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Polylactic acid filaments reinforced with natural fique fibers for 3D printing applications

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ABSTRACT

3D printing offers advantages in terms of geometry customization and material waste reduction; however, the formulation of polymeric composite materials with improved mechanical properties remains a challenge. This study analyzes the use of natural fique fibers as reinforcement in polylactic acid filaments for additive manufacturing applications. In order to improve their compatibility with the polymer matrix, the fibers were subjected to an alkalization treatment and then incorporated into the polylactic acid at a 10 wt. % using a single-screw extruder. The composite filament was characterized by scanning electron microscopy for morphological analysis, differential scanning calorimetry, and thermogravimetric analysis. The test specimens for mechanical evaluation were manufactured by 3D printing and subjected to tensile testing according to ASTM D638-22 using a universal testing machine. In addition, statistical analysis was performed using ANOVA to determine the significance of the differences between pure polylactic acid and the reinforced composite. The differential scanning calorimetry results showed an increase in the glass transition temperature and cold crystallization temperature due to the incorporation of the fibers. Thermogravimetric analysis showed lower thermal stability of the composite, reflected in a reduction in the degradation temperature. Morphological observations indicated low interfacial adhesion between the fibers and the matrix, which contributed to the decrease in tensile strength. However, the composite material had a higher modulus of elasticity, indicating an increase in structural rigidity.

KEYWORDS

fique fibres • 3D printing • biocomposite filaments • polymer–fibre composites • PLA reinforcement

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Introduction

3D printing, also known as additive manufacturing, is a technique that has revolutionised the industrial sector by making it possible to create prototypes and complex objects quickly and with highly customised designs, building them layer by layer [1]. Among the materials most commonly used in this process, polylactic acid (PLA) stands out for its biodegradability, ease of printing, and low level of shrinkage during cooling. However, its limitations in terms of mechanical strength, fragility, and thermal stability restrict its application in more demanding conditions, which has driven the search for polymer formulations and composites with improved properties [2]. A promising strategy for improving the properties of PLA is to reinforce it with natural fibers. Materials such as bamboo, kenaf, flax, hemp, and sisal stand out for their high mechanical strength, greater thermal stability, biodegradability, and low cost, making them viable alternatives for expanding the applications of additive manufacturing [3].

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The incorporation of natural fibers into polymer matrices reduces the density of the composite, favoring the manufacture of lighter parts. In addition, these composite materials have a lower environmental impact compared to pure synthetic polymers, which is advantageous for sectors such as the automotive industry, construction, and consumer goods [4]. The incorporation of natural fibers as reinforcement in polymeric materials not only reduces the cost of filaments, but also improves their degradability. In addition, this type of reinforcement gives printed parts a distinctive appearance that may be attractive to certain users or sectors, especially when accompanied by an appropriate marketing strategy [5]. The use of natural resources as reinforcement has generated interest due to their availability and their potential to modify the mechanical and thermal behavior of the material [6].

However, one of the main limitations in the manufacture of filaments with natural fibers is the incompatibility between the two phases: natural fibers are hydrophilic, while the polymer matrix is usually hydrophobic. This difference in their chemical nature can cause adhesion problems, affecting stress transfer and, consequently, the mechanical performance of the composite material, can cause adhesion problems, which can intensify when certain fiber content levels are exceeded, reducing the mechanical properties of the material [7]. Due to this limitation associated with the incompatibility between the polymer matrix and natural fibers, various treatments have been studied with the aim of improving the interfacial adhesion between the two phases [8].

In addition to compatibility between material components, processing conditions during 3D printing also play a decisive role in the behavior of natural fiber-reinforced thermoplastic composites. High temperatures in the print nozzle can degrade the fibers, negatively affecting the mechanical properties of the final product. Therefore, it is necessary to optimize parameters such as temperature and layer spacing to obtain appropriate mechanical performance according to the application requirements. Likewise, the presence of natural fibers can modify the crystallinity of the matrix, influencing its thermal stability and resistance to degradation [9,10].

There are numerous developments and studies on filaments made from polylactic acid and reinforced with natural fibres for use in 3D printing. Celik et al. [11] produced polylactic acid filaments reinforced with hemp fibres, evaluating their thermal, morphological and mechanical properties. The results showed that the addition of hemp fibres deteriorated the thermal properties after 3D printing, although the flexural strength increased slightly. Additionally, Faidallah et al. [12] evaluated filaments made from PLA reinforced with 7 % by weight of hemp and jute fibres, achieving tensile strengths of 38.8 and 62.38 MPa, respectively. These values represent significant improvements compared to the original and recycled pure PLA filaments.

Selvan et al. [13] developed a PLA composite reinforced with flax fibres, highlighting its mechanical properties. The 3D printing parameters were optimised, achieving a tensile strength of 61.13 MPa and an impact strength of 12.77 kJ/m^2. On the other hand, Wu et al. [14] fabricated 3D printing filaments from PLA and rice husk (RH), incorporating PLA modified with acrylic acid (PLA-g-AA) and rice husk treated with a coupling agent (TRH) to improve the properties of PLA/RH biocomposites. The results showed that PLA-g-AA/TRH biocomposites exhibited superior tensile properties to PLA/RH due to improved compatibility between the polymer and the reinforcement.

Suteja et al. [15] developed PLA composites reinforced with continuous fibres from pineapple leaves for 3D printing, improving the mechanical properties of thermoplastic materials. Rafiee et al. [16] created PLA composite filaments reinforced with birch fibres, highlighting their printability and potential in additive manufacturing. However, they pointed out the need to optimise extrusion and printing parameters to improve the strength and resolution of the final products, as, although the biocomposite filaments were printable, they require high settings to achieve maximum performance.

In turn, Aumnate et al. [17] manufactured PLA/kenaf biocomposite filaments, improving their mechanical properties through treatment with plasticizers. These filaments showed an increase in tensile strength and elongation, making them suitable for 3D printing applications in sustainable textiles, prosthetics, and medical devices.

Despite the aforementioned advances in the field of natural fiber-reinforced filaments for 3D printing, no studies have been found that use fique fiber as reinforcement. Similar approaches using advanced 3D-printed PLA structures have been reported in [18], and the extrusion process in FDM printing has been modeled to optimize performance [19]. Fique fiber, which comes from a plant native to Colombia, stands out for its exceptional mechanical properties, particularly its high strength [20], making it a promising option for the development of biocomposite filaments for 3D printing. Its incorporation could lead to significant improvements in both performance and functionality.

Therefore, this study develops and characterizes a PLA filament reinforced with 10 % by weight of alkali-treated fique fibers, manufactured by extrusion for application in 3D printing. The morphological and thermal properties of the filament were evaluated, as well as the mechanical properties of the material once printed.

Materials and Methods

Materials

Long fique fibres were supplied by the company Ecofibras, located in Santander, Colombia. Subsequently, they were cut to sizes of 1 to 2 mm (Fig. 1(a)). The average diameter of the fibres was 187.8 μm, according to the micrograph obtained by scanning electron microscopy (SEM), presented in Fig. 1(b).

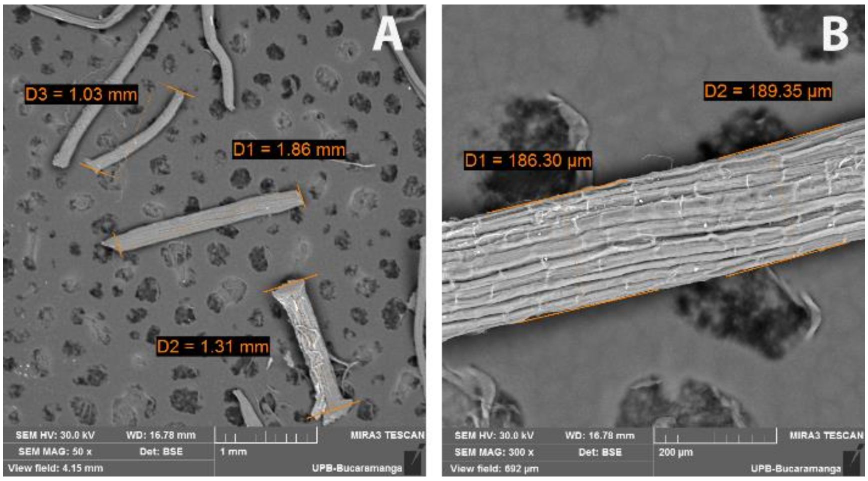

Fig. 1. SEM-images of fique fibres: (a) length of fibres after cutting; (b) average diameter of fibres

The PLA used was of 2003D grade, from renewable resources and presented in roll form. According to the manufacturer's specifications, this material has a density of 1240 kg/m^3, a melt flow rate of 6 g / 10 min (measured at 210 °C with a load of 2.16 kg). Before use, PLA was dried at 60 °C for 4 h and then processed into fragments of 1 to 2 mm in size.

Alkalinisation treatment

The fique fibers were subjected to an alkalization treatment using a 10 % by weight aqueous solution of sodium hydroxide (NaOH). The fiber/solution ratio was 1:10. The fibers were kept immersed in the solution for 30 min at room temperature. After this time, the solution was decanted and the fibers were washed repeatedly with distilled water and a small amount of acetic acid (CH_3COOH) until the alkaline residues were removed, confirming neutralization using pH indicator paper.

Subsequently, and unrelated to the previous immersion time, the fibers were subjected to a manual mechanical reduction process, decreasing their diameter to a range of 10–20 µm. Finally, the fibers were placed in a Petri dish and dried at room temperature for 24 h. To remove residual moisture, the samples were then dried in an oven at 60 °C for 6 h, until they reached a constant weight. Figure 2 shows the microfibrils obtained after the mechanical reduction process.

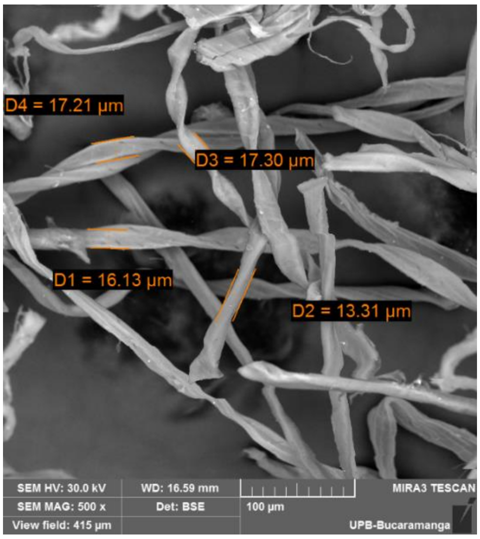

Fig. 2. SEM-images of microfibrils obtained by mechanical reduction

Filament processing

For the manufacture of the filament, a Wellzoom single-screw extruder, model Filament Extruder Line II, equipped with a 1.75 mm diameter nozzle, was used. The extrusion process was carried out at 205 °C, within the range recommended by the manufacturer for PLA and below the maximum degradation temperature of fique (337 °C), according to the study by Guzmán et al. [21], in which fique fibres were subjected to an alkalinisation treatment similar to the one used in this work. Before extrusion, the screw was preheated at 180 °C for 30 min. Extrusion was performed with a screw rotation speed of 10 rpm, which generated an exit speed at the nozzle of 8.46 mm/s.

The filament was manufactured with a 10 % weight fraction of the fique fibre. The procedure consisted of feeding the two components directly into the extruder in alternating layers, starting with 40 g of PLA, followed by 4 g of fique fibres, repeating this pattern successively.

Figure 3 shows the filament produced, from which continuous filaments of 180 cm in length were obtained. These filaments were used to manufacture the specimens for mechanical characterisation, by means of 3D printing.

Fig. 3. Extruded filament

Scanning electron microscopy

Scanning electron microscopy (SEM) was used to evaluate the adhesion between PLA and fique fibre in the extruded filament. The filament was sectioned into small fractions using a Ted Pella microtome and coated with a thin layer of gold using a Cressington Sputtering machine. This coating was done to improve the electrical conductivity of the material and to guarantee the quality of the observations during the analysis. A Tescan MIRA 3 FEG-SEM scanning electron microscope was used to capture micrographs at different focal planes, with magnifications of up to 1000X.

Thermal characterisation of the filament

A differential scanning calorimetry (DSC) analysis was performed on a 3 mg sample of the fique fibre filament and pure PLA using a TA INSTRUMENTS Discovery apparatus. The test was carried out in a nitrogen atmosphere with a flow rate of 20 ml/min, covering a temperature range of 25 to 300 °C and using a heating and cooling rate of 5 °C/min.

Thermogravimetric analysis

These findings are in line with other analyses that associate thermal degradation with printing defects in composite structures, and with studies showing that 3D printing defects strongly influence strength. The analysis was carried out in dry synthetic air atmosphere, with gas flow (25 mL/min) with a TGA5500 equipment of TA Instruments, applying a temperature increase of 5 °C/min until reaching 600 °C. TGA thermograms and derivative curves (DTG) were obtained for the filament of fique fibre with PLA, as well as for pure PLA.

Filament printing

The specimens for the mechanical characterisation of the biocomposite were manufactured by 3D printing using a Creality Ender 3 V2 and Creality Slicer 4.8 software. During the process, temperatures of 200 °C were set at the extruder and 70 °C at the printing bed, (according to the results of the thermal analysis). The use of supports for the model was not necessary, and the printing was performed at a controlled speed of 30 mm/s to ensure high precision in the details. Additionally, similar procedures have been validated for ABS-based fiber composites with infill variations. The parameters defined in the Crealty Slicer 4.8. software for 3D printing are shown in Table 1.

Table 1. Parameters defined in the printer

Quality	
Layer height, mm	0.2
Shell	
Wall thickness, mm	0.8
Wall line count	2.0
Top/bottom thickness, mm	0.8
Top thickness, mm	0.8
Botton thickness, mm	0.8
Top/bottom pattern, mm	lines
Infill	
Infill density, %	100
Infill line distance, mm	0.4
Infill pattern	lines
Minimun infill area, mm^2	0
Speed	
Print speed, mm/s	30
Infill speed, mm/s	30
Outer wall speed, mm/s	30
Travel speed, mm/s	120
Travel	
Retraction distance, mm	4
Retraction speed, mm/s	25
Cooling	
Fan speed, %	100
Regular fan speed at heigth, mm	0.6
Mimimun layer time	10

Tension test

The tensile test was performed using an MTS universal testing machine, model C43.104, following the guidelines of ASTM D638-22, entitled "Standard Test Method for Determining Tensile Properties of Plastics". Type V test specimens were used for this study, which are suitable when the amount of material available is limited. Five test specimens 3.2 mm thick and with the geometry specified in Fig. 4 (all dimensions expressed in mm) were prepared for both the PLA/fiche fiber composite and pure PLA in order to compare their mechanical behavior. The tests were performed at a crosshead displacement speed of 5 mm/min, as recommended by the standard. The values presented correspond to the average of the five tests performed for each material.

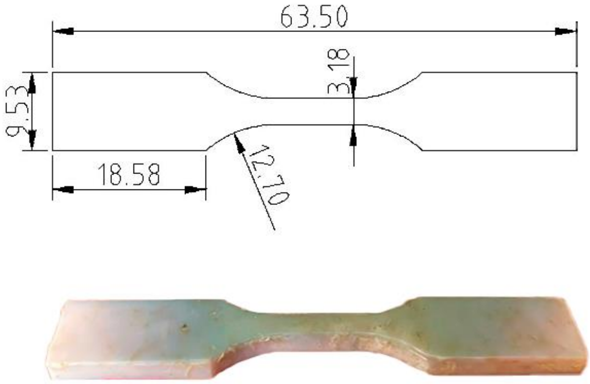

Fig. 4. Geometry of the specimen stress

Statistical analysis

The existence of statistically significant differences between the maximum stress and modulus of elasticity of the PLA–fique composite material and pure PLA were evaluated using analysis of variance (ANOVA). In this study, the ANOVA procedure was applied, which establishes that if the p-value obtained is lower than the adopted significance level (0.05), then it is concluded that the means of the mechanical properties differ statistically significantly.

Results

Morphological analysis

Figure 5 shows the adhesion and distribution of the fique fibre in the PLA matrix that makes up the manufactured filament. Scanning electron microscopy (SEM) images revealed significant voids at the matrix-fibre interface, showing poor interaction and suggesting inefficient charge transfer between the two components. Fibre agglomerates were also detected in some areas, pointing to inhomogeneous dispersion during the extrusion process.

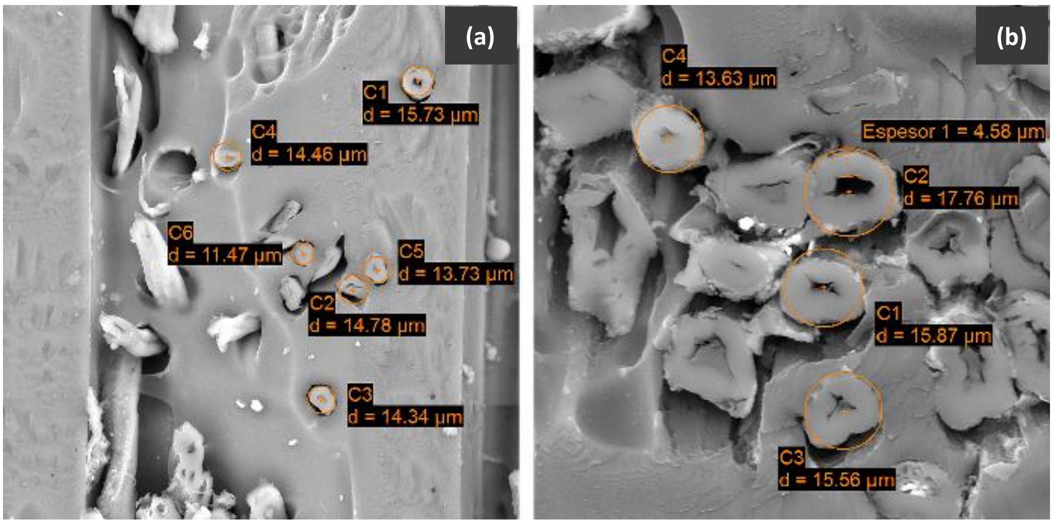

Fig. 5. Fibre-matrix adhesion micrograph: (a) 800X; (b) 1000X

This behaviour was also reported by Mazurt et al. [22] in their study on PLA filament composites reinforced with natural fibres (wood, bamboo and cork), where they observed the lack of continuity of the material and the presence of gaps between the applied filaments, which resulted in an increased porosity of the materials and subsequently affected their mechanical properties.

Thermogravimetric analysis

Thermogravimetric analysis (TGA) (Fig. 6) reveals that the incorporation of fique fibre reduces the thermal stability of PLA. In pure PLA, degradation starts at 290 °C and ends at 400 °C, while in the composite it occurs between 260 and 370 °C, advancing the decomposition process. In terms of mass loss, the pure PLA experiences a reduction of 94.63 %, while the composite loses 89.67 %, suggesting the presence of carbonaceous residues from the fique fibre, with possible effects on its thermal and structural stability. These findings are in line with other analyses that associate thermal degradation with printing defects in composite structures, and with studies showing that 3D printing defects strongly influence strength.

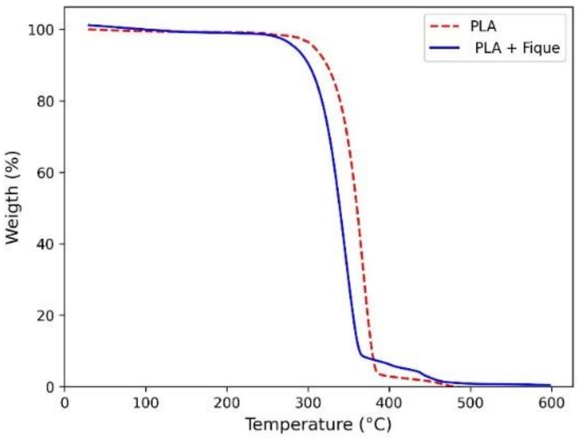

Fig. 6. TGA curves

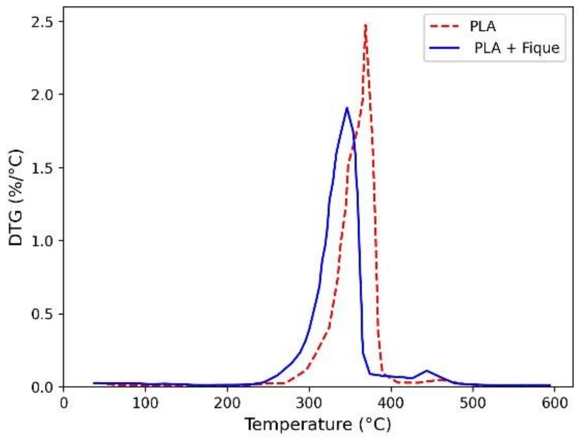

Fig. 7. DTG analysis curves

Differential thermogravimetric analysis (DTG) (Fig. 7) shows that pure PLA exhibits a single degradation peak at 380 °C, indicating rapid decomposition. In contrast, the PLA composite with fique exhibits a broader and shifted peak at 345 °C, indicating a more complex degradation process due to the decomposition of the lignocellulosic components of the fibre. The lower intensity of the peak in the composite indicates a reduction in the degradation rate, associated with the generation of carbonaceous residues that slow down the process.

Differential scanning calorimetry

The (differential scanning calorimetry) DSC analysis, represented in Fig. 8, shows that the incorporation of fique fibre modifies the thermal properties of PLA. The glass transition temperature (T_g) increased from 59.5 to 64 °C, suggesting a restriction in the mobility of the polymer chains due to the interaction with the fibre. Likewise, the cold crystallisation temperature (T_{cc}) increased from 103 to 107.5 °C, indicating a nucleating effect of the fibre influencing the reorganisation of the polymer chains. Finally, the melting temperature (T_m) showed a slight increase from 155.5 to 156.5°C, suggesting that the addition of fique does not significantly alter the crystalline phase of PLA. Numerical simulations of PLA during additive manufacturing have confirmed similar thermomechanical behaviour.

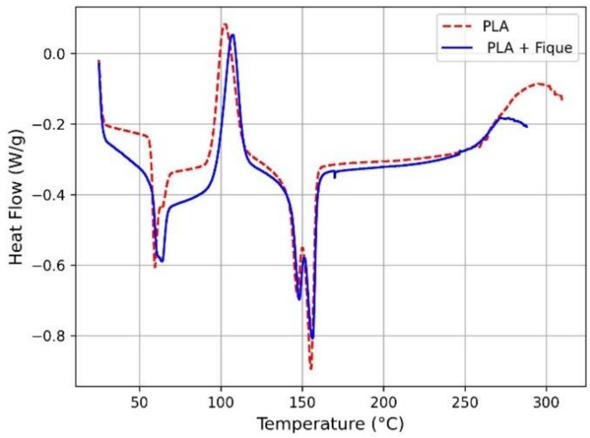

Fig. 8. DSC curves

The existence of statistically significant differences between the maximum tensile stress and the modulus of elasticity of the PLA composite reinforced with fique fibre and those of pure PLA was evaluated using an ANOVA (Analysis of Variance). According to this technique, when the p-value obtained is lower than the established significance level (0.05), it is concluded that the mean values of the mechanical properties differ significantly.

These results are consistent with those reported by Celik et al. [11], who observed similar behaviour in a PLA filament reinforced with hemp fibre. In their study, T_g increased from 55.86 to 59.7 °C, which aligns with the increase recorded in this work. Similarly, T_{cc} increased from 93.99 to 97.55 °C. Regarding Tm, although a slight decrease from 176.21 to 175.98 °C was observed, the variation was minimal and without significant impact, as also occurred in the present study.

The 3D-printing temperature settings for the PLA filament reinforced with fique fibre were established based on the thermal analysis of the material. The bed temperature was set at 70 °C to ensure proper adhesion of the first layer and to minimise deformation, as this value exceeds the glass transition temperature (T_g) of the composite, providing sufficient softening of the material at the interface.

The extrusion temperature was set at 200 °C, a value higher than the melting temperature (Tm), which guarantees adequate material flow during deposition, yet low enough to remain well below the degradation temperature identified through TGA, thus preventing thermal decomposition during printing.

Mechanical characterization

Figure 9 shows the stress–strain curves of pure PLA and the composite reinforced with fique fibre. Pure PLA exhibits the typical behaviour of thermoplastics, with an initial linear elastic response followed by plastic deformation until reaching its maximum strength, after which it quickly loses its load-bearing capacity and fractures in a brittle manner. In contrast, the composite with fique fibre presents a well-defined elastic response but with a lower capacity for plastic deformation before fracturing.

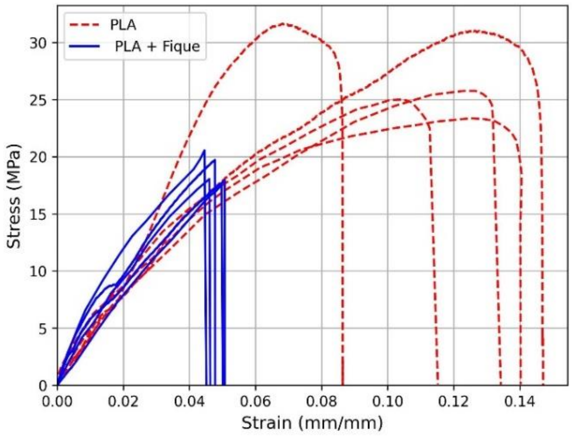

Fig. 9. Stress-strain curves

Figure 10 compares the tensile stress and modulus of elasticity of pure PLA and fique fibre reinforced composite. The tensile stress of the composite was 18.76 ± 1.30 MPa, which represents a 31.5 % reduction compared to neat PLA (27.36 ± 3.73 MPa). In contrast, its modulus of elasticity increased, reaching 593.10 ± 165.65 MPa compared to 441.34 ± 103.64 MPa in pure PLA.

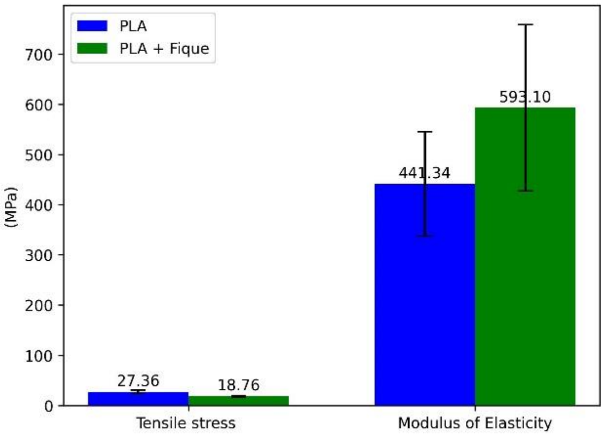

Fig. 10. Comparison of modulus of elasticity and tensile stress of PLA and PLA + Fique

The differences in tensile stress are due to poor interfacial adhesion between the fibers and the polymer matrix, as evidenced by electron microscopy images. This low adhesion hinders stress transfer, creating weak areas that reduce the strength of the composite material. Furthermore, the irregular distribution of fibers in the PLA matrix exacerbates this phenomenon, as their irregular accumulation produces stress concentrations, poor impregnation, and pore formation, further compromising the mechanical properties of the material. On the other hand, thermal analysis revealed that the incorporation of fique reduces the thermal stability of the material, accelerating its degradation.

The phenomenon of poor interfacial adhesion between the fibers and the polymer matrix—previously described through microscopic observations—could affect the structural integrity of the filament during 3D printing, negatively influencing its mechanical performance. Pitchaimani et al. [23] observed similar behavior in PLA filaments reinforced with short banana fiber, where poor interfacial adhesion reduced tensile properties by 31 % and resulted in brittle behavior, consistent with the results of this study. Comparable studies on biodegradable composites support these findings, highlighting the importance of interfacial adhesion in PLA and natural fiber systems, while other studies have reported greater thermal and mechanical stability with lignocellulosic reinforcements.

The increase in the modulus of elasticity is a key characteristic of the polylactic acid (PLA) composite reinforced with fique fibers, as discussed in the literature. This increase is due to the fact that the fique fibers, when integrated into the PLA polymer matrix, act as reinforcements. This mechanical reinforcement limits the deformation of the material under load and transfers the stresses to the more rigid fibers, resulting in a substantial improvement in the overall strength and stiffness of the composite material. Additionally, the increase in the glass transition temperature (T_g) and cold crystallization temperature (T_{cc}) of PLA with fique indicates a restriction in the mobility of the polymer chains, which favors greater crystallinity in the matrix. This effect contributes directly to the increase in the stiffness of the material, reflected in a higher modulus of elasticity.

The dual utility of fique in materials engineering is further supported by studies focused on its intrinsic properties. The fique fiber is particularly valuable not only for its structural reinforcement capabilities but also for its proven characteristics of sustainability and thermal performance, making it suitable for advanced material design. Research has confirmed the potential of Fique as a sustainable material and thermal insulation for buildings, along with studies detailing its decomposition and thermal conductivity [24]. Furthermore, the physical and mechanical properties of Fique, specifically its low thermal conductivity and high breaking strain, are essential for understanding its performance as a reinforcement and an insulating agent [25]. Its strong resistance to breaking provides the necessary mechanical reinforcement for load transfer and stiffness, while its low thermal conductivity contributes to the overall improved thermal profile of the resulting biocomposite.

Statistical analysis

Table 2 presents the ANOVA test results. These results show that the tensile stress of PLA, compared to PLA composite reinforced with natural fique fibre, has a p-value lower than 0.05, indicating statistically significant differences between the two materials. However, for the modulus of elasticity, no statistically significant differences were observed (p-value = 0.121), which means that the addition of fique fibre does not significantly affect the stiffness of the material under the evaluated conditions

Table 2. ANOVA test results

Property	Source	Sum of squares	Degrees of freedom	Mean square	FO	P
Tensile stress	Material	184.6	1	184.61	23.6	0.001
	Residuals	62.5	8	7.81		
	Total	247.1	9			
Modulus of elasticity	Material	57580	1	57580	3.02	0.121
	Residuals	152736	8	19092		
	Total	210316	9			

Conclusions

The article developed and characterized a PLA filament reinforced with 10 wt. % of alkali-treated fique fiber, analyzing its morphological, thermal, and mechanical behavior to assess its suitability for 3D printing applications. Based on the experimental evidence, the following scientific conclusions are established:

1. The incorporation of fique fiber generated measurable changes in the thermal transitions of PLA, specifically increasing the glass transition temperature (T_g) and cold crystallization temperature (T_{cc}). These modifications indicate a restriction in the mobility of the polymer chain, demonstrating that fique fibers act as nucleating agents that promote crystallization. This behavior coincides with the response observed in other lignocellulose-reinforced PLA systems, positioning fique as a functional thermal modifier.
2. Despite improvements in crystallinity-related transitions, the composite exhibited lower thermal stability, as confirmed by thermogravimetric analysis (TGA). The earlier onset of degradation suggests that the fiber introduces thermolabile components, such as hemicellulose and residual lignin. This finding is crucial for defining safe processing ranges, underscoring the need to optimize fiber purification or consider the use of thermal stabilizers.
3. Mechanically, fique-reinforced PLA achieved a significant increase in stiffness, reflected in an elastic modulus higher than that of pure PLA. This confirms that fique fibers provide effective reinforcement to support the load, transferring stress to the more rigid fiber domains and limiting deformation. This behavior demonstrates the mechanical potential of fique as a reinforcement for biodegradable structural composites.
4. However, a decrease in maximum tensile stress was observed, indicating premature failure of the composite. SEM analysis revealed insufficient fiber-matrix interfacial bonding, pores, and fiber detachment. These microstructural defects act as stress concentration points, explaining the loss of strength despite the increase in stiffness. This highlights the urgent need for improved surface treatments or compatibilizers to maximize mechanical performance.
5. Extrusion and 3D printing tests demonstrated that the developed filament is processable and compatible with standard FDM parameters, with no clogging or thermal degradation during printing. Although it has lower thermal stability, the material maintained its structural integrity during extrusion and layer deposition, demonstrating its potential for the additive manufacturing of biodegradable components with moderate mechanical requirements.
6. The results confirm that fique fiber is a technically viable and promising reinforcement for PLA-based biocomposite filaments, offering sustainability advantages due to its

availability, biodegradability, and high intrinsic strength. A solid foundation is established for understanding its behavior in filament form and identifies key areas for future optimization, such as refinement of chemical treatment, fiber dispersion strategies, and interfacial compatibilization.
7. Future research should focus on improving interfacial adhesion and thermal stability. As these two aspects currently limit tensile strength and processing robustness. Methods such as silane treatments, coupling agents, fiber microrefining, or reactive extrusion could significantly improve performance, enabling the development of high-strength biodegradable filaments suitable for engineering applications.

This study allowed the development and characterisation of a PLA filament reinforced with 10% by weight of fique fibre, evaluating its viability for 3D printing applications. The results showed that the incorporation of fique significantly modifies the thermal and mechanical properties of PLA.

It was observed that the addition of fique fibre increases the glass transition temperature and cold crystallisation temperature, indicating a restriction in the mobility of the polymer chains. However, it also reduces the thermal stability of the material, bringing forward its degradation. In terms of mechanical behaviour, the composite showed higher stiffness compared to pure PLA, although with a decrease in the maximum tensile stress, attributed to the low interfacial adhesion between the matrix and the fibre.

The results obtained show the need to improve the compatibility between the fique fibre and the polymeric matrix. The SEM analysis showed a low interfacial adhesion, with the presence of spaces and voids that affected the mechanical properties. Despite these limitations, the filament obtained proved to be suitable for 3D printing, opening up new opportunities for its application in the manufacture of sustainable and biodegradable parts.

CRediT authorship contribution statement

Sergio Gomez Suarez: review & editing, Writing – original draft; conceptualization, investigation, data curation; **Rolando Enrique Guzman-Lopez**: writing – review & editing, writing – original draft; conceptualization, investigation, data curation; **Roberto Alonso Gonzalez-Lezcano**: writing – review & editing, writing- original draft; conceptualization, supervision.

Conflict of interest

The authors declare that they have no conflict of interest.

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