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Hybrid composites with glass fiber and natural fibers of sisal, coir, and luffa sponge

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Abstract

Hybrid composites with synthetic and natural fibers are a good choice in the field of composites, as they combine the good mechanical performance of synthetic fibers with the advantages of natural fibers. In this work, polymeric hybrid composites associating glass fiber and natural fibers were developed. Three hybrid composites were developed: sisal/glass, coir/glass and Luffa/glass. The composites are five-layer laminate, three layers of E-glass interspersed with two layers of natural fibers that can be sisal, coir, or Luffa sponge (Luffa Cylindrica). In addition to hybrid composites, a five-layer fiberglass composite was also manufactured. The composites were manufactured by compression molding technique using orthophthalic polyester resin as matrix. Tensile and flexural tests were performed to characterize the composites. Considering the three hybrid composites, the best behavior was observed for the sisal/glass composite, being a potential replacement for fiberglass. The order of performance was the same in the tensile and flexural tests, sisal/glass, coir/glass, and luffa/glass, in this order. In the specimen's fracture analysis, for both tests, it was observed that the fracture was quite located with no damage in regions far from the fracture. This behavior indicates good adhesion between the layers of natural and synthetic fibers, despite the discrepancy of their properties.

Keywords

Hybrid composite, coir fiber, sisal fiber, Luffa Cylindrica, glass fiber

Introduction

As the world concern about environment preservation grows, the interest in the utilization of recycled and/or renewable raw material grows concurrently, with special highlight to natural fibers. The first patents on natural fiber composites date from the 60's. In the 60's and 80's synthetic fibers replaced natural fibers due to their better performance and economic aspects. From the 1990s, concern about environmental issues has raised interest in these composites. Studies using natural fibers reinforcing polymeric composites have received considerable investments in research and development in the last decades. It is worth emphasizing that the use of materials derived from biomass has been a differential for industries in different sectors.

Natural fibers composites can be used in many industrial sectors, such as civil construction, furniture, and automotive industry. Their advantages include low cost, low density, high availability, biodegradability, etc. Poor mechanical properties, compared to synthetic fibers, and high moisture absorption due to its hydrophilic nature, are limiting parameters in the application of these fibers.[1–3] Chemical modification of the fiber surfaces can reduce the water absorption and improve the mechanical properties.[4] Another option to improve the mechanical properties is to make hybrid composites by adding small amounts of synthetic fiber, such as

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glass fiber. Besides improving the mechanical properties, the glass fiber can act as a chemical barrier reducing the water absorption of the composite.[5–7] The literature regarding hybrid composites with synthetic and natural fibers highlights the cost reduction of the composite (due to low cost of the natural fiber), improvement of the mechanical properties, decrease of moisture absorption, and increase of the environmental aging resistance compared to the natural fiber composites.[5–10]

In this work sisal fibers, coir fibers, and luffa sponge were used, in association with the glass fiber, to make a hybrid laminated composite. The reason for choosing glass fiber is the fact that it is widely adopted in general use composites and presents a good cost-benefit ratio. The fibers of sisal, coir, and luffa were chosen due to their particular characteristics, such as mechanical properties, biodegradability, and availability, besides the social aspects.

The sisal fiber stands out from the other natural fibers for presenting high mechanical properties, being already used in many polymeric composites, as can be seen in the review work of Senthilkumaret et al.[11] Sisal is the main Brazilian semi-arid agro-industrial product. FAO data indicate that Brazil is the largest producer and exporter of sisal fiber.[12] Many families in the northeastern region of the Brazil depend on the production of sisal.

The Luffa cylindrica, also known as loofah or luffa sponge, is largely found in Central and South America. Its fruit, from the same family of the cucumbers, has a vascular system that forms a natural tridimensional mat when dried. This is an advantage since it provides higher toughness to composites.[13] In the literature there are studies on luffa sponge polymer composites,[13–18] but very few mention their use in hybrid composites.[19]

Regarding the coir fiber, the environmental concern and the high availability in Brazil were fundamental for the choice. Brazil is the fourth largest producer of coconuts in the world, behind Indonesia, Philippines and India.[12] However, Brazil is distinguished from the competitors by producing green coconut, from which is extracted the coconut water, being the first world producer of the beverage.[12] This large consumption generates a voluminous organic waste, represented by husks. This waste is usually buried in landfills, causing environmental issues, such as the proliferation of species that may act as vectors for diseases. From the coconut shell are extracted the fibers that have several applications: carpets, sacks, padded for the automobile industry, brushes, mats, ropes, cork and composite materials.[20] The difference in properties between the sisal fibers, coir fibers, and luffa sponge is remarkable.[4,11,13–15,21–23] The sisal fiber presents higher properties than the coir and the luffa sponge fibers.

Three hybrid laminated composites were developed in this work, sisal/glass, coir/glass and Luffa/glass. The polymeric matrix was orthophthalic polyester resin. The tensile and flexural mechanical properties were determined. In addition, microstructural and fracture behavior analyses were also performed. Finding new application possibilities for natural fibers is the focus of this work. The purpose is to develop a hybrid laminate that can compete with applications currently exclusive to fiberglass composites, with the advantage of using materials derived from biomass.

Material and methods

Materials

A commercially available unsaturated orthoftalic polyester resin with 1 wt.% of metil-ethil-ketone as initiator, was used as matrix for the composites; no accelerator was applied for the cure. Natural fibers were obtained from local commerce in northeastern Brazil.

The sisal fibers were received clean, without residues, and measuring around 1 m of length. They were cut at approximately 0.017 m and randomly distributed on a metal plate. A second plate was placed on the first one in order to press the fibers, forming a layer with 0.29 m x 0.17 m, and weighing 0.487 kg/m^2.

The coir fibers were received clean and measuring approximately 0.3 m; they were cut and pressed the same way as the sisal fibers. Sisal and coir fibers are shown in Figure 1, as well as the layers formed, both weighing 0.487 kg/m^2.

Luffa sponge is naturally mat-shaped. The preparation consisted in opening (by cutting) the sponge half depth, removing the seeds, and cutting it with the same dimensions of the other layers. The average weight of luffa sponge layer was 0.500 kg/m^2. Figure 2 shows a luffa sponge as received (whole) and after cut.

The E-glass fiber layer (chopped strand mat with 0.450 kg/m^2) was cut with the same dimensions of the other layers to fit the mold size. It is important to mention that the natural fiber layers (sisal, coir, and luffa) weight approximately the same as the glass fiber one.

Table 1 presents comparative data, available in the literature, of the characteristics and mechanical properties of the natural fibers (sisal, coir, and luffa) and E-glass fiber.

Composites manufacturing

The hybrid composite consists of a five-layer laminate composed of three layers of E-glass fibers interspersed

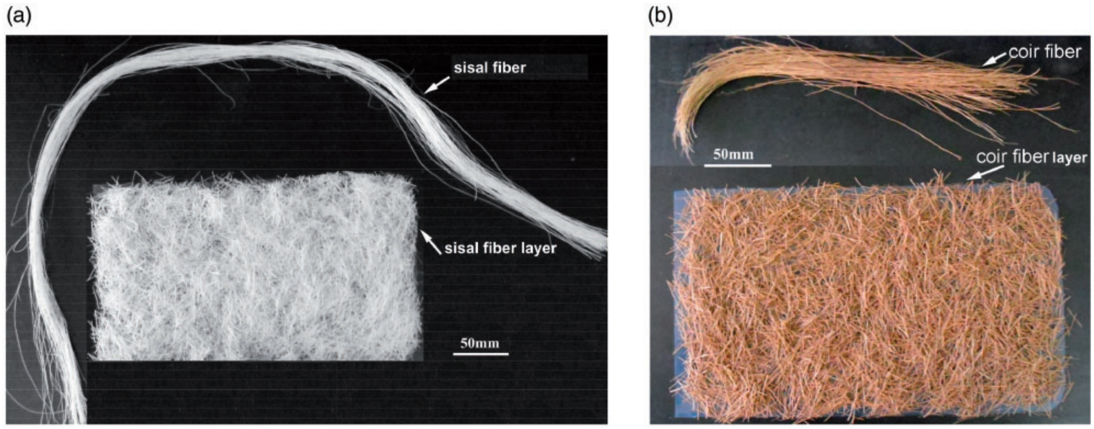

Figure 1. Sisal and coir fibers as received and the layers formed: a) Sisal fibers; b) Coir fibers.

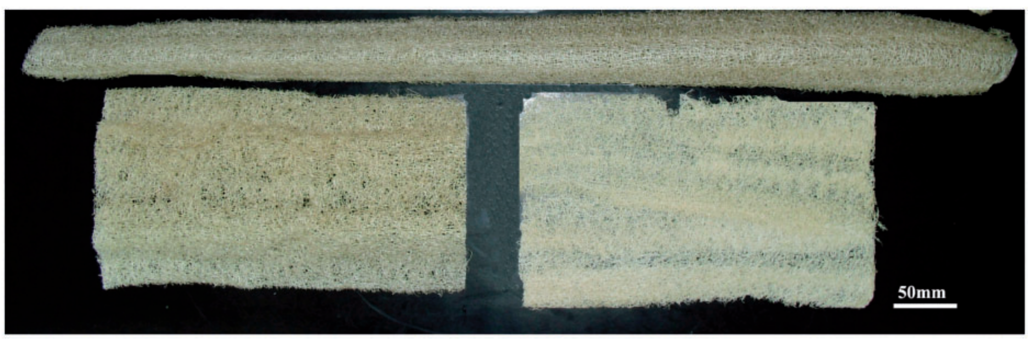

Figure 2. Luffa sponge as received (whole) and after cut.

Table 1. Characteristics and mechanical properties of fibers of sisal, coir, Luffa and E-glass.[4,11,13–15,21–23]

Fiber	Diameter (μm)	Density (kg/m^3)	Tensile strength (MPa)	Elasticity modulus (GPa)
E-glass	8–14	2500	2000–3500	70
Sisal	50–300	1400–1550	400–700	9.4–22
Coir	100–450	1150–1450	131–175	4–13
Luffa[1]	270	350–920	385 (±10.5)	12 (±1)

[1]The data of the luffa sponge are quite scarce and varies greatly from one reference to another.[13,22,23]

with two layers of natural fibers that can be sisal, coir, or luffa sponge. The layers distribution is shown in Figure 3.

Three hybrid composites were manufactured, sisal/glass, coir/glass, and luffa/glass. A non-hybrid composite with five layers of E-glass fibers was also manufactured using the same technique. This composite was used as a comparative parameter.

The manufacturing process was compression molding. The beginning of the process consisted in applying the mold release (carnauba wax) in the metal mold. In sequence, layers of fibers impregned with resin were alternately laid down in the metal mold (0.29 m × 0.17 m). In the end of the process, the laminate was covered with a plastic sheet and the excess of resin and entrapped air were removed by pressing a roller on it. The mold was locked with screws and after 24 h the composite was unmolded. The curing process occurred at room temperature, around 25 °C. As a result, 0.0033 m-thick plates were obtained. Some steps of the manufacturing process are presented in Figure 4.

Analyses and tests

The specimens for all the tests were machined from the molded plates. The specimens' laterals for the mechanical tests (tensile and flexural), were sanded with

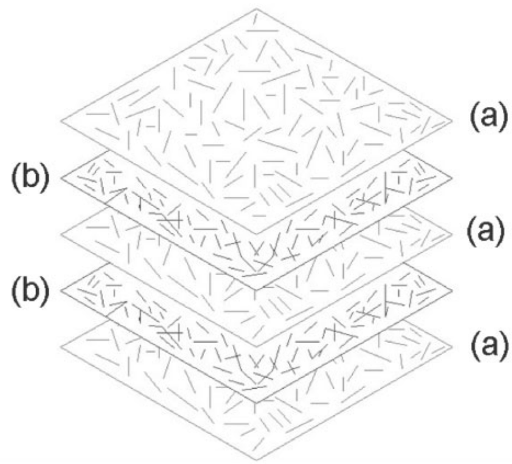

Figure 3. The layers' distribution in the hybrid composites: (a) E-glass fiber layers; (b) natural fiber layers.

sandpaper of decreasing granulation (120-240-320-400-600 grit) and, in the sequence, polished with alumina of 1.0 e 0.3 micron. This procedure eliminates damages from the machining process, avoiding any interference in the results, and allowing the specimens to be further analyzed by optical microscopy. The microscopic analysis comprises the composites' microstructure and fracture characteristics of the specimens. The analyses were performed using a stereoscope and an optical confocal microscope Leica DCM 3 D. A digital camera was also used for macroscopic photos.

Tensile test was carried out at room temperature (25 °C) according to ASTM D3039.[24] A minimum of eight specimens were tested in a universal testing machine EMIC DL10000.

Flexural (3-point bend) test was carried out at room temperature (25 °C) according to ASTM D790.[25] A minimum of eight specimens were tested in a universal testing machine EMIC DL10000. The Stress (σ) and Strain (ε) in flexural test were calculated according the equations 1 and 2 (ASTM D790[25]) respectively.

$$\sigma = \frac{3PL}{2bd^2} \tag{1}$$

$$\varepsilon = \frac{6Dd}{L^2} \tag{2}$$

where:

σ – Stress in the outer fibers at midpoint (MPa)
P – Load (N)
L – Support span (mm)
b – width of the specimen (mm)
d – thickness of the specimen (mm)
ε – strain in the outer surface, mm/mm
D – maximum deflection of the center of the specimen (mm).

The composites' density was determined according to ASTM D792.[26] The fiber glass content was determined in a calcination test according to ASTM D3171.[27] Samples measuring $0.025 \times 0.025 \times 0.0035\,m^3$ were utilized for both tests, density and calcination. In the calcination test, both resin and natural fibers were burned and only the glass fibers remained. Therefore, it is not possible to determine the content of the natural fibers and resin by this test.

Results and discussion

Density and constituents' content

The density and content of composites constituents are presented in Table 2. As expected, the density of the hybrid composites was lower than that of the fiberglass composite due to the lower density of the natural fibers (see Table 1). Luffa/glass hybrid composite had the lowest density followed by coir/glass and sisal/glass composites. This result agrees with the fiber density values presented in Table 1.

The glass fiber volume of the fiberglass composite (30.01%), agrees with the technique used. In manual lamination processes the glass fiber content is usually a maximum of 40% and the void content can be up to 15%, depending on the skill of the operator.[28] Surprisingly, in this work, the voids content was low (1.52%), probably due to the compression step after the lamination. The glass fiber volume of the hybrid composites was approximately half of the non-hybrid composite. The volume fraction of natural fibers, resin and voids were determined based on the theoretical density of the natural fibers once it is not possible to do it through the calcination test. Although these values do not represent the actual values of the composites, it is possible to take some conclusions. The resin volume of all composites is practically the same, however the void content is higher in the hybrid composites. The hybrid luffa/glass has the highest volume of natural fiber due to the lower density of the luffa fiber. The following density values were adopted in the calculation: glass fiber ($2500\,kg/m^3$), sisal fiber ($1500\,kg/m^3$), coconut fiber ($1200\,kg/m^3$), luffa fiber ($920\,kg/m^3$).[4,11,13–15,21–23] The mass fraction of the constituents, also shown in Table 2, was determined by weighing the materials before and after the composites manufacture.

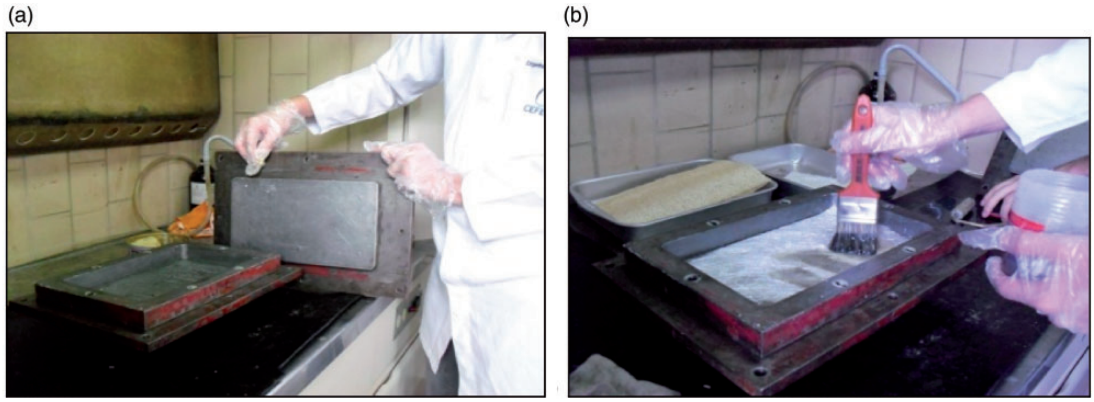

Figure 4. Some steps of the manufacturing process: (a) mold cavity; (b) lamination.

Table 2. Density and content of composites constituents (volume and mass fractions). Values with * were calculated based on the theorical density of the natural fibers in the literature.[4,11,13-15,21-23]

Composites	Fiberglass	Hybrid sisal/glass	Hybrid coir/glass	Hybrid Luffa/glass
Density (kg/m^3)	1580 ± 0.01	1400 ± 0.02	1300 ± 0.01	1123 ± 0.01
Volume fraction of glass fiber (%)	30.01 ± 0.26	16.82 ± 0.15	14.92 ± 0.13	14.30 ± 0.08
Volume fraction of resin (%)	68.47 ± 0.60	66.08 ± 2.29*	67.76 ± 0.46*	66.10 ± 0.84*
Volume fraction of natural fiber (%)		11.20 ± 0.93*	11.32 ± 0.10*	14.36 ± 1.36*
Volume fraction of voids (%)	1.52 ± 0.01	5.9 ± 0.44*	6.0± 0.26*	5.24 ± 0.23*
Mass fraction of glass fiber (%)	48.84 ± 0.43	30.67 ± 0.27	29.37 ± 0.26	26.07 ± 0.09
Mass fraction of resin (%)	51.16 ± 0.3	55.53 ± 0.47	59.18 ± 0.62	64.43 ± 0.44
Mass fraction of natural fiber (%)	–	13.80 ± 0.38	11.45 ± 0.51	9.5 ± 0.38

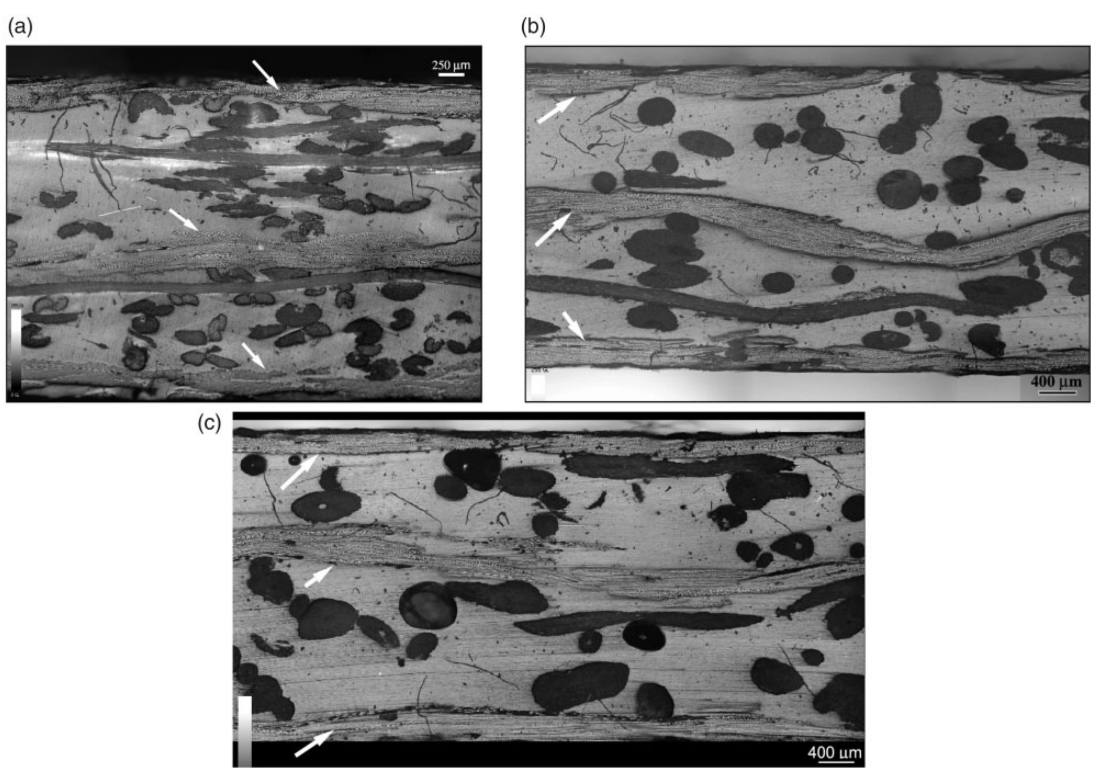

Figure 5. Microstructure of the hybrid composites. White arrows indicate the glass fiber layers. (a) hybrid sisal/glass, (b) hybrid coir/glass, (c) hybrid Luffa/glass.

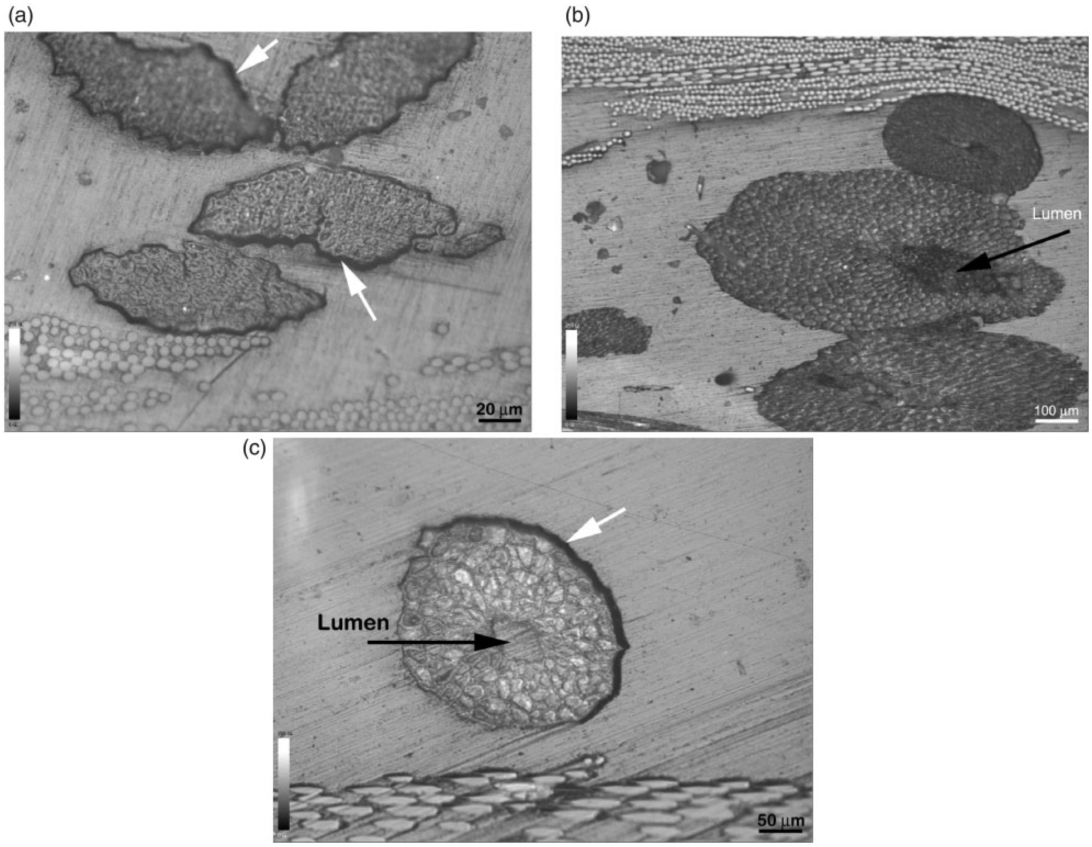

Figure 6. Details of the natural fiber's microstructure. White arrows indicate interfacial debonding. (a) hybrid sisal/glass, (b) hybrid coir/glass, (c) hybrid Luffa/glass.

Microstructure of the hybrid composites

Figure 5 shows the microstructure of the hybrid composites observed in the lateral section (thickness). White arrows indicate the glass fibers layers. The inner layers of natural fibers present irregular fibers distribution with predominance of the matrix phase. Misalignment of the glass fiber layers is also observed. Bubbles and voids are present in all composites mainly in the natural fiber's layers, in which the fibers impregnation is more difficult.

Details of the natural fiber's microstructure can be seen in Figure 6. All fibers have similar structure, i.e., small fibrils distributed around the hollow center called lumen (see Figure 6(b) and (c)).[4,23,29] Interfacial debonding was observed in some natural fibers (see Figure 6(a) and (c)), as a result of the weak fiber/matrix adhesion. It is noteworthy that these fibers were used without any special treatment to improve interfacial adhesion.

The significant difference in structure and diameter between the glass and the natural fibers is clear in the images. The natural fibers have irregular shape and can be separated into smaller fibers during the handling. On the other hand, the glass fibers have regular shape and much smaller diameter. The diameter ranges from 8 to 14 µm for glass fiber, and from 50 to 450 µm for natural fibers used in this work (see Table 1).

Tensile mechanical properties

Figure 7 shows Stress x Strain curves of the composites. Observing the curves, it can be said that partial replacement of fiberglass by natural fiber did not cause significant change in the behavior of curves, all show similar behavior. The behavior is typical of composites with thermoset matrices and synthetic fibers. In fact, the behavior is like that of the polyester resin matrix (which represents about 70% of the volume of the composite).

The tensile mechanical properties of the composites are presented in Table 3. Table 4 shows the retention percentage of the properties, considering the fiberglass composite as being 100%. The following properties were determined: Tensile strength, Young modulus and Maximum strain. It should be noted that the Young modulus was determined using the values up

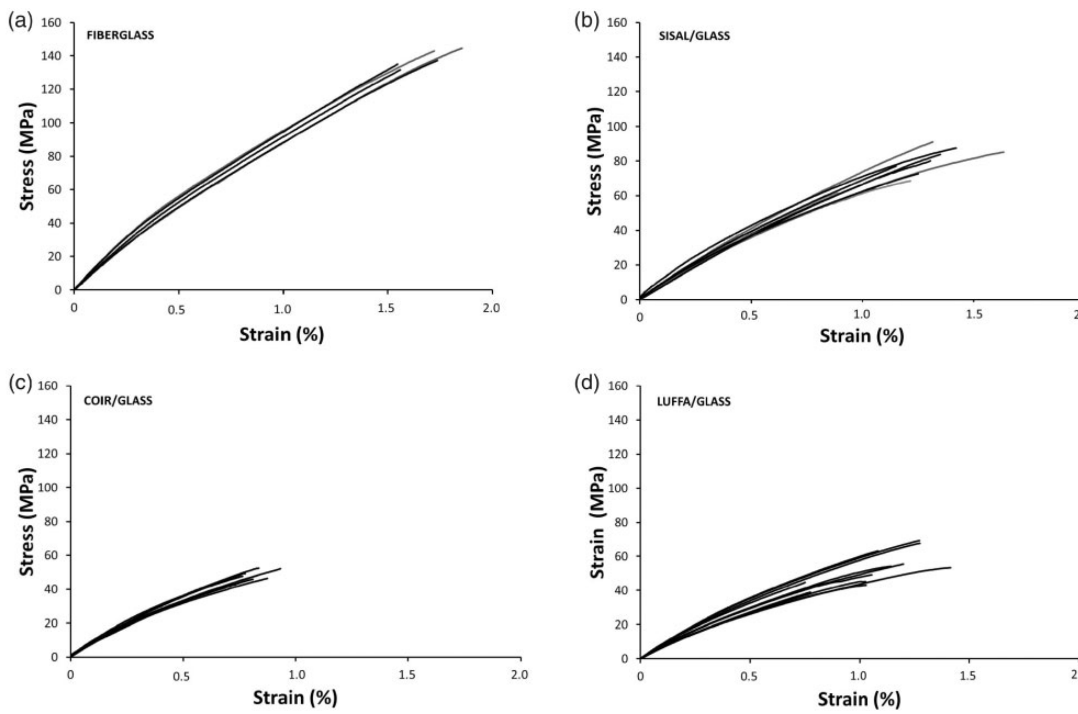

Figure 7. Stress × Strain curves from the tensile tests of the composites: (a) fiberglass, (b) sisal/glass, (c) coir/glass, (d) Luffa/glass.

Table 3. Tensile mechanical properties of the composites. The values between brackets represent the dispersions (the average of the distances between the result of each specimen and the average result). Specific tensile strength and specific Young modulus are based on the relative density of the composites.

Properties	Fiberglass	Hybrid sisal/glass	Hybrid coir/glass	Hybrid Luffa/glass
Tensile strength (MPa)	139.9 (±4.8)	80.2 (±7.5)	48.9 (±3.1)	47.7 (±4.6)
Young modulus (GPa)	9.8 (±0.67)	7.9 (±0.83)	7.5 (±0.52)	6.1 (±0.83)
Maximum strain (%)	1.8 (±0.17)	1.3 (±0.39)	0.8 (±0.07)	1.0 (±0.28)
Specific tensile strength (MPa)	88.54	57.28	37.60	42.47
Specific Young modulus (MPa)	6.20	5.64	5.76	5.43

Table 4. Retention percentage of the tensile mechanical properties of the composites, considering the fiberglass composite as being 100%.

Composites	Tensile strength	Young modulus	Maximum strain
Fiberglass	100%	100%	100%
Hybrid sisal/glass	57%	80.6%	72%
Hybrid coir/glass	35%	76.5%	44.4%
Hybrid Luffa/glass	34%	62%	55.5%

to 50% of the ultimate stress in order to prevent any damage influence in the modulus.

The hybrid sisal/glass presented the best performance compared with the fiberglass composite, with retention of 57%, 80.6% and 72% in the Tensile strength, Young modulus, and Maximum strain, respectively. This result can be considered excellent since approximately 50% of the fiberglass (in volume) has been replaced by sisal fiber, whose mechanical properties are significantly inferior. It is worth highlighting the low reduction of the Young modulus, a fundamental property in projects using composite materials.

The hybrids coir/glass and luffa/glass presented approximate values of mechanical properties. The coir/glass composite presented retention of 35%, 76.5% and 44.4% in the Tensile strength, Young modulus, and Maximum strain, respectively, compared with the fiberglass composite. The Luffa/glass composite presented retention of 34%, 62% and 55.5% in the Tensile strength, Young modulus, and Maximum strain, respectively.

Considering the specific tensile strength, the hybrid sisal/glass still shows the best performance among the hybrid composites, however, the hybrid luffa/glass (the lower density composite), surpasses the performance of the hybrid coir/glass. Considering the specific modulus, the three hybrid composites has practically the same values and close to the fiberglass composite.

The tensile mechanical properties of the composites, presented in Table 3, corroborate the fiber's properties presented in Table 1; the glass fiber has the higher properties followed by sisal, Luffa sponge, and coir, in this order. The great discrepancy between the properties of natural fibers and synthetic fibers reinforces the good result found in this work, highlighting the low reduction in the modulus after the hybridization.

Fracture analysis of the tensile specimens. Figure 8 shows the fracture region of some tensile specimens of the hybrid composites. The fracture was quite localized for all composites (hybrid and non-hybrid), which means the specimen did not present evidence of damage in the areas distant from the fracture. The fiberglass composite presented complete fracture with total separation of the specimen. On the other hand, the specimens of the hybrid composites maintain partial ligament after the fracture, as seen in Figure 8.

As already observed in the microscopic analysis (Figure 6), the interfacial adhesion between the natural fibers and the polymeric matrix is weak, which favors the interfacial debonding followed by pull-out mechanism during the fracture process. Some fibers can act as a "bridge", linking the fracture surfaces, as observed in Figure 8(a) and (b) (black arrows).

Flexural mechanical properties

Figure 9 shows Stress x Strain curves of the composites. The fiberglass composite presented linear behavior up to fracture, with a tendency to brittle behavior. The hybrid composites presented "more ductile" behavior the curves are linear until 50% of the maximum load, approximately.

The flexural mechanical properties are presented in Table 5. The following properties were determined: Flexural modulus, Flexural strength, and Maximum

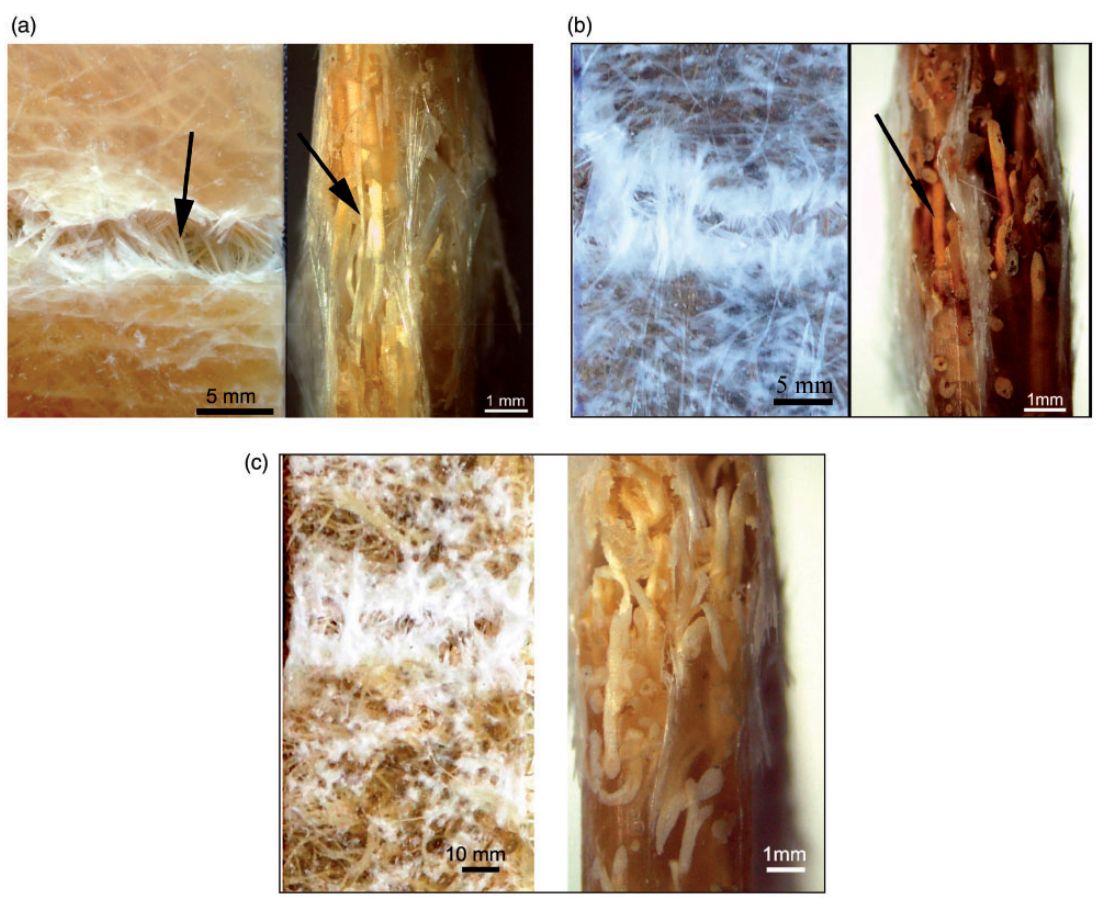

Figure 8. Front and side view (thickness) of the fracture region of the tensile specimens. The black arrows indicate the phenomenon of "fiber bridging". (a) sisal/glass, (b) coir/glass, (c) Luffa/glass.

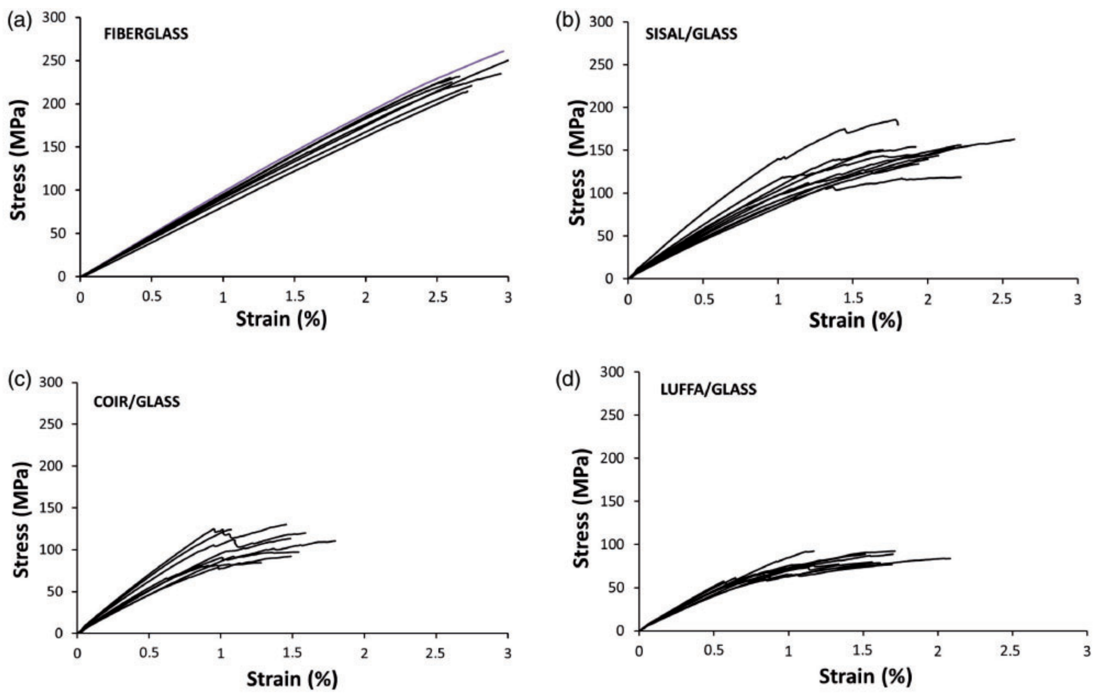

Figure 9. Stress × Strain curves of the flexural tests: (a) fiberglass, (b) sisal/glass, (c) coir/glass, (d) Luffa/glass.

Table 5. Flexural mechanical properties of the composites. The values between brackets represent the dispersions (the average of the distances between the result of each specimen and the average result.). Specific flexural strength and specific flexural modulus are based on the relative density of the composites.

Properties	Fiberglass	Hybrid sisal/glass	Hybrid coir/glass	Hybrid Luffa/glass
Flexural strength (MPa)	232.31 (±14.89)	149.63 (±14.68)	109.54 (±16.06)	84.16 (±7.88)
Flexural modulus (GPa)	11.02 (±0.80)	11.11 (±1.93)	11.32 (±1.87)	9.34 (±1.91)
Maximum flexural strain (%)	2.76 (±0.21)	2.09 (±0.45)	1.50 (±0.16)	1.65 (±0.56)
Specific flexural strength (MPa)	147	106.9	84.3	74.9
Specific flexural modulus (MPa)	6.97	7.9	8.7	8.3

Table 6. Retention percentage of the flexural mechanical properties of the composites, considering the fiberglass composite as being 100%.

Composites	Flexural strength	Flexural modulus	Maximum flexural strain
Fiberglass	100%	100%	100%
Hybrid sisal/glass	64%	100.8%	75.7%
Hybrid coir/glass	47%	102.7%	54.3%
Hybrid Luffa/glass	36%	84.7%	59.7%

flexural strain. Table 6 shows the retention percentage of the flexural mechanical properties, considering the fiberglass composite as being 100%.

As expected, the fiberglass composite presented the best performance. Not surprisingly, the sisal/glass stood out from the other hybrids, being the closest to the fiberglass composite, with retention of 64% and 75.7% in the Flexural strength and Maximum flexural strain, respectively. The Flexural modulus of the sisal/glass and coir/glass hybrid composites presented the same value of the fiberglass composite, considering the dispersions in the values. The hybrid Luffa/glass had retention of 84.7% in the Flexural modulus.

In the flexural loading, the outer layers of the laminated are very influential on the mechanical properties, mainly in the flexural modulus that is measured in the beginning of the test, with low loading levels, less than 50% of the maximum load, to prevent initiation and propagation of cracks. Of course, the hybrid laminated configuration had a fundamental role in this behavior. The outer layers of glass fibers were decisive in the Flexural modulus, which explains the excellent results found.

Despite the advantage of having a tridimensional natural mat appearance, which makes the lamination process easier, the hybrid composite with luffa sponge has the lowest properties when compared to other hybrid composites, as also observed in the tensile test. However, this analysis changes when the specific properties are considered. The specific flexural modulus of the hybrid luffa/glass (the lower density composite), is greater than that of the fiberglass and sisal/glass composites. Considering the specific flexural strength, the hybrid sisal/glass still shows the best performance among the hybrid composites, however, the performance of the hybrid luffa/glass is closer to that of other hybrid composites. These results highlight the great improvement in the performance of natural fibers composites with the hybridization process.

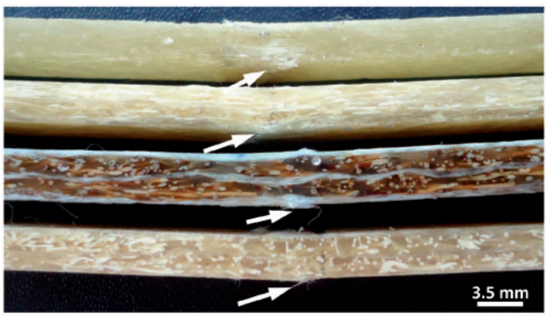

Figure 10. Specimens after the flexural test with white arrows indicating the tensile face (from top to bottom: fiberglass, sisal/glass, coir/glass, Luffa/glass).

Fracture analysis of the flexural specimens. Some specimens after the flexural test are presented in Figure 10, with white arrows indicating the tensile face of the specimens. It is worth mentioning that in the flexural test the crack starts on the tensile face of the specimen and propagates to the compressive side, toward the neutral line, characterizing the typical flexural fracture.

None of the specimens showed complete rupture. In addition, it was observed that the fracture was quite localized, i.e., no damage was observed in regions far from the fracture. This demonstrates a good performance of the composites in the flexural loading, and that the hybridization process does not affect the fracture behavior of the material, since the fiberglass composite showed similar behavior.

Figure 11 shows details of the fracture process in the hybrid composites. In Figure 11(a) and (b), sisal/glass

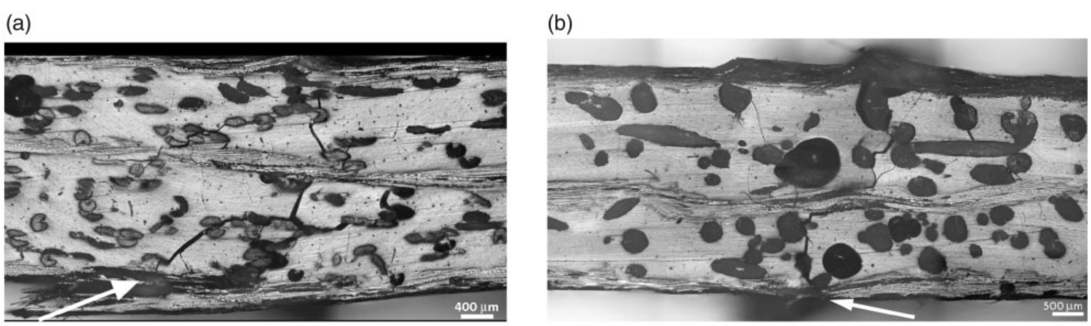

Figure 11. Crack propagation in the flexural test of the hybrid composites, with white arrows indicating the start of the main crack on the tensile side: (a) hybrid sisal/glass; (b) hybrid luffa/glass.

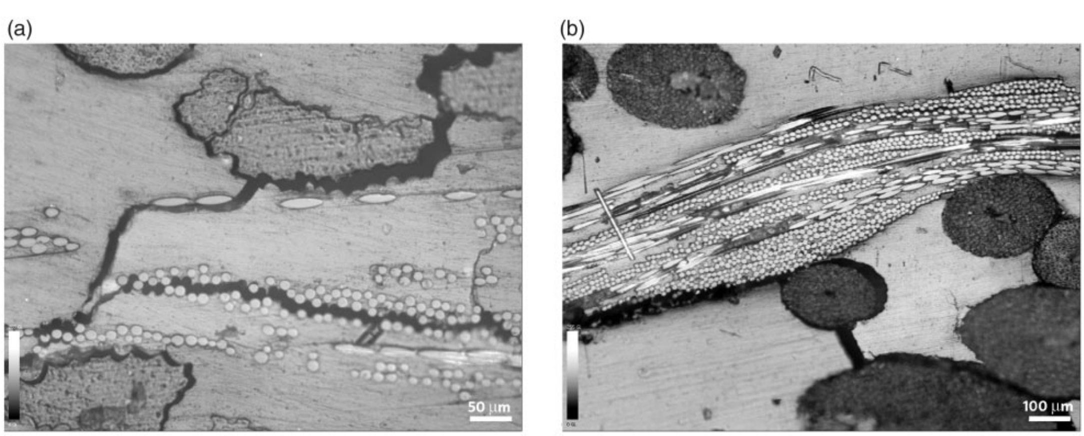

Figure 12. Microscopic aspects of crack propagation in the flexural test of the hybrid composites: (a) hybrid sisal/glass; (b) hybrid coir/glass.

and luffa/glass, respectively, a main crack is observed that starts in the tensile face (indicated by white arrow) and propagates across the various layers toward the compressive face. At this stage, the cracks are usually referred to as "split". The propagation occurs preferentially at the transversal mode in relation to the specimen's length; however, transversal splits may cause longitudinal splits when the split crosses a composite layer. The tensile face always presents greater damage extension, as observed in Figure 11(a). Delamination is observed between the outer layer of fiberglass and the internal layer of natural fiber (white arrow).

Figure 12 shows microscopic aspects of the crack propagation in the hybrid's sisal/glass and coir/glass. The crack propagates preferentially in the fiber/matrix interface, which is the path of least resistance. However, it is also observed crack propagation in the matrix and between the layers of E-glass fiber and natural.

Conclusions

According to the literature, the behavior of the natural fiber composites is inferior to that of the synthetic fiber composites. However, mechanical behavior is enhanced with hybridization, as confirmed by this work.

Considering the three hybrid composites developed in this work, the best mechanical behavior was observed for the sisal/glass composite, being a potential replacement for fiberglass composite, with the advantage of using materials derived from biomass. The order of performance was the same in the tensile and flexural tests, sisal/glass, coir/glass, and luffa/glass, in this order. The hybrid luffa/glass has the lowest retention percentage of the properties compared to the fiberglass composite, however performance improves when the specific properties are considered, once this composite has the lower density.

The flexural modulus of the hybrid composites stood out from the other properties for presenting practically the same value of the fiberglass composite. The specific flexural modulus of all hybrid composites was greater than that of the fiberglass composite. Of course, the hybrid laminated configuration with outer layers of glass fibers had a fundamental role in this behavior.

Through macroscopic and microscopic analyses, it was observed that the inner layers of natural fibers present irregular fiber distribution with predominance of the matrix phase. Misalignment of the glass fiber layers was also observed. Voids and bubbles were always present in the composites, although in low percentage.

In the specimen's fracture analysis for both tests, tensile and flexural, it was observed that the fracture process was quite localized, with no damage in regions far from the fracture. It was also observed that the interfacial adhesion between the natural fibers and the polymeric matrix is weak, which favors the interfacial debonding followed by pull-out mechanism during the fracture process. Small delamination between the layers of glass fiber and natural fibers were observed.

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References

1. Begum K and Islam MA. Natural fiber as a substitute to synthetic fiber in polymer composites: a review. *Res J Engineering Sci* 2013; 2: 46–53.
2. Al-Oqla FM and Sapuan SM. Natural fiber reinforced polymer composites in industrial applications: feasibility of date palm fibers for sustainable automotive industry. *J Clean Prod* 2014; 66: 347–354.
3. Bledzki AK and Gassan J. Composites reinforced with cellulose based fibres. *Prog Poly Sci* 1999; 24: 221–274.
4. Tita SPS, Medeiros R, Tarpani JR, et al. Chemical modification of sugarcane bagasse and sisal fibers using hydroxymethylated lignin: influence on impact strength and water absorption of phenolic composites. *J Compos Mater* 2018; 52: 2743–2753.
5. Atiqah A, Jawaid M, Sapuan SM, et al. Physical and thermal properties of treated sugar palm/glass fibre reinforced thermoplastic polyurethane hybrid composites. *J Mater Res Technol* 2019; 8: 3726–3732.
6. Rodrigues LPS, Silva RV and Aquino EMF. Effect of accelerated environmental aging on mechanical behavior of curaua/glass hybrid composite. *J Compos Mater* 2012; 46: 2055–2064.
7. Mukhtar I, Leman Z, Zainudin ES, et al. Hybrid and nonhybrid laminate composites of sugar palm and glass

Fibre-Reinforced polypropylene: effect of alkali and sodium bicarbonate treatments. *In J Polym Sci* 2019; 2019: 1–12.
8. Behera A, Dehury J and Thaware MM. A comparative study on laminated and randomly oriented Luffa-Kevlar reinforced hybrid composites. *J Nat Fibers* 2019; 16: 237–244.
9. Thwe MM and Liao K. Effects of environmental aging on the mechanical properties of bamboo-glass fiber reinforced polymer matrix hybrid composites. *Compos Part A* 2002; 33: 43–52.
10. Akil HM, Santulli C, Sarasini F, et al. Environmental effects on the mechanical behaviour of pultruded jute/glass fibre-reinforced polyester hybrid composites. *Compos Sci Technol* 2014; 94: 62–70.
11. Senthilkumar K, Saba N, Rajini N, et al. Mechanical properties evaluation of sisal fibre reinforced polymer composites: a review. *Constr Build Mater* 2018; 174: 713–729.
12. Food and Agriculture Organization of the United Nations. Future fibres, www.fao.org/economic/futurefibres/fibres/sisal/en/ (accessed 20 September 2019).
13. Shen J, Xie Y, Huang X, et al. Mechanical properties of luffa sponge. *J Mech Behav Biomed Mater* 2012; 15: 141–152.
14. Chen Q, Shi Q, Gorb SN, et al. A multiscale study on the structural and mechanical properties of the luffa sponge from Luffa Cylindrica plant. *J Biomech* 2014; 47: 1332–1339.
15. Chen Y, Su N, Zhang K, et al. Effect of fiber surface treatment on structure, moisture absorption and mechanical properties of luffa sponge fiber bundles. *Ind Crops Prod* 2018; 123: 341–352.
16. Bisen HB, Hirwani CK, Satankar RK, et al. Numerical study of frequency and deflection responses of natural fiber (luffa) reinforced polymer composite and experimental validation. *J Nat Fibers* 2020; 17: 505–519.
17. Papanicolaou GC, Psarra E and Anastasiou D. Manufacturing and mechanical response optimization of epoxy resin/Luffa Cylindrica composite. *J Appl Polym Sci* 2015; 132: 41992.
18. Jayamani E, Hamdan S, Rahman M, et al. Processing and characterization of epoxy/luffa composites: investigation on chemical treatment of fibers on mechanical and acoustical properties. *Bioresources* 2014; 9: 5542–5556.
19. Daniel-Mkpume C, Ugochukwu C, Okonkwo E, et al. Effect of Luffa Cylindrica fiber and particulate on the mechanical properties of epoxy. *Int J Adv Manuf Technol* 2019; 102: 3439–3444.
20. Santos DE, Martinez FCC and Juiz PJL. Coconut fiber as raw material for product development: a technological prospection in patent banks. *Cardenos de Prospecção* 2018; 12: 153–164.
21. Paglicawan MA, Cabillon MS, Cerbito RP, et al. Loofah fiber as reinforcement material for composite. *Philipp J Sci* 2005; 134: 113–120.
22. Seki Y, Sever K, Erden S, et al. Characterization of Luffa Cylindrical fibers and the effect of water aging on the mechanical properties of its composite with polyester. *J Appl Polym Sci* 2012; 123: 2330–2337.
23. Mohanty AK, Misra M and Hinrichsen G. Biofibres biodegradable polymers and biocomposites: an overview. *Macromol Mater Eng* 2000; 276-277: 1–24.
24. ASTM D3039. Standard test method for tensile properties of polymer matrix composite materials, 2006.
25. ASTM D790. Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials, 2002.
26. ASTM D792. Standard test method for density and specific gravity (relative density) of plastics by displacement, 1991.
27. ASTM D3171. Standard test methods for constituent content of composite materials, 2004.
28. ASM International. *ASM handbook volume 21: composites*. Cleveland: ASM International, 2001.
29. Li Y, Ma H, Shen Y, et al. Effects of resin inside fiber lumen on the mechanical properties of sisal fiber reinforced composites. *Compos Sci Technol* 2015; 108: 32–40.