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Does the Layer Configuration of Loofah (*Luffa cylindrica*) Affect the Mechanical Properties of Polymeric Composites?

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Abstract: The arrangement of layers of natural long fibers that compose a polymeric composite can result in a final material with greater mechanical strength, in addition to replacing synthetic glass and carbon fibers. This study proposed different configurations of layers of loofah fibers (*Luffa cylindrica*) to produce reinforced polymeric–polyester composites, determining their potential mechanical properties such as flexural strength and Rockwell hardness. The layers were arranged by varying parallel and perpendicularly the direction of the loofah fibers pieces. The reinforcement decreased the density of all composites, with the lowest value, 1.03 g cm^{−3}, indicated by the configuration 90°/0°/90°. The composites in the configuration 0°/90°/0° presented the highest value among the reinforced compositions (10.8 MPa), in addition to the highest rigidity value during bending tests (774.8 MPa). In the Rockwell hardness tests, the treatment reinforced with fibers in the configuration 90°/90°/90° had the highest value among all experimental treatments with a value of 86.9 HHR. The configuration angle of the loofah layers has a significant impact on the mechanical performance of the composites and should be taken into account in their confection. Furthermore, composites reinforced with loofah fibers in different configurations have physical–mechanical properties that qualify them for non-structural applications in indoor environments.

Keywords: lignocellulosic fibers; sustainable materials; vegetal fibers; resistance; density



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1. Introduction

The demand for environmentally friendly materials has encouraged the development of research to replace synthetic glass and carbon fibers, which are the most used as reinforcements in polymer composites, with natural fibers [1,2]. The high demand for polymeric composites reinforced with glass fibers for manufacturing parts has generated a significant waste of materials in the manufacturing process [3]. These materials' manufacturing processes and disposal promote severe environmental impacts [2]. Traditional disposal methods such as landfills or incineration are accumulating these synthetic materials outdoors and promoting environmental pollution [4]. According to Ponsoni et al. [2], natural

fibers have remarkable properties compared to synthetic fibers, such as lightness, low cost, and biodegradability.

Plant fibers are biodegradable materials with several advantages for replacing synthetic carbon, glass, and aramid fibers for use in automotive, construction, aerospace, packaging, biomedical, furniture, and other applications [5]. Thermosetting composites reinforced with plant fibers have been widely accepted and used in various applications [6]. According to Paula et al. [7], polymeric composites with a polyurethane matrix reinforced with wood powder and sisal fibers can be used to develop handicrafts and decorative elements. Still, according to Sajin et al. [8], polymeric polyester composites reinforced with jute fibers can be used for structural engineering applications, since they are lightweight and low-cost materials. They can be an alternative material for making automotive, aerospace, and construction components [9].

For Sivakandhan et al. [10], composites manufactured with natural fiber reinforcement have been presented as an alternative to replace synthetic fibers, as they also provide good mechanical properties. Regarding the mechanical properties of the composite, there are several possibilities for “leveraging” resistance to external damage and impacts, such as the use of reinforcement with high-density natural fibers, application of high-hardness thermosetting resins, adjustment of pressing pressure parameters (if necessary) and temperature of solidification of the components, changing the matrix/reinforcement ratio, and establishing formation in layers. Many of these adaptations require intense changes in the established process, which can result in the acquisition of larger and more expensive equipment, as well as the search for specific fibers and matrices. The option of producing a composite in layers of crossed natural fibers could be the simplest and most attractive from the point of view of practicality and cost free. The crossing of layers is mainly responsible for the excellent mechanical performance and dimensional stability of the laminate plywood, and for being applied to natural fibers, they must have a long structure to enable the layer’s easy orientation.

Among the varieties of vegetal fibers that can be inserted into the polymeric composite, alternating the directions of the layers, is the Asian species *Luffa cylindrica*, popularly known as loofah. In Brazil, the loofah is widely cultivated in the North and Northeast regions, where it is used as bath sponges and to produce biodiesel, making of insulation boards, and wastewater treatment [1,7,11–13]. The mature bushing presents a fibrous structure with excellent properties of resistance, stiffness, and energy absorption capacity, in addition to having a low cost, being light, abundant in nature, and having a morphology that favors good fiber–matrix adhesion [7,14,15]. Adeyanju et al. [16] cited that polymeric composites reinforced with vegetal loofah present average tensile strength values ranging from 13 to 36 MPa, showing potential for use as reinforcement in composites. Mk-Pume et al. [17] stated that epoxy matrix composites reinforced with 4% by weight of vegetal loofah presented an increase in tensile strength properties. However, research with polymeric composites manufactured in differently oriented layers of natural fibers are scarce in scientific documents.

The present research aimed to verify the influence of different configurations of layers of loofah fibers in improving the mechanical properties of the final product. Information on the physical–mechanical properties of these materials still needs to be made available. Studies in the literature do not usually evaluate different layer configurations in composites with natural fibers. Much of this is due to the difficulty of finding fibers long enough to deposit and form a correctly oriented layer. The loofah does not precisely correspond to a perfect orientation as the fibers grow and, in a certain way, curl. Nevertheless, it can be said that there is a longitudinal orientation of the fibrous structure of the material. The findings are extremely useful for future research focusing on the orientation of the reinforcing material of composite layers with lignocellulosic fibers. In addition intending to fill this gap, this work also presents the Rockwell hardness in the R scale, as well as scanning electron microscopy (SEM) micrographs showing how the interaction of the loofah fibers with the polyester resin matrix occurred.

2. Materials and Methods

2.1. Collection and Preparation of the Raw Material

Loofah fibers employed as reinforcement were obtained from fruits collected in urban and rural areas located in the State of Rio Grande do Norte, Brazil. The commercial polyester resin (ortho-phthalic unsaturated crystals) used as a matrix was purchased from local stores in the city of Mossoró, Brazil. Methyl-ethyl ketone peroxide was used as the catalyst. Styrene monomer was adopted to decrease resin viscosity, and carnauba wax was used as a release agent for the composites (Figure 1).

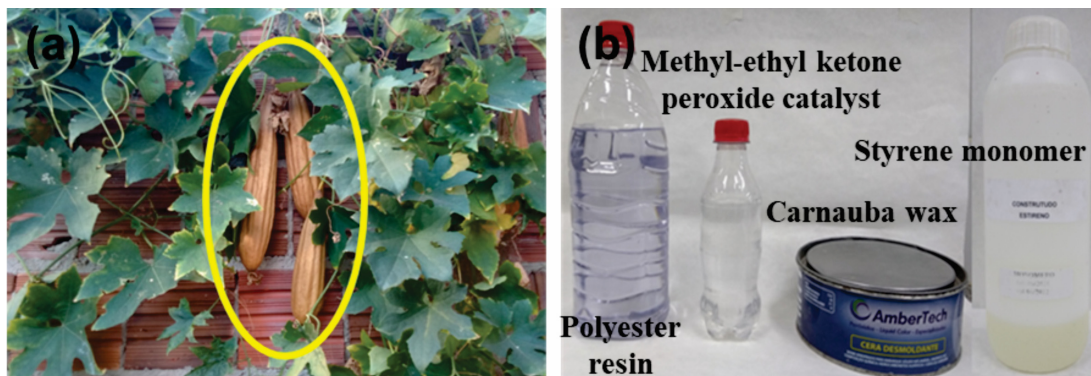


Figure 1. Materials used in the production of composites: (a) dry loofah fruits (source of fibers); (b) composite assembly components.

The loofah fruits were sorted out, peels and seeds were removed, and undamaged individuals were selected with a minimum length of 20 cm. Subsequently, the fruits were peeled, and mucilage and seeds were removed. The fruit fibrous bodies were longitudinally cut, washed in running water, dried in an oven with forced air circulation ($60 \pm 2^\circ\text{C}$ for 24 h), and pressed in a manual hydraulic press (0.2 MPa) to reduce the volume and to reach a laminated form. To manufacture the composites, two configurations for the fibrous bodies were assigned. The first one was cut in the longitudinal direction of the loofah (considered angle 0°) and the other was cut in the transverse direction (considered as angle 90° or perpendicular) (Figure 2).

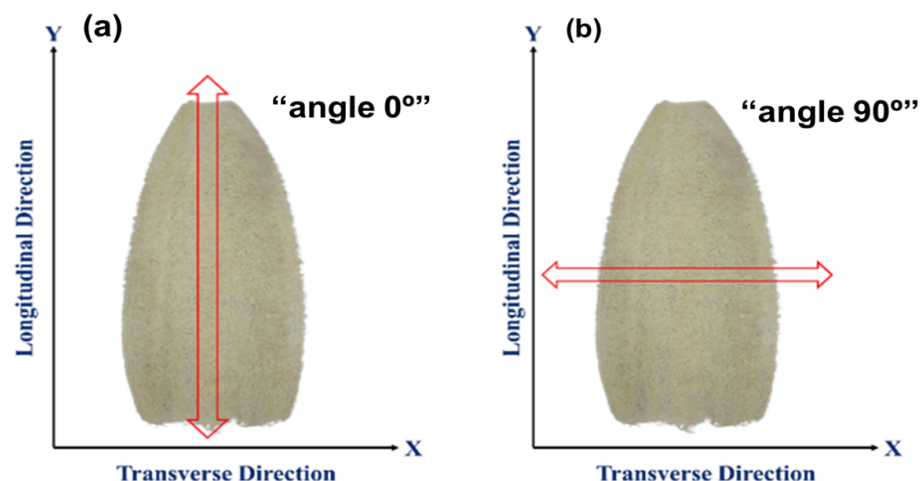


Figure 2. Directions of application assigned to the loofah fibrous bodies in the composites' structure: (a) longitudinal "angle 0° "; and (b) transversal "angle 90° ".

2.2. Production of Composites

The polyester resin was initially taken to a chamber connected to a vacuum pump with a negative pressure of approximately 600 mmHg for 30 min to remove bubbles (Figure 3). Subsequently, 1% (*w/w*) of styrene monomer was mixed with the polyester resin to reduce

viscosity and 1% (*w/w*) of methyl-ethyl-ketone peroxide catalyst. Mold preparation began with applying three alternating layers of carnauba wax to act as a release mold on the upper and lower surfaces of the lamination mold, one layer every 5 min. The mixtures of resin and loofah were placed alternately in the mold, previously impregnated with the release agent carnauba wax, with a layer of resin and another of vegetal loofah fiber, until reaching a total of 3 layers in the pre-established configurations (Figure 3d). The manufacturing process was carried out by cold pressing, in which the mold was closed and taken to the pressing stage (0.15 MPa) in a manual hydraulic press for 24 h for the resin to cure (Figure 3e). After curing, the composites were demolded to remove samples for physical and mechanical tests (Figure 3f).

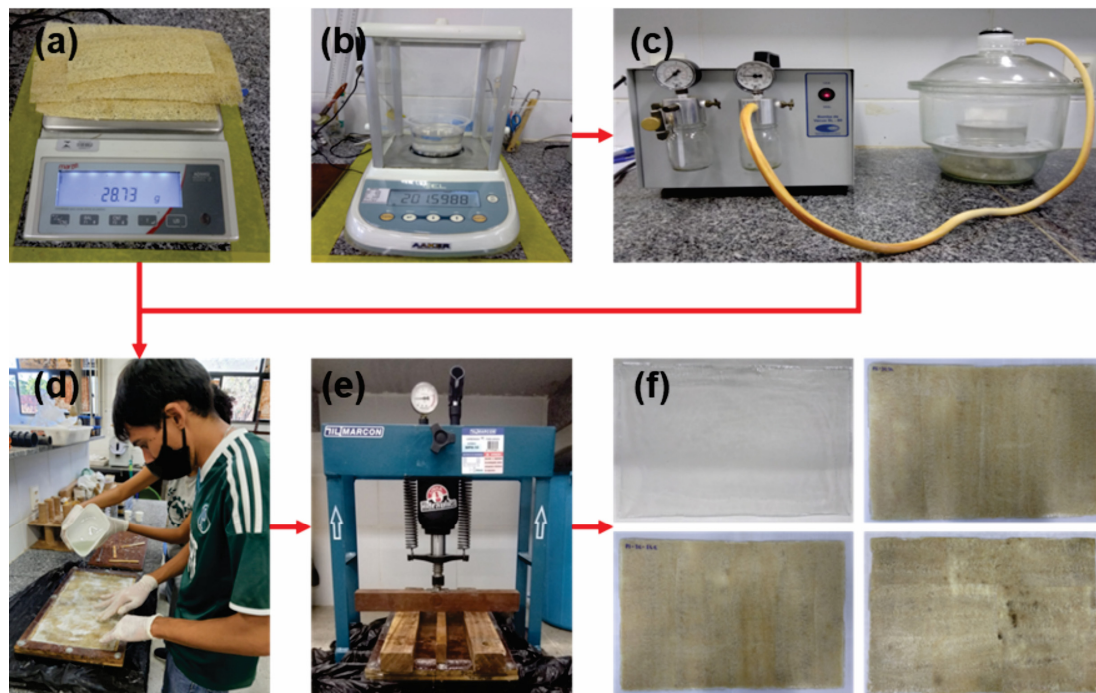


Figure 3. Production of the polyester–matrix composites reinforced with loofah fibers; (a) loofah fibers weighing; (b) polyester resin weighing; (c) vacuum removal of bubbles from polyester resin; (d) addition of polyester resin and loofah fibers in the mold; (e) pressing the composite; (f) demolding of composites.

Altogether, 12 composites were made in dimensions $260 \times 40 \times 4$ mm, with 3 boards for each experimental treatment. Pieces of loofah were arranged in 3 configurations: LF-1 treatment, without crossing ($90^\circ/90^\circ/90^\circ$); (c) LF-2 treatment, with crossing of layers in the format $90^\circ/0^\circ/90^\circ$; (d) LF-3 treatment, with crossing of layers in the format $0^\circ/90^\circ/0^\circ$. Also, a control treatment with three replicates was produced employing 100% polyester resin. The proportions of each composite layer were 20% of the loofah fibers reinforcement and 80% of the polyester–resin matrix (*w/w*) (Figure 4). For the cutting of the test specimens, a template was developed with the Autodesk Inventor software for markings on the composites and further cutting with a small craft drill (Figure 5).

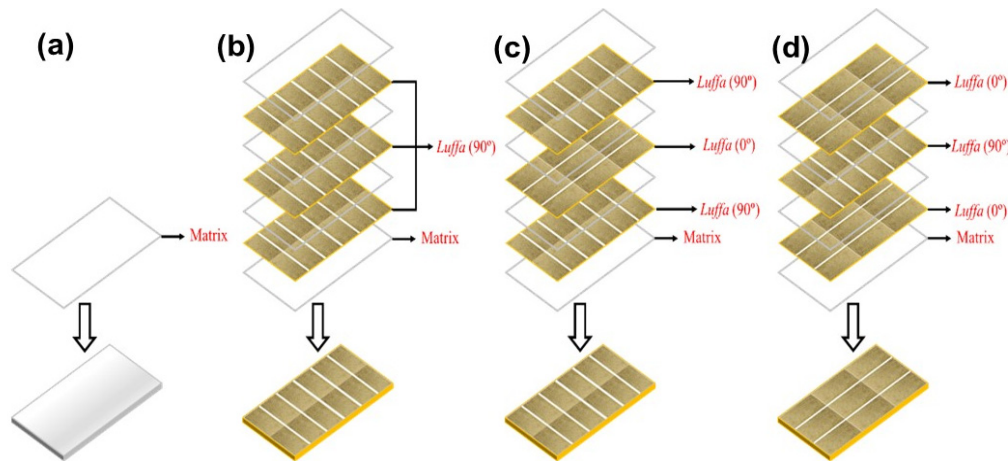


Figure 4. Angular configurations of the layers of the composites: (a) polyester resin (PR); (b) LF-1 treatment ($90^\circ/90^\circ/90^\circ$); (c) LF-2 treatment ($90^\circ/0^\circ/90^\circ$); (d) LF-3 treatment ($0^\circ/90^\circ/0^\circ$).

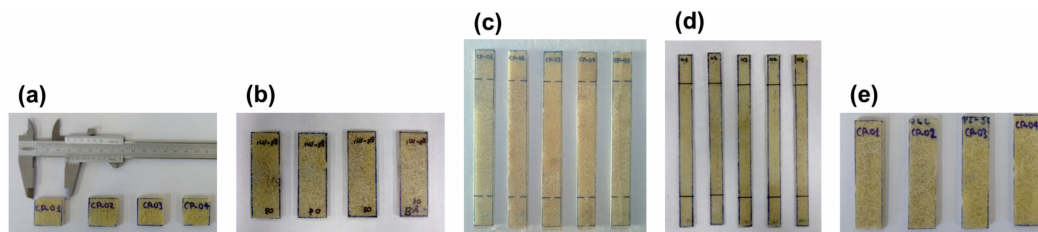


Figure 5. Samples used in physical–mechanical tests. (a) Density; (b) moisture content, water absorption, and thickness swelling; (c) tensile strength; (d) flexural strength at three points; (e) Rockwell hardness resistance.

2.3. Physical–Mechanical Characterization of the Composites

2.3.1. Apparent Density and Moisture Content

The assays to determine the apparent density followed the Brazilian Standard 14810-2 [18]. The samples were oven-dried under forced air circulation for 24 h at $50 \pm 2^\circ\text{C}$. Subsequently, each piece was weighed and measured in length, width, and thickness. Apparent density was calculated by dividing the mass by the volume of the composites. In total, 60 samples were assayed with fifteen test specimens for each treatment evaluated in the experiment.

The moisture content was determined to verify the behavior of the composites in environments with high humidity and thus observe if the material performs well for practical applications in such an environment. The tests were carried out following the standard NBR 14810-2 [18]. The samples were weighed to obtain the wet weight. Then, they were oven-dried for 24 h at $50 \pm 2^\circ\text{C}$. After drying, they had their dry weight determined, being tested 48 samples, 12 for each treatment.

2.3.2. Water Absorption and Thickness Swelling

The water absorption and swelling thickness tests were performed to assess the behavior of the composites when submerged in water, thus verifying if the material presents an acceptable performance to be used in practical situations in ambient conditions subjected to continuous wetting. Both tests followed the parameters established by the standard ASTM D570-22 [19]. Samples were oven-dried for 24 h at $50 \pm 2^\circ\text{C}$. Then, they were left for 30 min in a desiccator until they reached room temperature and weighed to obtain the dry mass. The samples had their thickness measured and submerged in distilled water at $30 \pm 2^\circ\text{C}$ for 2 h. So, the wet weight was determined, and the thickness was measured in the marked spots. The procedure was repeated every 24 h for 8 days. Data were collected, and the results for water absorption and swelling in thickness were obtained using the

equations provided by the standard used. A total of 48 samples were tested, 12 for each treatment evaluated in the research.

2.3.3. Tensile and Three-Point Bending Strengths Tests

The tensile strength assays were conducted in a DL-10000 universal testing machine (EMIC, São Paulo, SP, Brazil) equipped with a 100 kN load cell, following the parameters established in the ASTM D3039 [20] standard. The test speed was 2 mm/min, and the test was finished after the total fracture of each sample. The data provided by the machine were organized in software spreadsheets to calculate the maximum rupture tension and the modulus of elasticity. In total, 60 samples were tested, 15 for each treatment evaluated.

The tests to determine the three-point bending strength were carried out following the procedures established by ASTM D7264 [21]. The test specimens were individually placed in horizontal orientation at a distance of 130 mm between two supports of DP5.02 type designed to ensure accuracy in the space of supports. The speed adopted for the test was 6 mm/min, and the test was completed after the fracture of each specimen. The results of maximum rupture tension and the modulus of elasticity were obtained from the equations provided by the standard used. In total, 60 samples were tested, 15 for each treatment evaluated in the research.

2.3.4. Rockwell Hardness

Hardness is a measure of the resistance offered by a material subjected to penetration, indentation, kneading, and abrasion tests. Rockwell hardness on the R scale classifies the resistance of a given material according to the pattern, as the higher the value of the scale, the higher the hardness of the analyzed material [22]. The Rockwell hardness test was performed using a Mitutoyo digital tester (HR-300) with a 0.5 inch spherical steel indenter, following the test parameters described in the standard ASTM D785-08 [23]. Before starting the tests, the penetration sites were determined. They were marked at a distance of 8 mm from the center of the diameter to the edges and 12 mm from the center to the center of the diameter between the markings (Figure 6). The test specimens were placed horizontally in the equipment, and a preload of 10 kgf (lowest load) was applied, followed by a load of 60 kgf (highest load). The equipment provided the hardness result in HR on the R scale. In total, 8 points were assayed in each of the 12 tested samples.

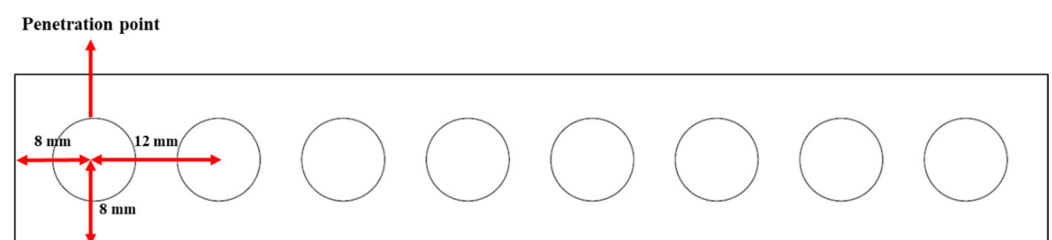


Figure 6. Mark established in the specimens to the Rockwell hardness test.

2.4. Scanning Electron Microscopy (SEM)

Samples were oven-dried for 24 h at 50 ± 2 °C. Then, they were fixed in a metallic sample holder and placed for 8 min in a Q150R ES metallizer (Quorum Technologies, Puslinch, ON, Canada), where a 9 nm thick layer of gold was applied in the fracture region. After metallization, the samples were inserted into a chamber inside the scanning electron microscope (Tescan Vega 3 LMU, Tescan, Brno, The Czech Republic), and the voltage was adjusted to 10.0 KV. After the tensile strength tests were conducted, the micrographs were captured in the composite samples' fracture region captured with a standard magnification of $2000\times$.

2.5. Experimental Design

The experiment was set up following a completely randomized design with four treatments and three replications for each panel manufactured. The number of samples

used in the tests followed the guidelines established by the technical standards for each type of test performed. The experimental data on physical and mechanical properties were organized in spreadsheets. The data were subjected to the Shapiro–Wilk normalization test and Levene’s homogeneity test, both of which were conducted with utmost thoroughness. This was followed by a comprehensive analysis of variance (ANOVA). When statistical differences were detected, the means were compared using the Tukey test at 95% probability, leaving no room for doubt in our conclusions.

3. Results and Discussion

3.1. Apparent Density and Moisture Content

The results obtained from the density test showed that the polyester–resin treatment without reinforcement (PR) presented the highest value for this property, 1.12 g cm^{-3} . The lowest value was 1.05 g cm^{-3} determined for the composite (LF-3 treatment), reinforced with loofah fibers in the configuration $0^\circ/90^\circ/0^\circ$ (Figure 7a). However, the treatment with the lowest value did not present statistically significant differences when compared with the composites (LF-1) and (LF-2), reinforced with *Luffa cylindrica* in the configurations $(90^\circ/90^\circ/90^\circ)$ and $(90^\circ/0^\circ/90^\circ)$, respectively. Given this, it appears that adding loofah fibers to the polyester–resin matrix decreased the apparent density of the composite material, making it lighter independent of the layer configurations. Manimaran et al. [24] observed that the density of natural fibers plays a crucial role in the composite material’s weight. Low-density fibers with improved tensile properties are preferred for applications in structures requiring lightweight composite materials.

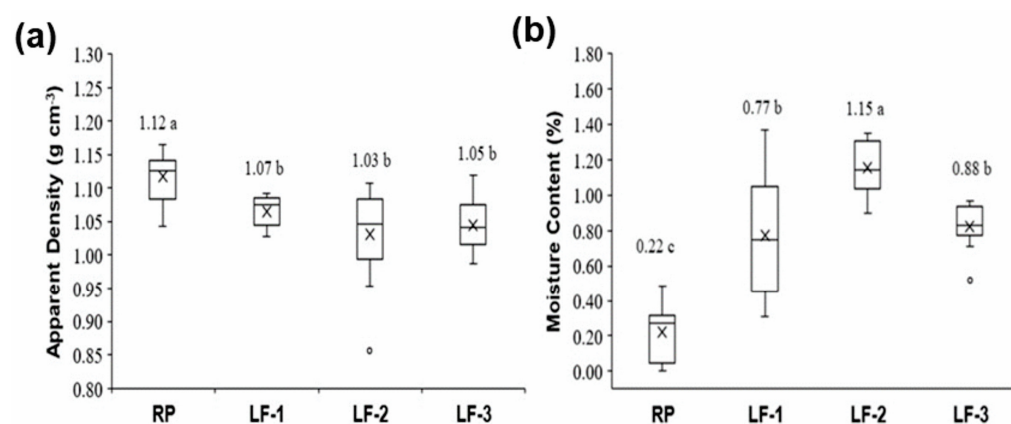


Figure 7. Apparent density (a) and moisture content (b) determined for the experimental treatments. Means followed by different letters were different according to the Tukey test at a 95% level of significance.

According to Akter et al. [25] and Feng et al. [26], vegetal fiber reinforcement promotes a series of advantages compared to synthetic fibers, such as lightness, biodegradability, renewability, moderate resistance, low production cost and more significant superiority in the life cycle. Still, composite materials reinforced with natural fibers can economically present an excellent cost–benefit for manufacturing panels for car bodies and interiors, industrial and civil construction panels, partition panels, and false ceilings (karthi et al. 2020). In the assay to determine the moisture content of the composites, the results showed that the treatment (PR) was the one that presented the lowest absorption value, 0.22%. The highest value was 1.15%, indicated by the composite LF-2 (Figure 7b). The results showed that the characteristic absorption of vegetal fibers significantly increased the moisture content value of treatments reinforced with loofah fibers compared to PR treatment. According to Bousfield et al. [27], plant fibers are hydrophilic materials, and their ability to retain moisture is a factor that directly influences adhesion with polymeric resins, leading to the formation of voids in the interface region between the fibers and the matrix.

3.2. Water Absorption and Thickness Swelling

The PR treatment presented the lowest absorption value and the shortest period to reach stability, 2.46% in 96 h. The composite LF-2 had the highest absorption, with a value of 14.87%, going stable in 96 h. The composites from the treatments LF-1 and LF-3 had intermediate absorption between the treatments with the lowest and highest absorption values, with no statistically significant differences between them (Figure 8a).

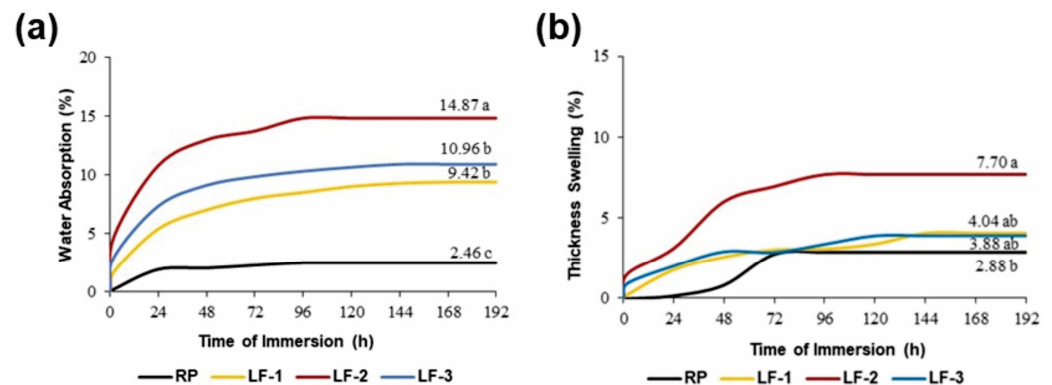


Figure 8. (a) Water absorption x time of immersion; and (b) thickness swelling x time of immersion. Maximum values followed by different letters are dissimilar according to the Tukey test at a 95% level of significance.

The LF-2 angular configuration likely provides the greatest exposed surface area of loofah fiber from the top and bottom layers available to absorb water. Therefore, the angular configuration “90°” of loofah showed a greater tendency for water absorption in relation to the angle “0°”. This fact can be confirmed by the values of moisture content (see Figure 6). As a general trend, the results showed that adding loofah fibers as reinforcement in the polyester–matrix composites increased water absorption. Yorseng et al. [28] explain that in the first days of immersion, the test specimens presented an increase in the water absorption rate, but as the days went by, this rate tended to decrease. Araújo et al. [29] found 2.68% for water absorption 24 h when analyzing composites formed by recycled low-density polyethylene as a matrix, reinforced with 40% of cocoa wastes, lower absorption value than those reinforced with loofah in this work. According to Dayo et al. [30], the ability for water absorption presented by composites reinforced with natural fibers is factors directly dependent on the hydrophilic potential of the fibers, immersion temperature, amount of natural fibers, fiber orientation, and the area exposed to immersion. The high tendency for water absorption shown by natural fibers can cause poor adherence in the fiber–matrix interface region and thus decrease the composite strength [31].

The results of the thickness swelling test are represented in Figure 8b. PR treatment had the lowest swelling value and the shortest time to reach stability, 2.88% in 96 h. The treatments LF-1, LF-2 and LF-3, with different loofah fibers configurations, did not show statistically significant differences (Figure 8b). Because of the analyzed results, the percentage of water absorption is a factor that directly influences the increase in the swelling rate in the thickness of composites reinforced with loofah. Despite considerable water absorption, the swelling was low. This fact may have occurred due to the intertwined structure of the loofah fibers, which prevents the accumulation of water. The lignocellulosic material has a waxy appearance on the surface cuticle, which reacts as a kind of water-repellent to much of the loofah. Another fact is the punctual “protection” of the fibers by the polyester resin that covers them.

As Posper et al. [32] commented, the hydrophilic characteristic of natural fibers contributes to moisture absorption from composites. Consequently, it influences the material’s physical, mechanical, and thermal properties [7]. According to Karimah et al. [31], dead cells, oils, waxes, hydroxyl groups, and other non-polar groups existing in natural fibers provide an incompatibility of natural fibers with polymeric materials, resulting in the

emergence of aggregates. Gholampour and Ozbakkaloglu [33] stated that chemical modification on natural fibers could improve the adhesion between the constituents of the matrix/natural reinforcement.

3.3. Tensile Strength

Treatment PR presented the highest value for the maximum tensile stress, 28.5 MPa. Adding the loofah fibers to the composites to the polyester resin matrix significantly decreased the mechanical tensile strength of the composites. It was also observed that the configuration of the loofah fibers did not influence the strength of the composites, since the results did not differ statistically among the configurations LF-1, LF-2 and LF-3 (Table 1), which have the same value, 10.8 MPa, for tensile of rupture. Loofah fibers also promoted a significant reduction in the deformation of the composites during the test (Figure 9).

Table 1. Results of the tensile strength test.

Treatments	Tensile of Rupture (MPa)	Maximum Deformation (mm/mm)	Modulus of Elasticity (MPa)
PR control	28.5 ± 4.9 a	0.031 ± 0.004 a	911.1 ± 99.1 a
LF-1	10.8 ± 1.6 b	0.017 ± 0.002 c	657.6 ± 107.8 b
LF-2	10.8 ± 1.4 b	0.021 ± 0.004 b	535.5 ± 124.2 b
LF-3	10.8 ± 1.4 b	0.017 ± 0.003 c	656.2 ± 93.6 b

In columns, means followed by different letters are dissimilar according to the Tukey test at a 95% level of significance.

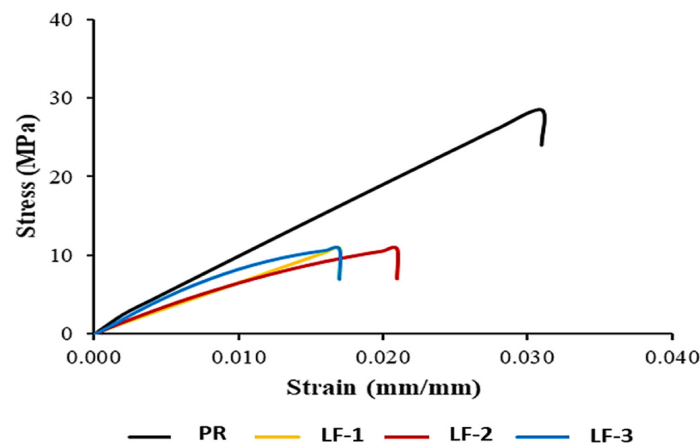


Figure 9. Maximum rupture tension x strain determined from the tensile strength test.

The lower deformation obtained for the composites with loofah may have occurred due to the empty spaces present between the fibers of the lignocellulosic material, which may have acted as “fragile zones” in the composite, facilitating rupture. The low tensile strength observed for the loofah fibers composites may be attributed to the poor adhesion between the vegetal fibers and the polyester resin. Murali et al. [34] studied epoxy matrix composite reinforced with fibers from the *Baehmeria nivea* and found a tensile strength of 6.80 MPa. Tensile strength of 1.41 MPa was obtained by Sair et al. [35] for polyurethane matrix composites reinforced with 15% by weight of hemp fibers. Loan et al. [36] cited an improvement from 15 to 40% (na increase from 7.3 to 8.5–9.51 MPa) for tensile strength in composites produced with LDPE matrix, reinforced with 30% of maize stem, using maleic anhydride as a coupling agent.

As for the tensile of rupture stress, the highest modulus of elasticity was found for the PR treatment, with a value of 911.1 MPa. The result for the LF-1 did not differ statistically from the composites from LF-2 and LF-3. As a result, the orientation of the layers in the same or different directions had no effect on the stiffness of the composite. Adding loofah fibers to the polyester–resin matrix decreased the stiffness of the composite materials subjected to tensile stress. These stiffness values were still higher than the 292.6 MPa

obtained by Ramesh et al. [37] for epoxy matrix composites reinforced with natural fibers extracted from the *Calotropis gigantea*, 256.6 MPa for epoxy matrix composites reinforced with 30% of carrot fibers [38].

From the images obtained by scanning electron microscopy (SEM) of the fractured regions (Figure 10), the main factors influencing the resistance of the four treatments submitted to the tensile tests could be assessed. Figure 10a refers to the PR treatment showing specific regions where plastic deformations and empty channels resulted from the material manufacture.

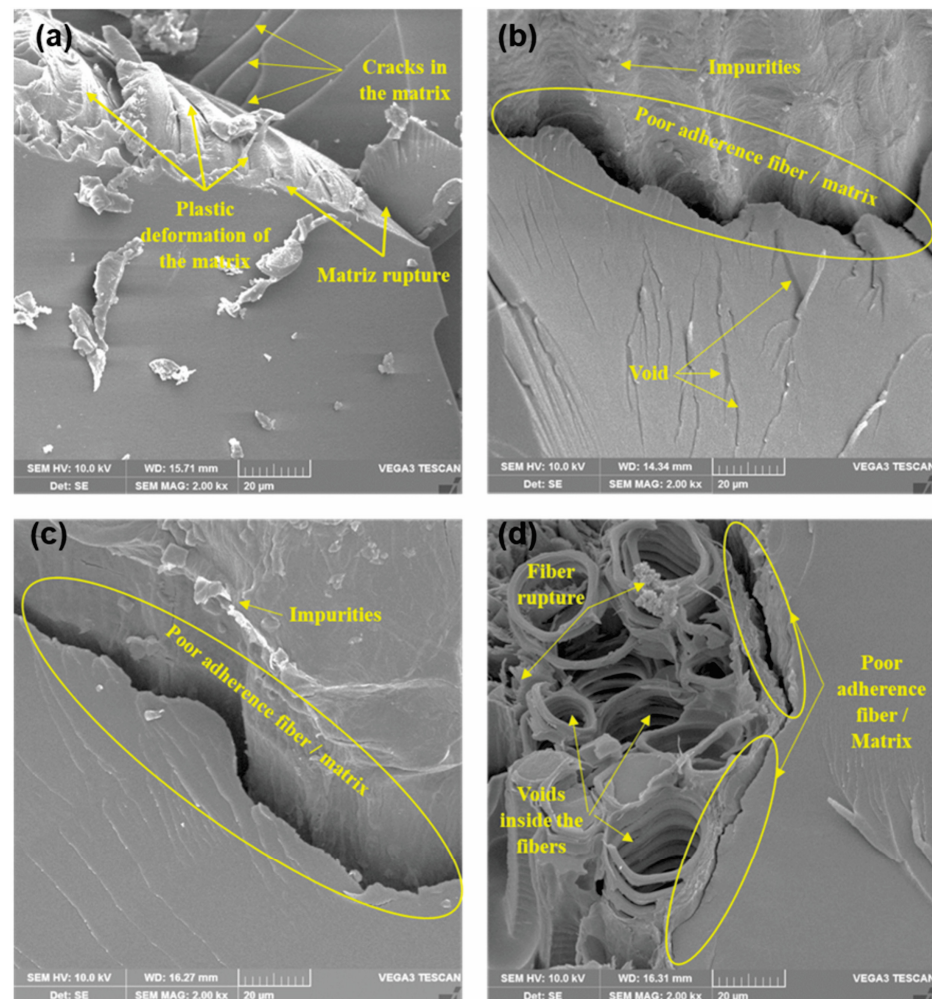


Figure 10. Fracture regions of the specimens; (a) PR; (b) LF 1; (c) LF-2; and (d) LF-3 (magnification 2000×).

The images of the fractures of the LF-1, LF-2, and LF-3 composites are similar regarding the presence of regions with low adherence between the loofah fibers and the polyester matrix (Figure 10b–d). The images also allow the identification of impurities in the LF-1 and LF-2 composites, regions of plastic deformation in the matrix, and void channels in the LF 1 composites (Figure 10b,c). Also, plastic deformations in the LF-3 composites were identified (Figure 10d). These factors directly influence and mechanical properties of the natural composites developed. Analyzing the surface morphology of epoxy polymeric composites reinforced with *Calotropis gigantea* fibers, Ramesh et al. [37] also found empty spaces and regions of poor adhesion caused by impurities. According to Dayo et al. [30] and Madhu et al. [39], the surfaces of the fibers present a quantity of waxes, oils, and contaminants, they can hinder the interaction between the fibers and the resin.

3.4. The Three-Point Bending Strength Test

In the three-point bending strength test, PR treatment had the best performance with 38.6 MPa. The results for stress of rupture did not differ statistically with the addition of loofah, independent of the configuration LF-1, LF-2, or LF-3. Compared with the PR treatment, the results demonstrated that the samples were broken at lower stresses when adding loofah fibers in the composites during bending (Figure 11; Table 2). According to Paula et al. [7], materials formed by an interwoven fibrous structure such as loofah can cause some voids and imperfections when they need to compose the layer of a composite. In addition, these defects could have emerged during manufacturing because the empty spaces may not be adequately filled by the resin, forming bubbles, which could generate weak points in the structure. Although the polymeric composites reinforced with loofah fibers in this work presented a lower stress of rupture than the polyester resin matrix when subjected to three-point bending stress, the final value for this parameter was higher than the 3.83 MPa obtained by Sair et al. [35] for polyurethane-matrix composites reinforced with 20% by weight of hemp fibers, and 7.50 MPa obtained by Gobikannan et al. [40] for PVA matrix composites reinforced with 30% wood particles, 25% paper, and 35% sisal fibers.

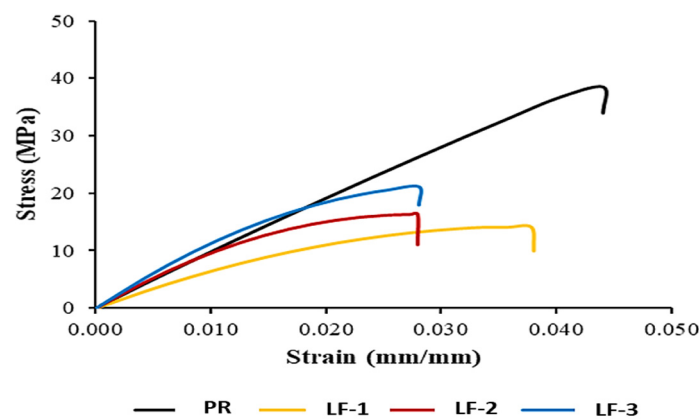


Figure 11. Maximum rupture tension x strain determined from the three-point bending test.

Table 2. Stress of rupture, maximum deformation and the modulus of elasticity obtained from the three-point bending strength tests.

Treatments	Stress of Rupture (MPa)	Maximum Deformation (mm/mm)	Modulus of Elasticity (MPa)
RP control	38.6 ± 19.0 a	0.042 ± 0.007 a	928.7 ± 402.1 a
LF-1	14.1 ± 4.3 b	0.037 ± 0.009 a	410.8 ± 136.3 b
LF-2	16.2 ± 5.0 b	0.028 ± 0.007 b	667.1 ± 207.8 ab
LF-3	21.2 ± 4.4 b	0.028 ± 0.005 b	774.8 ± 163.0 a

In columns, means followed by different letters are dissimilar according to the Tukey test at a 95% level of significance.

The maximum deformation was statistically equal for PR and LF-1 treatments, in which there was no crossing of loofah directions. When the structures of the fibrous layer are arranged in the same direction, there is a greater tendency for the fibers to move together similarly when they are stressed by external forces, tending to greater deformation.

The modulus of elasticity calculated from the bending strength test points out that there was statistical equality comparing the PR control with the angulations LF-2 and LF-3. The different directions of layers of these treatments may have contributed to greater structural rigidity. When layers are crossed, there is a greater tendency for voids in one layer to be filled in by the fibers of the adjacent loofah layer, as well as the correction of imperfections. The configuration LF-1, in which there was no crossing, the accommodation of the fibrous structure may have occurred less efficiently during pressing, not providing the intended stiffness for this treatment. The low adhesion between the loofah fibers and

the polyester matrix (region of the interface) may be another cause. This fact may have occurred as a result of the degradation of the matrix–reinforcement interface [25,41].

Establishing a general comparison, composites with alternating angulations obtained better stiffness properties when compared to the non-alternating configuration. Factors such as processing techniques, manufacturing design configuration, percentage of fiber loading, and size and shape of the reinforcement material directly influence the mechanical properties of manufactured biocomposites [6]. Araújo et al. [29] found 172.3 MPa for the modulus of elasticity when analyzing composites formed by recycled low-density polyethylene as a matrix, reinforced with 40% of cocoa wastes, a lower strength value than those reinforced with loofah in this work. Notwithstanding, the mean values shown here are higher than 51 MPa and 306 MPa obtained by Oliveira Filho et al. [42] for orthophthalic polyester polymeric composites reinforced with uniaxial piassava fibers and hybrid reinforcement with piassava and e-glass fibers, respectively.

3.5. Rockwell Hardness

The reinforcement with layers of loofah fibers applied to the polyester resin matrix reduced the Rockwell hardness. No significant differences were found between the measured hardness of the configurations LF-1 and LF-2. Among the composites reinforced with the loofah, the lowest value was 66.5 HRR for the angulation LF-3. The PR treatment had the highest hardness, with 117.8 HRR (Figure 12).

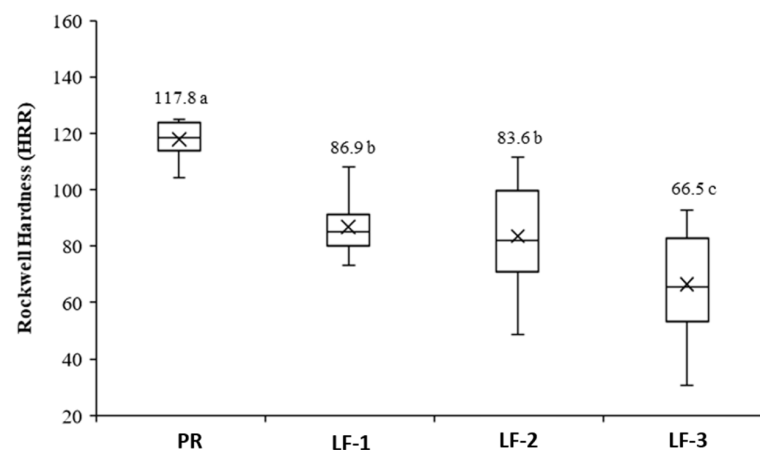


Figure 12. Results of Rockwell hardness tests. Values followed by different letters were different according to the Tukey test at a 95% level of significance.

When the force is applied to a pure resinous surface, it implies a predominantly homogeneous region free of imperfections such as flaws and voids. The presence of the loofah layers provides a lighter, softer and less rigid structure against point load application. From the analysis of the results, the configurations of the loofah fibers influenced the resistance to the hardness of the composites because the LF-1 and LF-2 treatments with the direction of the fibers at “angle 90°” on the external parts pointed to better results than the LF-3, with the fiber configuration at “angle 0°”. It is evident that in hardness tests on composites structured in layers, the external part is the most required in terms of strength, followed by the intermediate layers and, lastly, the lower ones. Furthermore, the middle layer serves as a support for the first layer. In the case of LF-1 and LF-2, the intermediate layers provided the same level of support for the top layer, regardless of cross-format or same-direction configuration. According to Sanjay et al. [43], the properties of polymeric composites reinforced with natural fibers depend on factors such as the type of polymeric matrix, the origin of the vegetal fiber, the kind of reinforcement, the orientation of the fibers, the manufacturing process, and size of the crystalline fibers, the functional groups of the fibers, the volume and weight fraction of the vegetal fibers, and surface treatments. Even though the composites reinforced with loofah fibers presented a hardness lower than the polyester matrix without reinforcement, results for the LF-1 and LF-2 treatments had

values higher than 68.0 and 74.0 HRR obtained by Mansingh et al. [44] for polyester matrix composites reinforced with 10 and 30% of fibers from coconut palm peduncle, and 71.0 and 82.0 HRR indicated by polyester composites reinforced with 10 and 30% of glass fibers. Therefore, polyester composites reinforced with loofah fibers may have Rockwell hardness higher than natural and synthetic composites.

Including these fibers as a raw material could result in resistant and less fragile materials with lower production costs. Then, the use of loofah as reinforcement in composites can be reduced. It may have the potential to reduce the amount of resin used and, consequently, lower the costs of these materials, in addition to making them more eco-friendly [11,13,45,46].

4. Conclusions

In this research, different configurations of layers of loofah fibers were tested for the improvement of the mechanical properties of the polymeric composites. The employment of loofah fibers as a reinforcement in a polyester polymeric composite decreased the apparent density in all assessed configurations. The configuration LF-2 ($90^\circ/0^\circ/90^\circ$) obtained the highest water absorption (14.87%) among the composites evaluated. Thickness swelling was greater for the composites with the addition of loofah, independent of the angulation. Regarding the mechanical properties, composites with loofah layers in the analyzed configurations lost stiffness, according to the tensile strength test. LF-2 and LF-3 cross-configurations were statistically equal to the control when evaluating the modulus of elasticity during the bending test (667.1 and 774.8 MPa, respectively). The configuration of the top layer “angle 90° ” stands out for Rockwell hardness. Although the addition of loofah fibers with different configurations should perform better in some physical–mechanical tests compared to the polyester resin without reinforcement, the resulting composite was lighter. This lightness might result in a low cost, followed by other advantages such as sustainability and biodegradability, contributing to reducing the use of materials derived from synthetic fibers. The crossing of layers makes the material viable for non-structural applications and use in indoor environments with values within the acceptable range of its physical and mechanical properties. Polymeric composites manufactured with plant bushing can be an interesting alternative for the manufacture of insulation panels, roof linings, handicrafts, internal components of motor vehicles, etc.

The use of loofah fibers as reinforcement in polymeric composites still requires further research to reduce the fibers’ hygroscopic properties, increase adhesion to the matrix fiber, improve mechanical strength properties, and characterize the thermal and acoustic properties of the composites, or even their dimensional stability. Surface chemical treatments on natural fibers increased tensile strength, as chemical products contribute to the elimination of pores, voids, and cracks on the surface of the fibers.

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