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Article

Musa fiber-reinforced PLA biocomposites and their mechanical properties

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Abstract

This study analyzed polylactic acid biocomposites reinforced with banana (Musa) fiber, evaluating its effect on mechanical properties before and after accelerated aging. Analyses (FTIR, XRD, TGA) confirmed that the fiber contains hemicellulose, cellulose, and lignin, with a higher cellulose fraction due to its high crystallinity. Before aging, tensile strength and tensile modulus did not show a significant improvement with increasing fiber content, although impact strength and hardness did improve slightly. Nevertheless, elongation at break decreased. After 240 h of exposure in the UV chamber, the mechanical properties of the biocomposites degraded, with a reduction in tensile strength and modulus and an increase in elongation at break. Despite this, the reinforced biocomposites showed better mechanical properties than pure PLA after aging.

Keywords:

composite material, Musa fiber, polylactic acid.

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Introduction

The exponential increase in plastic pollution and environmental regulations are driving industries to develop more sustainable materials. A key alternative is biocomposites, such as polymers reinforced with natural fibers, which have gained relevance due to their biodegradability and low ecological impact (Gholampour *et al*., 2020; Zwawi *et al*., 2021).

These fibers, obtained from agricultural byproducts, offer advantages such as renewability, low cost, non-toxicity and high resistance (Christian *et al*., 2016; Elshaarani *et al*., 2013), positioning them as viable substitutes for synthetic fibers in industrial applications (Werchefani *et al*., 2020). Current research focuses on biodegradable polymeric composites reinforced with natural fibers, where chemical treatments (acetic acid and alkaline solutions) improve fiber-matrix compatibility by removing hemicellulose and lignin, preserving cellulose (Qian *et al*., 2013; Nouri *et al*., 2021).

A recent study with PLA and reed fibers showed that the chemical treatment significantly increased the mechanical properties (elasticity modulus, tensile strength, and elongation), evidencing its efficacy (Kharchi *et al*., 2025). On the other hand, Berzin *et al*. (2019) evaluated the fiber content of pineapple leaves in a PP matrix on the rheological and mechanical properties, using fiber contents of 10 to 30% by weight.

The rheological behavior was affected, increasing the viscosity as a function of the fiber content; for their part, the mechanical properties showed an increase in Young's modulus and the tensile stress proportional to the fiber content. Pant *et al*. (2025) evaluated PP hybrid composites that were reinforced with pineapple leaf and areca nut; the results of this study showed that the polymer matrix presented good adhesion with the fiber mixtures, and that the mechanical properties increased proportionally to the fiber content, which was attributed to a higher amount of holocellulose for higher fiber contents.

For their part, Binti *et al*. (2023) conducted a comparative study of different fibers, Kenaf, Bamboo and coconut, in a PLA matrix. The different fibers were applied in a single direction, which improved the mechanical properties regardless of the type of fiber. They also observed that water absorption was higher compared to the base material, increasing by 40% due to the fiber content.

This work seeks to evaluate how the content of Musa (banana) fiber in a PLA (polylactic acid) matrix affects its mechanical properties, especially under aging conditions. The purpose is to understand better the relationship between the natural fiber and the polymer matrix, and how this influences the mechanical properties of the biocomposite. In addition, it seeks to generate alternatives that comply with new regulations and standards for various applications.

Materials and methods

Banana fiber, also known as Musa fiber, was selected as a natural fiber due to its excellent resistance. This fiber is obtained from the stem of the banana plant and is a sustainable alternative used to make various products. The biopolymer used in this study is a polylactic acid thermoplastic; its melting temperature is around 210 °C, with a melted flow index of 7 g 10 min and a density of 1.2 g cm^{-3}.

Characterization of Musa fiber

Musa fiber was characterized by analytical techniques to evaluate its structural, thermal, and crystallographic properties. FTIR-ATR spectroscopy (Thermo Scientific Nicolet iS10) was used to identify functional groups, thermogravimetry (TGA) (TA Instruments Q500) to analyze its thermal stability under nitrogen atmosphere (25-750 °C, 10 °C min^{-1}) and X-ray diffraction (XRD) (Bruker D8 Advance, Cu-Kα) to determine its crystal structure (2θ = 5-40°, 30 mA, 40 kV). The results provided key insights into its molecular composition, thermal behavior, and crystal arrangement.

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Biocomposite preparation

To make the biocomposites, the PLA resins and Musa fibers were vacuum dried in an oven at 70 °C for 8 h. A Brabender internal mixer of 60 cm^3 capacity was used with roller-type rotors. The samples were processed at a temperature of 190 °C for 10 min and a speed of 70 rpm. Table 1 shows the composition of the different biocompounds prepared.

Table 1. Identification and formulation of biocomposites.

Sample ID	Resin 90 (g)	Banana fiber (g)	Banana fiber (%)
Blank	90	0	0
1	89.1	0.9	1
2.5	87.25	2.25	2.5
5	85.5	4.5	5
10	81	9	10
15	76.5	13.5	15
20	72	18	20
25	67.5	22.5	25

To prepare the study specimens, plates of 3 mm thick by 15 cm long and wide were made, using Carver hydraulic presses. Ninety grams of the previously dried biocomposite were placed and melted at 190 °C for 8 min, applying 5, 10 and 15 t of pressure; after this process, the plate was cooled to room temperature using cooling presses, maintaining the constant pressure of 15 t during the cooling time. Once the plates were obtained, they were machined into Type 5 specimens following the ASTM D638 standard.

Mechanical testing

Various mechanical tests were carried out to evaluate the properties of Musa fiber. First, a tensile test was performed using a mechanical testing equipment, model SFM, equipped with pneumatic grips. A 500 N load cell with a reference length of 10 mm and a crosshead speed of 5 mm min were used for the measurements.

The specimens were conditioned according to the ASTM D618-96 standard, and 5 measurements were taken, and the average was recorded. In addition, an Izod-type impact test was carried out with a Tinius Olsen equipment, following the ASTM D256-10 standard, in which 5 measurements were also taken, and their average was recorded. Finally, the hardness of the biocomposites was determined by a PTC 306L durometer with a 1 kg load, as specified in the ASTM D2240-15 standard.

QUV accelerated aging chamber

To expose the specimens to UV radiation, a QUV-LAB accelerated aging chamber was used with fluorescent lamps with a wavelength of 340 nm. The samples were fixed in a metal frame and placed inside the chamber. The test conditions were established based on the ASTM D4329 standard and are shown in Table 2.

Table 2. Conditions in the UV chamber.

Description	Time	Temperature	Irradiation at 340 nm
UV radiation Condensation	8 h 4 h	60 ±3 °C 50 ±3 °C	0.89 W m^{-2} nm^{-1}

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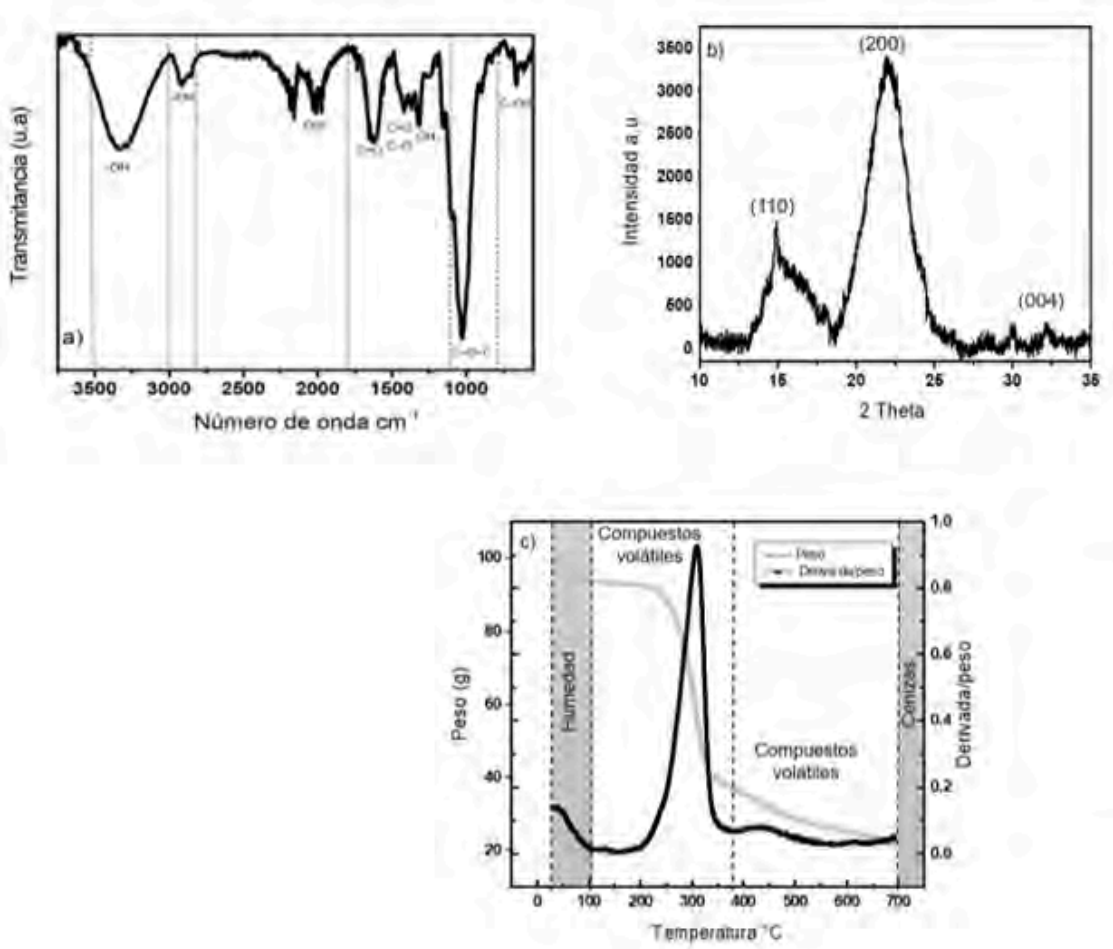
Results and discussion

Characterization of Musa fiber

The characterization of the Musa fiber is presented in Figure 1, which contains images from the FTIR, XRD, and TGA analyses. Figure 1a shows the FTIR spectrum of the Musa fiber, where a broad absorption band could be observed in the region of 3 000 to 3 500 cm^{-1}; this band is associated with the presence of stretching vibrations of the -OH groups, which are found in the main components of the fiber (cellulose, hemicellulose, and lignin) (Pereira *et al*., 2014). Peaks around 2 918 cm^{-1} and 2 851 cm^{-1} are attributed to asymmetrical and symmetrical stretches of the aliphatic -CH bond present in hemicellulose and cellulose (Das *et al*., 2018).

Figure 1. Characterization of Musa fiber. a) FTIR, b) XRD and c) TGA.



The absorption bands observed at 1 733 cm^{-1} and 1 244 cm^{-1} are related to the stretches of C=O and C-O bonds of the acetyl group due to hemicellulose. The asymmetrical and symmetrical stretches of the carbonyl C=O conjugated with the aromatic ring skeleton are observed at 1 602 and 1 509 cm^{-1}, which are attributed to the aromatic characteristics of lignin. The absorption bands of peaks 1 423 and 1 367 cm^{-1} are associated with the symmetrical bending of -CH_2 found in lignin, hemicellulose, and cellulose.

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The peak at 1 319 cm^{-1} is attributed to the deformation of the -OH plane of cellulose (Das *et al*., 2017). The particular peak of #-glycosidic bonds of cellulose is located at 1 155 cm^{-1} and at 898 cm^{-1}, assigned to the symmetrical stretching of C-O-C. The absorption peaks at 1 103 cm^{-1} and 1 028 cm^{-1} are generated due to the skeletal vibration of the C-O-C pyranose ring of cellulose and the asymmetrical stretching of C-O-C in cellulose and hemicellulose. The band located at 655 cm^{-1} corresponds to the out-of-plane deformation of C-OH in cellulose (Cecci *et al*., 2020).

Figure 1b) shows the XRD analysis, where it is possible to observe a typical cellulose diffractogram (Prerna *et al*., 2016), evidencing characteristic reflections (peaks) at 2# positions equal to 15.9°, 21.9°, and 32°, corresponding to the planes (110), (200), and (004). The crystallinity index for Musa fiber was determined by adding the area of the peaks and dividing it by the total area of the diffractogram, obtaining a CI of 87.6%; this result shows that the Musa fiber presents a high degree of crystallinity, which can be beneficial for the mechanical properties (Xu *et al*., 2015).

To analyze the thermal stability of the Musa fiber, a thermogravimetric analysis (TGA) and its derivative (DTG) were performed, as shown in Figure 1c. Fiber weight loss was observed in three phases. The first occurred in a temperature range of 21° to 110 °C, with a weight loss of 6.9%, attributed to the evaporation of the water contained in the fiber (Yousefi *et al*., 2013).

The second phase, which represented a weight loss of 56%, occurred between 150° and 380 °C and is related to the pyrolysis of hemicellulose and cellulose. Finally, the third phase showed a weight loss of 14.5%, corresponding to the depolymerization of lignin. Regarding the derivative of the analysis, two peaks were observed that reflect the maximum degradation temperatures of the fiber: one at 310 °C, associated with hemicellulose and cellulose, and another at 443 °C, related to lignin. These decomposition ranges have been reported in previous studies, such as that by Díez *et al*. (2020).

Effect of fiber content on mechanical properties

Table 3 shows the results of the tensile modulus, tensile strength, and elongation at break evaluated under different fiber contents. From the data presented in Table 3, it was observed that the fiber content in the polymeric matrix of the PLA does not promote significant reinforcement, since the values of the tensile modulus are very similar to those of the blank material. On the other hand, elongation at break and tensile strength decrease with the different contents of Musa fiber, but it was not possible to observe a monotonic behavior based on fiber content.

Table 3. Mechanical properties of biocomposites before being subjected to accelerated aging.

Fiber (%)	Tensile strength (MPa)	Tensile modulus (MPa)	Elongation at break (%)
Blank	47.4	4 494.9	2.3
1	50.5	4 744.3	1.6
2.5	36.9	4 453.8	1.2
5	40.3	3 745.8	1.6
10	42.7	4 113.4	1.9
15	34.6	4 166.3	1.5
20	42.7	5 000.4	1.6
25	30.2	3 674.2	1.1

These results suggest that the PLA biocomposite became more brittle; this behavior is to be expected and could indicate poor matrix-fiber adhesion; another possible factor could be associated with fiber agglomerations in the PLA due to poor fiber dispersion, as has been reported in other studies (Yaisun *et al*., 2023; Oksman *et al*., 2003). Poor adhesion has been related to the low hydrophilicity and polarity of PLA compared to Musa fibers (Chun *et al*., 2012).

Figure 2 represents the impact strength values; a slight increase can be observed for fiber contents of 1, 2.5 and 5% compared to the blank material. For fiber contents of 10, 15, 20 and 25%, the

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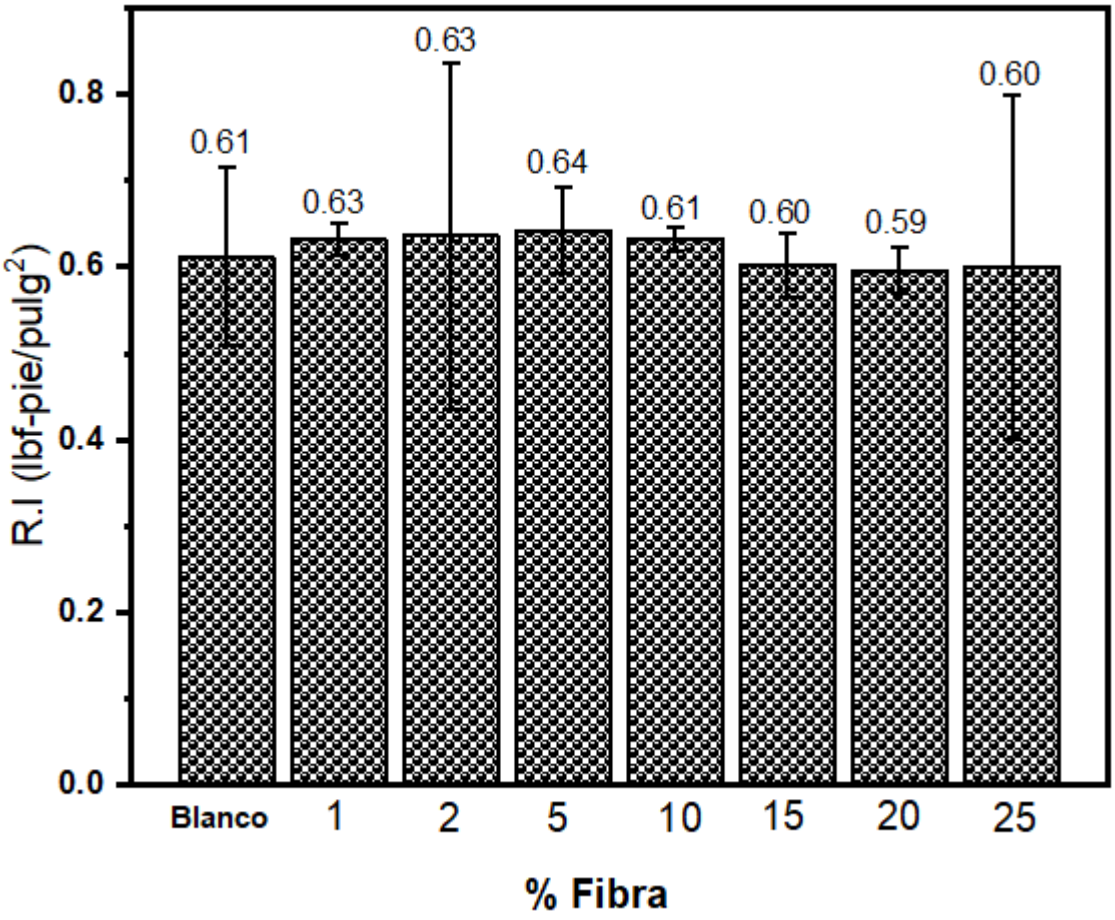
values tend to decrease, showing a behavior similar to that of the blank material. This trend, added to the high variation shown in the standard deviations, could indicate poor dispersion of the fiber in the polymer matrix, which limits the transfer of stresses and, consequently, prevents a substantial improvement in the impact strength of the biocomposite.

Figure 2. Impact strength of biomaterials formulated with different contents of Musa fiber.



There are two mechanisms by which fibers could impair the impact strength of the biocomposite; the first indicates that fibers tend to inhibit the deformation and ductile mobility of polymer molecules, which would reduce the ability of the composite to absorb energy during crack propagation; in the second, the fibers also generate regions of high tension that require less energy to initiate a crack; this regions can be located at the ends of the fibers, areas of poor interfacial adhesion, and areas where the fibers come into contact with each other (Park *et al*., 1997). To obtain good impact strength, it is necessary to promote an optimal bond, as mentioned by Servais *et al*. (2002).

Hardness shows a clear increase with fiber content (Figure 3); this behavior is not reflected in tensile properties (Table 3). This difference can be attributed to the fact that hardness assesses surface resistance to penetration, while tensile properties depend on structural integrity and stress transfer throughout the biocomposite. The presence of fibers stiffer than PLA explains the increase in hardness (Abbass *et al*., 2020), but potential poor matrix-fiber adhesion and non-uniform dispersion could negatively affect tensile properties (Oksman *et al*., 2003; Chun *et al*., 2012).

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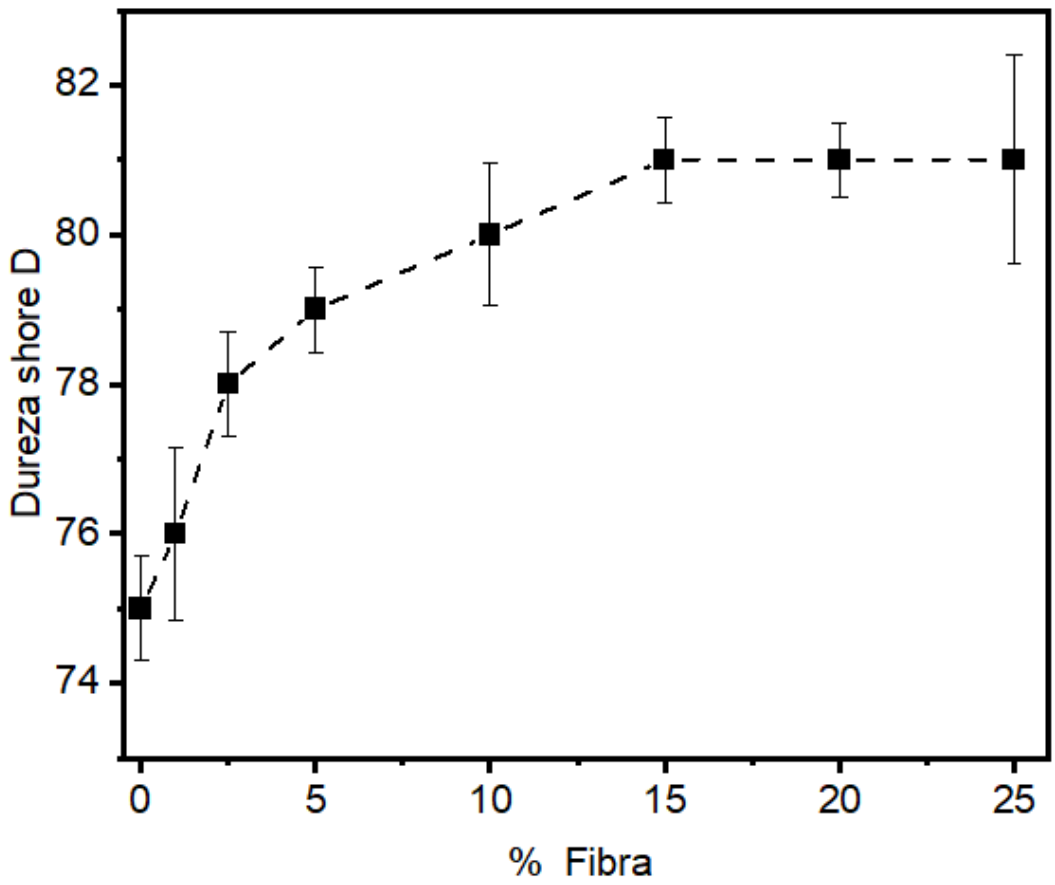
Figure 3. Effect of Musa fiber content in the biocomposite on hardness.



Visual analysis

Effects of accelerated aging on mechanical properties

Figure 4 shows photographs before and after exposing biocomposites with different fiber contents in the accelerated aging chamber. It was observed that the physical appearance of the samples underwent a complete change, with a rougher texture being generated and opacity in the coloration being evident in all cases.

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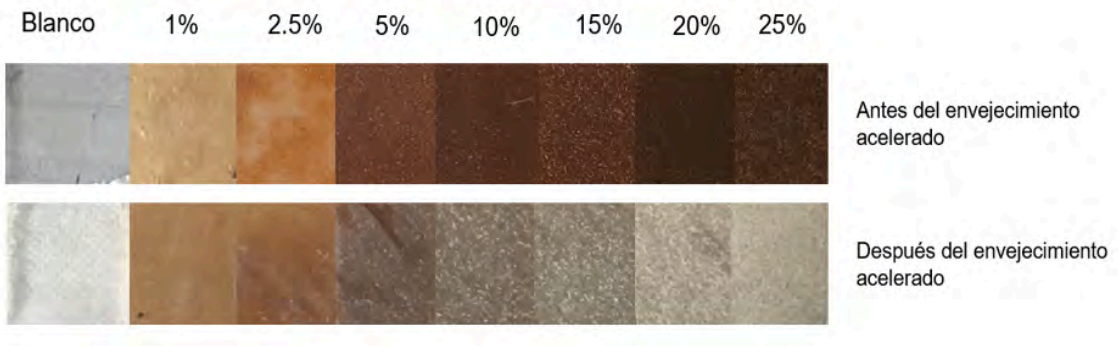
Figure 4. Visual appearance of biocomposites before and after being subjected to accelerated aging.



For higher fiber contents, 10-25%, surface erosion is promoted, exposing the fibers on the surface, as shown in Figure 4. The chemical changes that occur on the surface of different biocomposites are commonly known as photodegradation (Adhikary *et al*., 2008; Zivkovic *et al*., 2016).

Table 4 shows how accelerated aging affects the mechanical properties of biocomposites. The tensile strength and modulus decrease significantly, up to 50% and 90%, respectively, exhibiting material embrittlement. Nevertheless, elongation at break increased in all cases, possibly due to the degradation of the fibers that act as plasticizers, as reported by Samilpa *et al*. (2022); Islam *et al*. (2010). Despite degradation, biocomposites retained better properties than the base material, suggesting that Musa fibers could provide long-term mechanical benefits.

Table 4. Mechanical properties of biocomposites after being subjected to accelerated aging.

% fiber	Tensile strength (MPa)	Tensile modulus (MPa)	Elongation at break (%)
Blank	23.6	391.7	2.3
1	25.4	163.9	3.5
2.5	24.7	449.3	3
5	12.2	500.7	2
10	24.1	529.3	3
15	17.1	551	2.2
20	28.3	155.3	3.3
25	11.3	324.7	2.6

Conclusions

Musa fiber-reinforced PLA biocomposites showed an increase in the tensile modulus for contents of 1% and 20%, with improvements of 5.5% and 11.2%, respectively, compared to pure PLA. For concentrations of 2.5%, 5%, 10%, 15% and 25%, there was a reduction in tensile strength, attributable to inhomogeneous dispersion of the reinforcement and poor interfacial adhesion.

After 240 h of accelerated aging by UV radiation, tensile strength decreased by 50% to 90%; however, the composites with 1% and 20% fiber maintained higher values than the blank material, evidencing a plasticizing effect due to partial degradation of the fibers, which was also reflected in an increase in elongation at break.

The Shore D hardness showed a linear trend with the increase in fiber content, reaching an increase of 20% in the biocomposite with 25%, associated with the high crystallinity of the cellulose (CI= 87.6%). Impact strength slightly increased in formulations with 1-5% fiber, attributed to the ability of the fibers to dissipate energy. These results suggest that low fiber contents offer a favorable balance between stiffness, toughness and stability against UV aging.

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