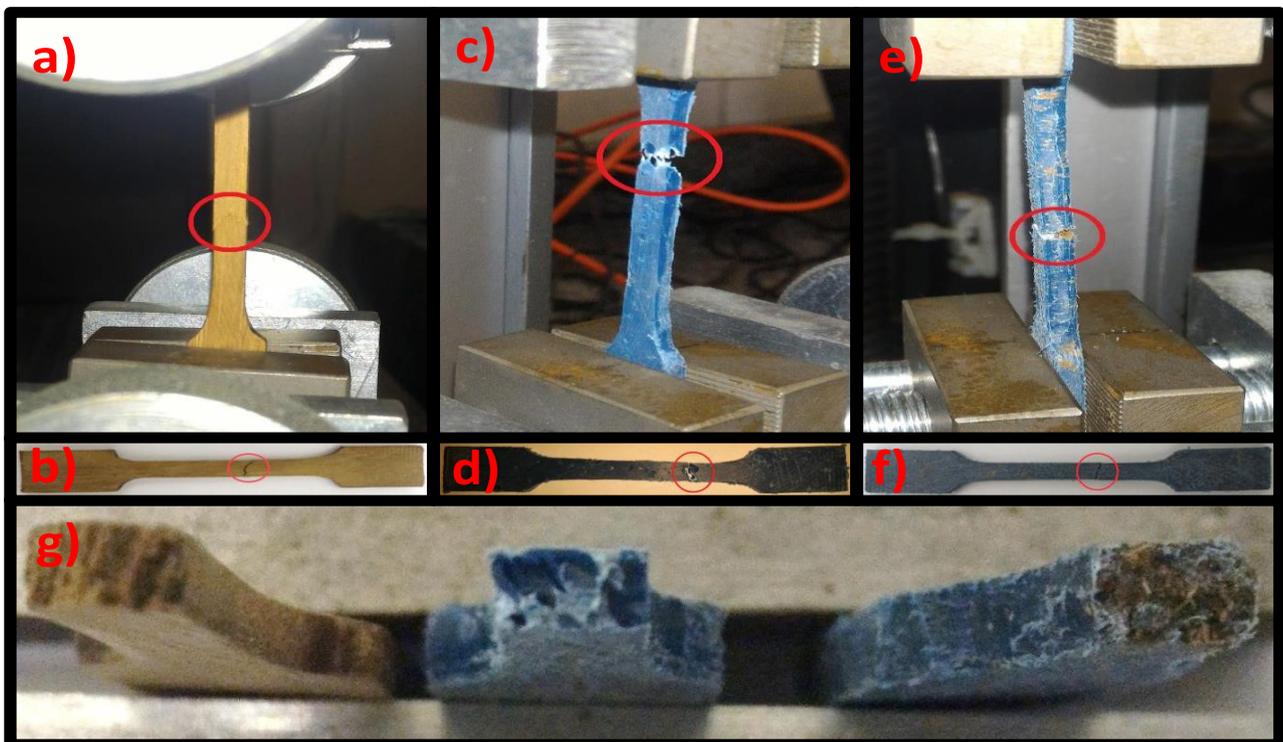

Figure 5. Specimens used in the tensile tests. a) wood specimen after fracture; b) detailed view of the wood specimen after fracture; c) HDPE specimen after fracture; d) detailed view of the HDPE specimen after fracture; e) composite specimen after fracture; f) detailed view of the composite specimen after fracture; g) Top view of the tensile fractures.

Figures 5.e) and 5.f) illustrate samples of the composite HDPE + babassu fractured after the tensile test. The samples of this composite showed intermediate values for both UTS and strain, requiring an average of 17.72 ± 1.89 MPa to break the material and an average final elongating of about 42.90 ± 3.78 %.

Figures 5.e) and 5.f) compared to Figures 5.c) and 5.d) indicate a less ductile fracture due to the already explained increase in stiffness of the material. The greater rigidity of the material due to the addition of babassu is also observed by the lesser dispersion of the results between the samples, and this lower dispersion may be explained by the agglomerating effect of babassu on the HDPE, reducing the number of voids in the specimens. Babassu, however, was not completely homogeneously distributed throughout the specimen, forming agglomerates (clusters) along with the specimen. While these clusters provide greater rigidity to the material, its interface also acts as a stress concentrator, generally being the initial site of crack propagation, as illustrated in Figure 5.e).

Figure 5.g) illustrates the top view of the fractured regions of the three materials. In this figure, it is clear that wood showed a greater tendency to cleave than other materials due to its greater rigidity. The HDPE supported the smallest loads due to the presence of porosities, being the inherent ductility of the polymers an insufficient magnitude factor to overcome these stress concentrators. Finally, the composite presented a fracture with a mixed aspect between the wood and the HDPE, making it clear that babassu gives greater rigidity to the specimen despite clearly behaving like a second phase.

3.2. Compression Tests

Analogously to the tensile tests, Figure 6.a) illustrates the variation of stress as a function of strain, and Figure 6.b) the maximum rupture stress and maximum strain. Figures 7.a) and b) illustrate, respectively, wood samples during and after the compression test. As in the tensile tests, wood samples also presented the highest UTS values and lowest maximum strain values, being necessary, respectively, on average 53.30 ± 1.41 MPa to break the material and presenting an elongation of about 28.47 ± 0.59 %.

Figures 7.c) and 7.d) illustrate, respectively, HDPE samples during and after the compression test, both figures illustrating the presence of porosities in the specimen. The HDPE samples also presented the lowest UTS values and the highest maximum strain, being required respectively, on average 25.82 ± 2.68 MPa to break the material and presenting an elongation of about 91.77 ± 2.34 %.

An example of a compression test performed for one composite specimen is illustrated in Figure 7.e). Figure 7.f) represents a specimen fractured after the test. A cluster of babassu is highlighted in red in the approximately central region of the fracture, corroborating the theory that these clusters, despite increasing the composite stiffness, act when too large as stress concentrators. In a similar way to the tensile tests, this material presented an intermediate behavior between wood and HDPE, presented as UTS and maximum elongation values, respectively 36.59 ± 2.68 MPa and 67.72 ± 2.18 %.
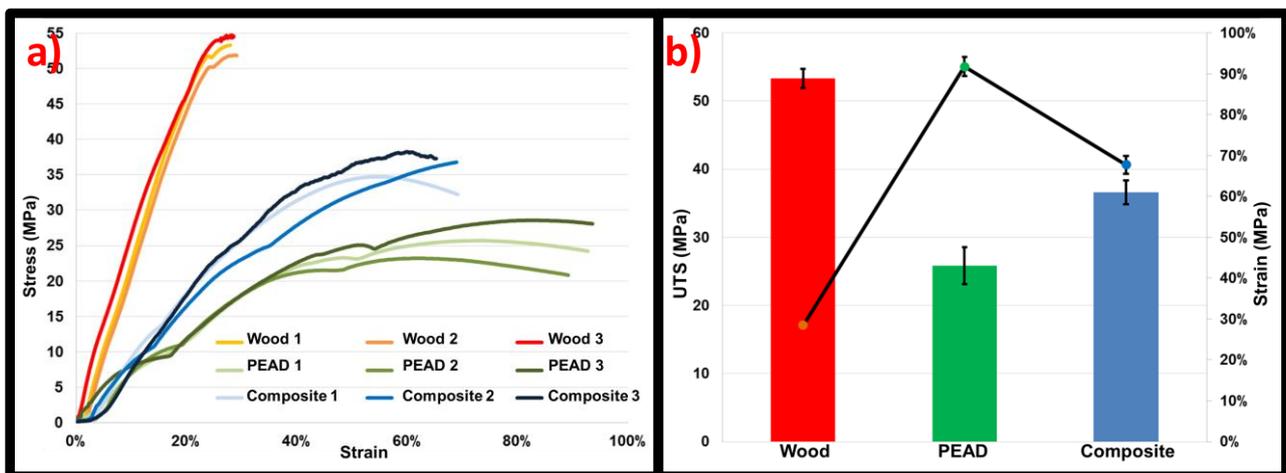

Figure 6. Stress-strain relation for the evaluated materials in compression tests. a) Stress x Strain curves; b) Ultimate tensile strength (UTS) and maximum strain for the evaluated materials.

Figure 7.g) illustrates the top view of the fractures of the three materials subjected to compression tests, showing the crushing of the wood fibers, the presence of porosities in the HDPE, and the babassu agglomerates in the composite. Even though the wood presents higher UTS and strain values in the compression tests, proportionally, both HDPE and composite gains were much higher, as shown in Figure 8.

This fact can be explained based on the fact that the voltage concentrators referring to the presence of voids in the HDPE and the composition interfaces in the composite have their effects compensated by the lower tractive loads characteristic of this type of test. These lower tractive loads are because $K2c$ and $K3c$ are the predominant stress-

enhancing factors in this type of test. Since the magnitude of K2c and K3c are lower than that of K1c (due to its purely tractive nature), cracks receive less energy to propagate, as not all energy is converted into traction (and cracks propagate only by traction). This lower energy input to propagate the cracks results in higher loads for the material to break. Since the effects of these structural and compositional flaws in HDPE and composite were mitigated but not eliminated, the standard deviation between their results decreased when compared to their equivalents in the tensile test; however, they are still superior to those of wood.
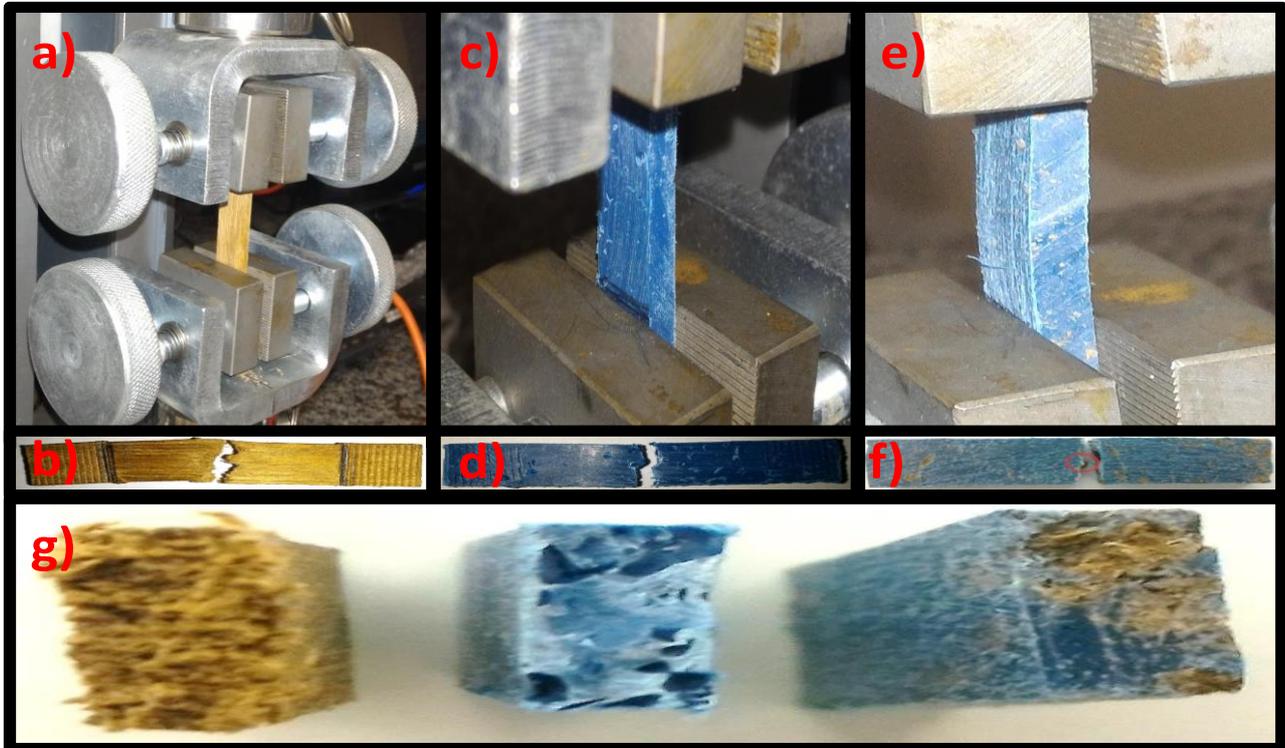

Figure 7. Specimens used in the compression tests. a) wood specimen after fracture; b) detailed view of the wood specimen after fracture; c) HDPE specimen after fracture; b) detailed view of the HDPE specimen after fracture; e) composite specimen after fracture; g) Top view of the tensile fractures.
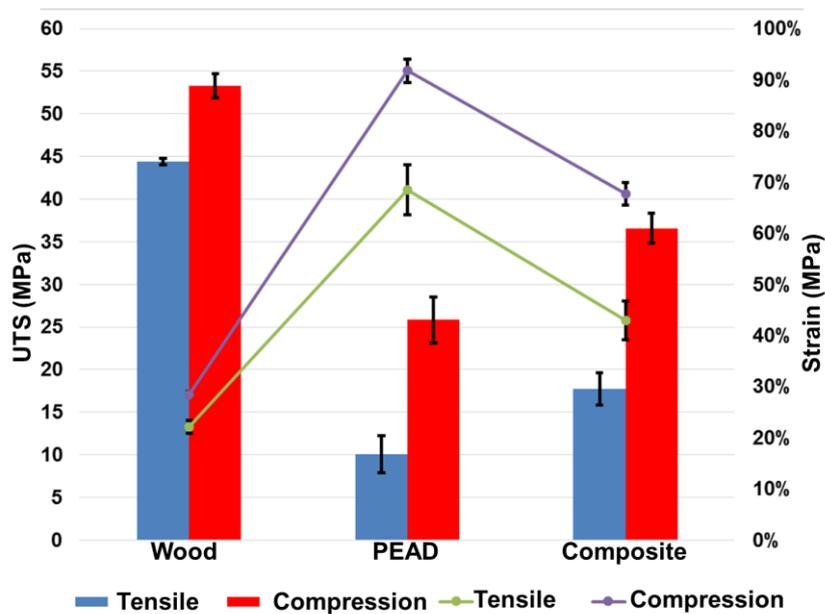

Figure 8. Comparison between the maximum strain rupture stress values of the tensile and compression tests.

3.3. Bending Tests

Figure 9.a) illustrates the variation of stress as a function of deformation in the bending tests of the analyzed materials. Figure 9.b) illustrates the maximum tensile strength (UTS) and the maximum strain obtained in the same tests. As explained in the methodology, the maximum displacement possible for the equipment was 5 mm (or 125% deformation), and for this deformation, there was no fracture of the HDPE samples. The lower loads borne by materials in bending when compared to materials in tension and compression are due to the fact that, together with the shear force, there is a bending moment acting on the specimen.

Figures 11.a) e 11.b) illustrate the fractured wood samples' front and side views after the bending test. Even though there was no complete rupture of the specimens, the fiber and fracture direction meant that the material did not offer flexural strength after the failure, as illustrated by the abrupt drop in tension for the wood samples in Figure 10.a).

Sample Wood 3 presented two stress peaks. The probable explanation for this is that the initial peak is related to the stress relief promoted by the propagation of a secondary crack, followed by the second peak in which the main crack propagated, fracturing the specimen. Once the bending combines regions of tension and compression in the specimen, the wooden specimens presented the highest TMR and smallest maximum deformations, respectively 5.04 ± 0.18 MPa and 34.21 ± 3.98 %.
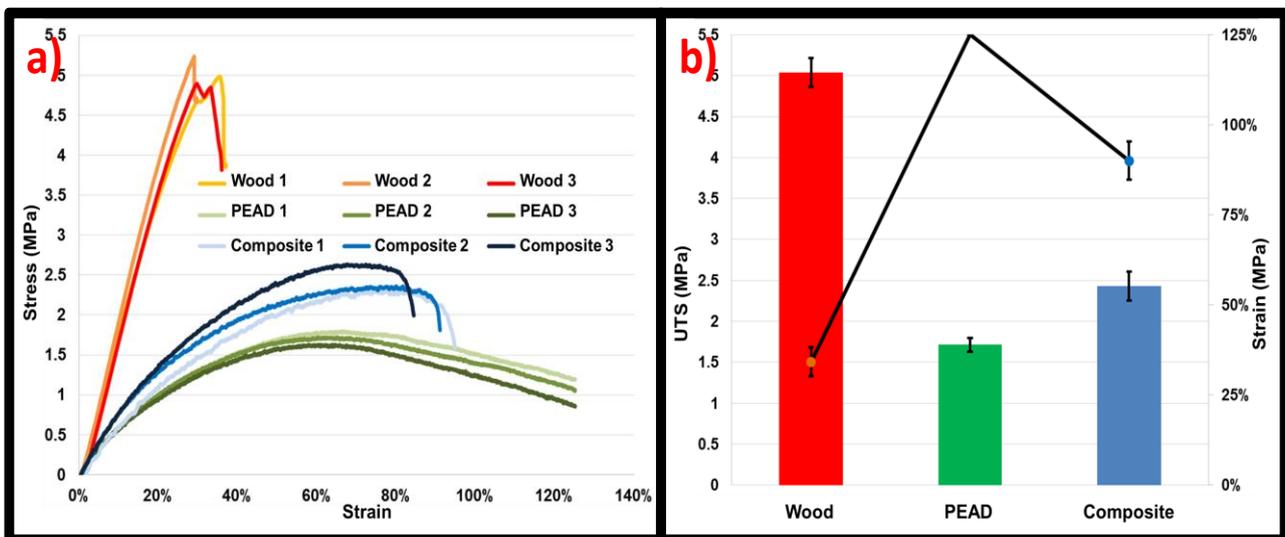

Figure 9. Stress-strain relation for the evaluated materials in compression tests. a) Stress x Strain curves; b) Ultimate tensile strength (UTS) and maximum strain for the evaluated materials.

Figures 10.a) and 10.b) illustrate, respectively, the front and side views of the fractured wood samples after the bending test. Even though there was no complete rupture of the specimens, the fiber and fracture direction meant that the material did not offer flexural strength after the failure, as illustrated by the abrupt drop in tension for the wood samples (Figure 10.a). The wood sample 3 presented two stress peaks; the probable explanation for this is that the initial peak is related to the stress relief promoted by the propagation of a secondary crack, followed by the second peak in which the main crack propagated, fracturing the specimen. Once the bending combines regions of tension and compression in the specimen, the wooden specimens presented the highest UTS and smallest maximum deformations, respectively 5.04 ± 0.18 MPa and 34.21 ± 3.98 %.

Figures 10.c) and 10.d) illustrate, respectively, the front and side views of the HDPE samples after the bending test. For all specimens, even after 5 mm of displacement, there was no apparent fracture.

However, a voltage drop was observed throughout the tests, the probable cause being the beginning of crack propagation in the material. These specimens resulted throughout the tests in the lowest stress values, this being in the range of 1.72 ± 0.09 MPa, and, since there was no fracture, the maximum strain values cannot be stipulated.

Finally, Figures 10.e) and 10.f) illustrate the fractured composite sample's front and side views after the flexion test. As for the wooden specimens, again, there was no complete disruption of the specimens. Figure 10.e) clarifies, from the areas indicated in red, that the fracture starts in the babassu clumps, which concentrate tensions. This material presented an intermediate UTS between wood and HDPE, with this magnitude in the range of 2.43 ± 0.17 MPa. The material presented greater resistance to bending deformation than wood, deforming 90.03 ± 5.26 % until fracture.
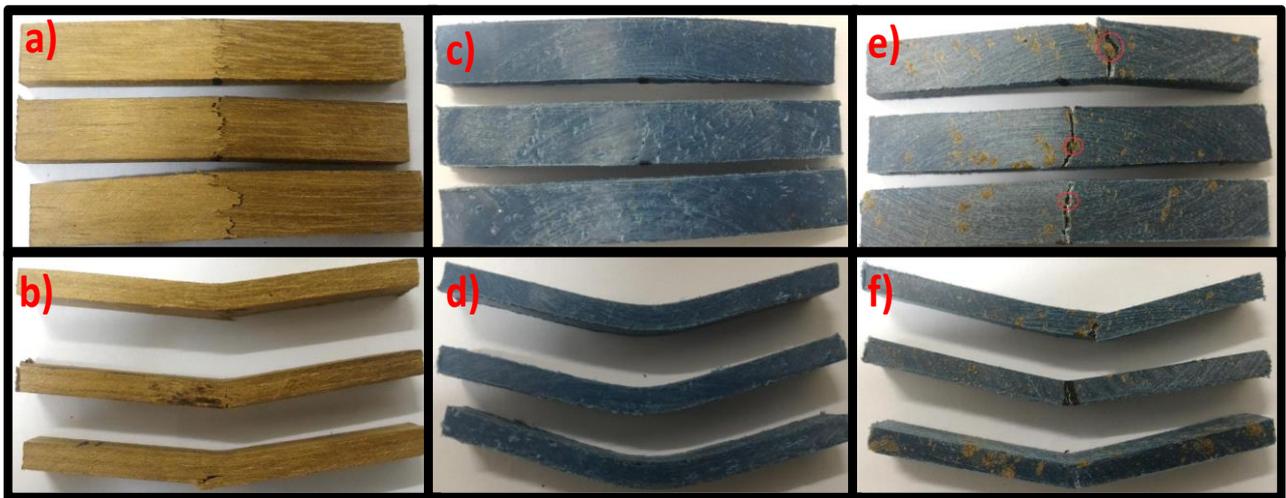
Figure 10. Specimens used in the bending tests after fracture. a) wood specimen front view; b) wood specimen side view; c) HDPE specimen front view; b) HDPE specimen side view; e) composite specimen front view; f) composite specimen side view.

3.4. Impact tests

The values for the energy absorbed during impact for the materials tested can be seen in Figure 11. The wood absorbed a considerably more significant amount of energy than both the composite and HDPE, which was expected because the wood had the highest UTS in tensile, compression and bending tests. Also, following the trend of previous tests, the composite presented a behavior superior to that of HDPE, reinforcing the effectiveness of babassu in reducing bubbles and increasing the material's stiffness. Again, the standard deviations of HDPE and composite were higher than those of wood due to the inhomogeneity of the distribution of bubbles in the former and babassu agglomerates in the latter.
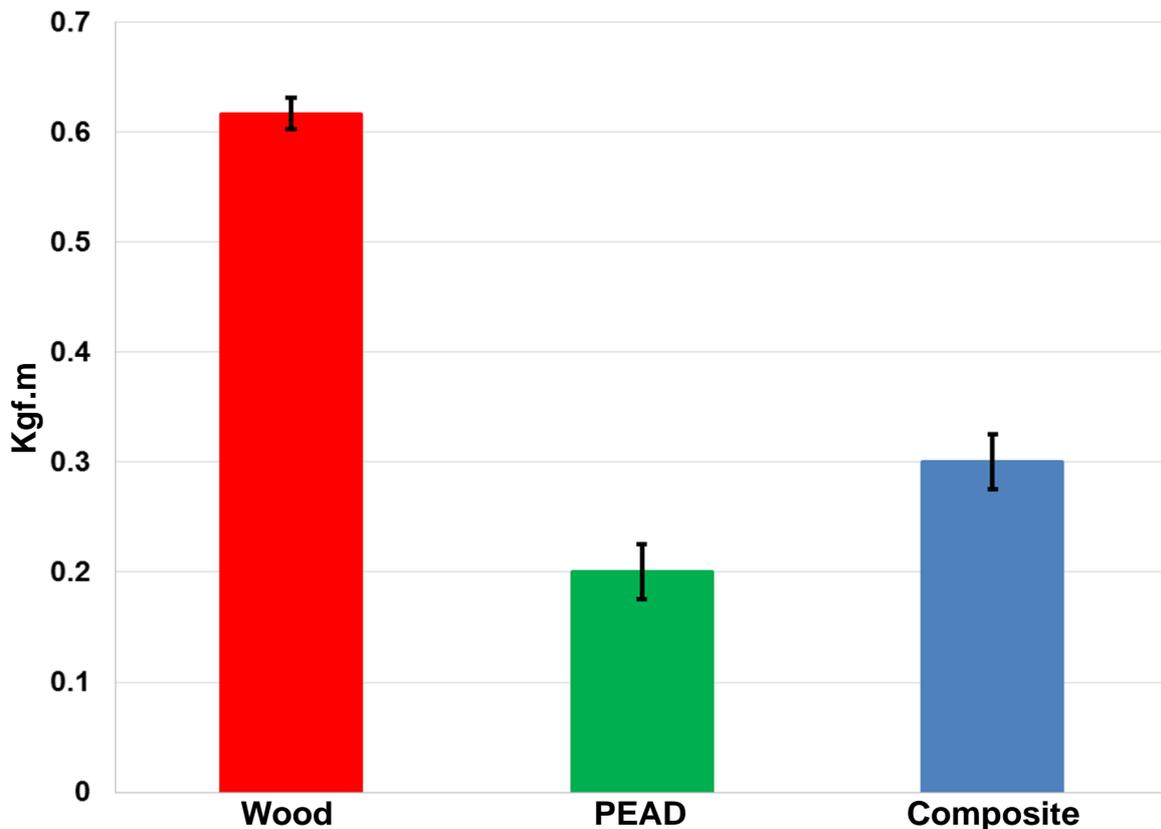

Figure 11. Energy absorbed by the specimens during the impact test.

3.5. Hardness tests

In order to compare the hardness of the materials tested, 5 Shore A hardness measurements were performed on the materials tested, the values of these measurements being indicated in Figure 12.a). However, this hardness scale was not valid for the analysis of these materials, considering that all measurements were at the upper limit of its resolution, making it impossible to measure differences in hardness between these materials. Shore D hardness measurements were then taken, which is more effective in measuring the hardness of stiffer polymers. The results of the Shore D hardness measurement are shown in Figure 12.d). Shore D hardness indicated that wood is the least hard of materials and composite the hardest. The highest standard deviation observed in the composite is because babassu can occupy larger or smaller areas of the indentation between measurements, which directly influences the hardness value obtained, unlike other materials with only one phase.
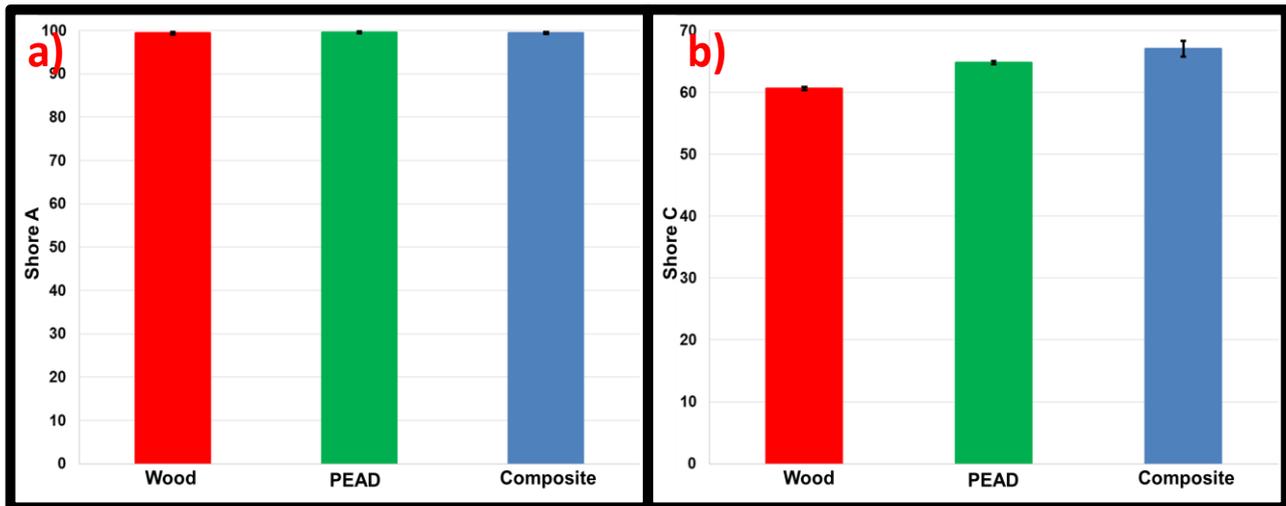

Figure 12. The hardness of the specimens. a) Shore A hardness; b) Shore C hardness.

4. CONCLUSIONS

The benefits of wood plastic for the environment are enormous due to the reduction in deforestation and plastic waste recycling. However, what makes this product a professional success is its economic viability, as its aging time is equivalent to the decomposition time of the plastic itself.

As it is a product that is still little known and used, it is necessary to increase its dissemination and make society aware of the need to adopt a new consumption mentality, giving preference to sustainable and ecologically correct products. After a detailed analysis, all the tests carried out in this work indicate that the wood presents mechanical properties superior to the HDPE and the composite formed by HDPE and Babassu coconut epicarp powder. The addition of powder proved to be effective in improving the hardness of HDPE, mainly due to its effect on reducing the number of internal bubbles in the extruded material.

Since the polymer and composite rigidity was lower than that of wood, the dimensions of the components to be manufactured with these materials must be larger to have a structural capacity similar to wood and serve as a substitute.

However, it is observed that the improvement of the HDPE production process to reduce bubbles and the composite to reduce babassu agglomeration, as well as the use of larger fibers instead of powder, can result in greater stiffness gains making the resulting composite more competitive.

5. ACKNOWLEDGMENTS

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