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# Contribution to manufactured a new thermoplastic biocomposite reinforced with natural fabric of date palm fibers without any treatment

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## ABSTRACT

Although significant progress has been made in the production of biocomposites, persistent challenges remain in the processing, distribution and arrangement of natural fibres. These problems stem mainly from the lack of standardised methods for fibre processing, insufficient access to specialised equipment and time-consuming preparation processes. This work breaks new ground by developing a polylactic acid (PLA) biocomposite reinforced with a fabric of untreated date palm fibres, eliminating costly pre-treatment steps. The digitally controlled hot compression method ensures optimal interfacial adhesion, validated by scanning electron microscopy (SEM) analysis. The main results of this work reveal a significant improvement in mechanical properties (Young's modulus +24%, strength +31%) with 10% fibre, combined with a reduction in costs and environmental impact. The reproducibility of the processes and the biodegradability of the material make it a sustainable solution for light structural applications. The minor defects identified open up avenues for industrial optimisation.

**Keywords:** bio-composite, polylactic acid, date palm fibers  fabric, mechanical manufacturing, scanning electron microscopy.

## INTRODUCTION

In an era prioritizing sustainable energy and eco-friendly materials, industries such as aerospace, energy, and construction are increasingly prioritizing biocomposites reinforced with plant-based fibers. These materials, derived from renewable sources like flax, hemp, and banana plants [1–4], offer a viable alternative to synthetic reinforcements due to their favorable mechanical properties, reduced density, and environmental benefits such as biodegradability and recyclability. Among these natural fibers, date palm derivatives including petiole, rachis, and fibrillium have gained attention for their abundance and versatility. Researchers such as Awad et al. [5], Ghoria et al. [6], and Al-Otaibi et al. [7] have explored their potential as cellulose-rich reinforcements in biocomposites. These materials are typically integrated into two polymer classes: thermoplastics (e.g., polypropylene (PP) [7, 8], polylactic acid (PLA) [1, 5, 9–10]) and thermosets (e.g., epoxy, phenolic resins [11]). Manufacturing methods like extrusion-injection and extrusion-compression [12–13] are commonly employed, often followed by melding techniques (e.g., pressure, vacuum, or contact melding) to shape the final product. These processes require precise temperature control to melt the polymer matrix without degrading the fibers. However, challenges persist in fiber preparation, including intensive extraction steps (e.g., retting, decortication) [14–15] and cost variability depending on techniques and equipment. In a global context focused on sustainability, biocomposites based on natural fibres are emerging as promising alternatives to synthetic materials. Date palm fibres, which are abundant and underused, have remarkable potential as environmentally friendly reinforcements. However, their complex and costly pre-treatment limits their industrial adoption. This study proposes an innovative solution: a PLA matrix biocomposite reinforced with untreated date palm fibre fabrics, manufactured using a digitally controlled hot compression method. The work is structured in three main parts: (1) design and fabrication of the biocomposite, including detailed fibre characterisation and optimisation of compression parameters; (2) assessment of mechanical properties via tensile tests and microstructural analysis using scanning electron microscopy (SEM); (3) discussion of the results, highlighting fibre-matrix adhesion mechanisms and reproducibility challenges. The aim of this systematic approach is to demonstrate the viability of a material that is high-performance, economically competitive, and fully biodegradable, while identifying areas for improvement for industrial applications.

## MATERIALS AND METHODS

### Materials

In order to manufacture the new bio-composite, which is composed of PLA as matrix and date palm fibrillum as reinforcement, we have designed and manufactured an electromechanical mechanism, which enables this bio-composite to be obtained by hot compression. The die, designed to accommodate the PLA/DPFs biocomposite layers, is secured to the lower grip of the universal testing machine. Meanwhile, the punch is fixed to the upper grip, as depicted in Figure 1.

### Methodology

The methodology of the present research work is explained in Figure 2. The characterization procedure of our new bio-composite is broadly divided into three main steps:

Step 1:
- fabrication of DPFs fabric: The fabric was trimmed to the required dimensions, with mass adjusted to either 5% or 10% of the composite's total weight;
- PLA processing: The polymer was manually fragmented into 0.5–1 cm parts and weighed to match the pre-determined composite formulation (PLA/DPFs-5 or PLA/DPFs-10);
- composite sheet production: Layers of PLA and DPFs were hot compressed using a hot compression device, following a predefined full factorial design of experiments (DoE).

Step 2:
- cutting specimens;
- tensile tests;
- carry out scanning electron microscope observations on selected samples to see the quality of adhesion between the DPFs and the PLA and the main structural defects.

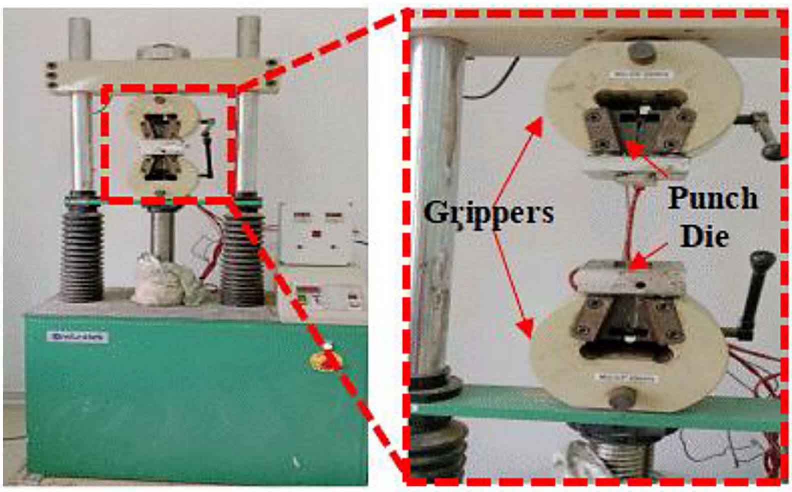


**Figure 1.** Experimental device

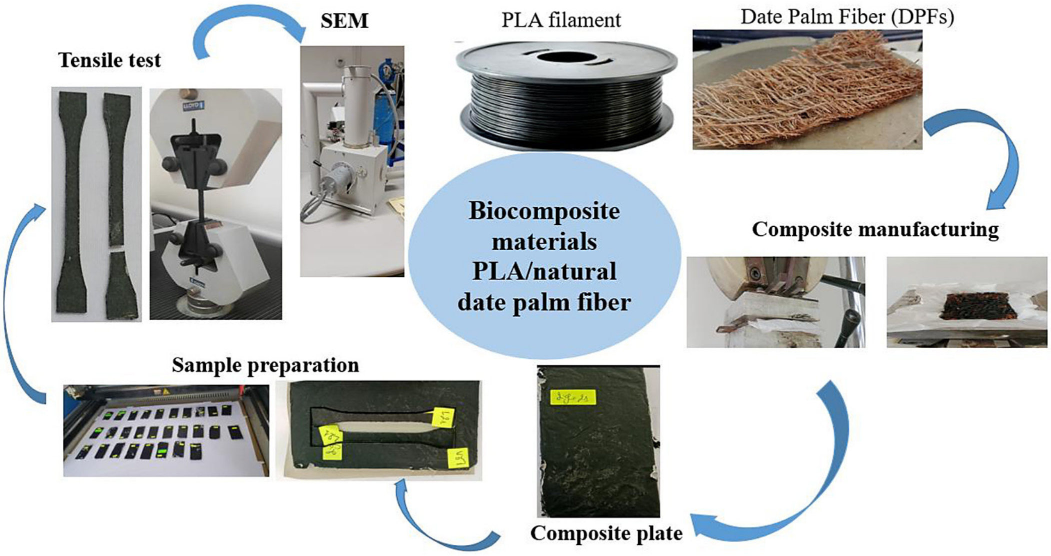


**Figure 2.** Samples manufacturing and testing process for the experiment

Step 3:

Synthesis of the results of this study: determination of the mechanical properties of the biocomposite, state of cohesion DPFs and PLA, etc.

## Description date palm fibers fabric

The observed date palm fiber fabric (Figure 3) exhibits a complex three-dimensional structure characterized by a heterogeneous distribution of fiber diameters, orientations, and waviness. The individual fibers display significant variations in diameter along their length, ranging from finer strands to thicker segments, indicative of natural growth patterns and structural adaptation. This variability may influence the mechanical performance of the fibers, particularly in tensile and flexural properties. The fiber arrangement reveals an intricate network with diverse orientations, including linear, slightly curved, and highly undulated structures. These waviness variations contribute to the overall flexibility and impact resistance of the fabric, as they allow for energy dissipation under mechanical loading. The waviness amplitude and frequency are not uniform, suggesting a natural adaptation to external environmental factors during growth.

In terms of three-dimensional morphology, the fibers exhibit an interconnected, intertwined configuration, leading to variations in thickness across different sections of the material. This spatial variation creates a non-uniform porosity, which may play a role in adhesion properties when integrated into composite materials. The interlacing of the

**Figure 3.** Date palm fiber fabric

fibers forms a semi-rigid framework with potential reinforcement capabilities in polymer matrices. Such structural complexity in natural date palm fiber fabrics presents valuable opportunities for application in bio-composites, particularly in sustainable material development for lightweight and high-strength engineering solutions.

### Testing and characterization

#### *Mechanical testing*

To evaluate the mechanical properties of the composite, tensile testing was performed using a universal testing machine. Test specimens were laser-cut from the composite plates, adhering to dimensions specified by the ISO 527 standard [16]. Laser cutting was selected to ensure clean, precise edges without post-processing and to eliminate challenges associated with traditional mechanical cutting methods, such as delamination or edge deformation.

### Scanning electron microscopy

SEM analysis allows us to provide a qualitative result on our bio-composite. Indeed, a set of images was taken for different samples of the bio-composites to qualitatively evaluate the adhesion to the fiber/matrix interface and determine the nature of the structural defects of the new bio-composite (presence of holes, internal and external microcracks, etc.).

## RESULTS AND DISCUSSION

### Tensile tests of new material

In order to characterize our bio-composite by determining its mechanical properties such as the Young's modulus E, the maximum stress $\sigma_{Max}$ reached and the corresponding strain ε, we opted to carry out a series of tensile tests. In this study, the mechanical properties of the matrix and reinforcement are unknown. Indeed, DPFs of unknown properties are generally recovered from waste abandoned in date palm oasis regions, whereas PLA was recovered from the market without any indication of its properties. For this reason, we opted to divide the study into 3 stages. The first is to study the reinforcement (DPFs) alone, then the matrix (PLA alone) and finally the PLA/DPFs bio-composite.

#### *Tensile test of natural date palm fiber*

The DPF fabrics used in this work are collected from date palm trunks. They are dried, cleaned, separated manually and cut to the desired dimensions. It is noted that DPFs raw materials has been collected for 6 years following the annual maintenance of date palms ranging in age from 10 to 30 years from the governorate of Gabes in southern Tunisia. Figure 4a shows the DPFs (fibrillum) before and after they have been removed from the tree trunk. Figure 4b shows the random shape of the DPFs fabric of plates. There are three type of plates (1, 2

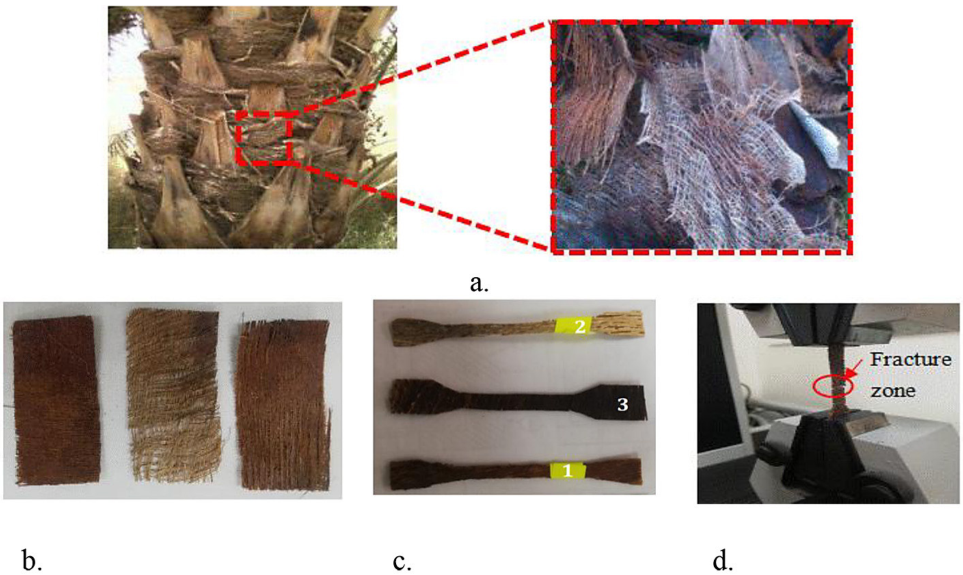


**Figure 4.** DPFs removed from the tree trunk (a), DPFs fabric plates (b), specimens tensile test (c), specimen after fracture (d)

and 3), which will be used later in the development of our bio-composite, where the DPFs fabric varies from one plate to another. Indeed, we find plates of type (2) where the threads of the DPFs fabric are spaced from each other, in this case we have less dense plates. This is not the case for type (3) plates, where the DPFs fabric is denser and more rigid due to the large number of wires that make it up and the rigidity of the connections between its wires. The number of wires and the rigidity of the connections between them of plate type (1) classifies the latter between type (2) and type (3) plate. Figures 4(c, d) show respectively DPFs samples cut in the form of specimens adapted to the tensile testing machine and a DPFs specimen mounted on a tensile testing machine before fracture.

The random shape of the DPFs fabric drastically influenced mechanical properties of the fabric. Indeed, specimen 1, from a denser type 1 plate (Figure 4b and 4c) required more loading until it broke than specimen 3 from the less dense type 3 plate (Figure 4b and 4c). This may later influence the mechanical properties of the new bio-composite. Figures 5(a–d) show the morphology of each of the plate of types 2 and 3. There is a clear difference between the fabric density of each plate. Indeed, for the same surface, plate of type 3 contains more fibers than plate of type 2. It can also be seen that the shape, dimensions and orientation of the fibers on each of the plates are random.

### *Tensile test of PLA*

To characterize our PLA, used here as a matrix, a series of tensile tests on at least seven samples were carried out to determine its mechanical properties. Figure 6 shows the PLA specimens tested after rupture.

Tensile tests were carried out on pure PLA (Figure 7) in accordance with the ISO 527 standard, which enabled us to record a dispersion of 15% for maximum stresses, 12% for strains, and 13% for Young's moduli. These results demonstrate improved consistency compared to previous studies on PLA, such as those by Hamad et al. [17], who reported a 15% dispersion for Young's modulus in recycled PLA, highlighting the influence of processing parameters on variability. Polylactic acid (PLA) in this study exhibits a measured density of 1200 kg/m³ (± 6), aligning closely with the range of 1250–1270 kg/m³ reported by Auras et al. [18] for commercial PLA, though slightly lower, potentially due to minor porosity or additive interactions. The tensile strength of 55

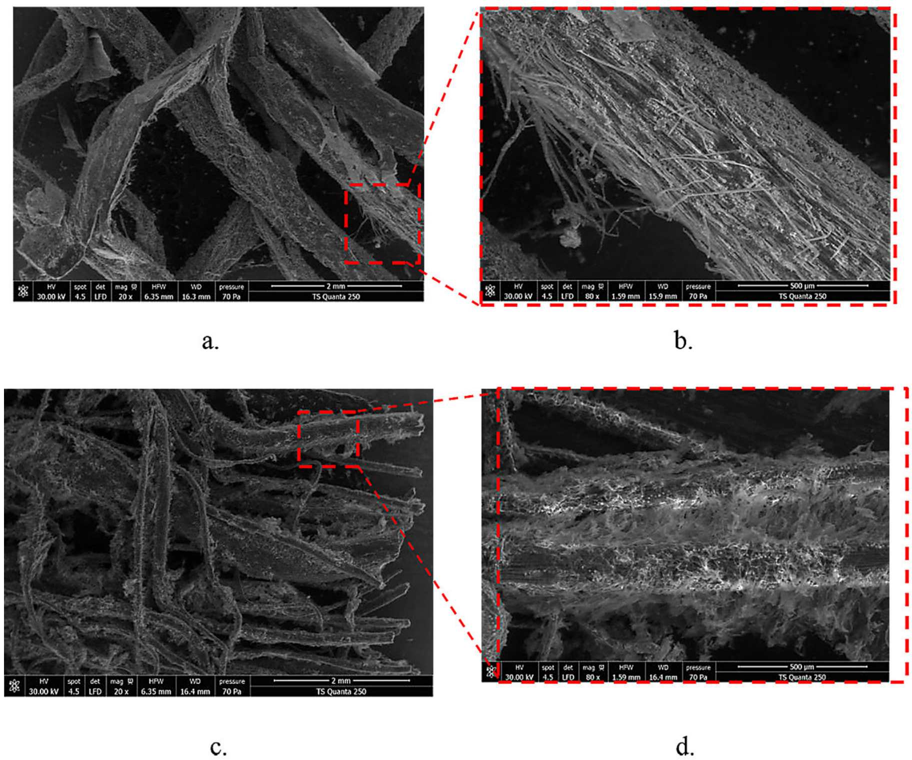


**Figure 5.** SEM observation: morphology of fibers fabric: fibers from specimen 2 (a), zoom on the fiber in sample 2 (b), fibers from specimen 3 (c), zoom on the fiber in sample 3 (d)


**Figure 6.** PLA specimens after tensile tests

MPa (±5) falls within the typical range for pure PLA (50–70 MPa) described by Farah et al. [19], confirming its suitability for semi-structural applications. The elongation at break of 2.2% (±0.4) shows a marked improvement over brittle PLA formulations (often < 2%), approaching values observed by Garlotta et al. [20] for PLA with controlled crystallinity. This suggests enhanced ductility, possibly due to optimized processing conditions. Additionally, the Young's modulus of 3.72 GPa (±0.7) is consistent with the 3–4 GPa range reported by Lim et al. [21], indicating a balanced stiffness typical of unmodified PLA.

The reduced dispersions (≤ 15% across all parameters) compared to earlier works, such as the 40% variability in Young's modulus noted by Saeidlou et al. [22], underscore advancements in manufacturing reproducibility, likely attributable to stricter adherence to ISO 527 protocols and improved material homogeneity.

By achieving lower dispersions and enhanced mechanical consistency, this study addresses the reproducibility challenges highlighted by Saeidlou et al. [22] in PLA processing. The results bridge gaps identified by Farah et al. [19] regarding variability in PLA's tensile properties, while the near-standard density (1200 kg/m$^3$) reinforces its alignment with industrial benchmarks [21]. This work provides actionable insights for optimizing PLA in applications requiring reliability, such as biomedical devices or sustainable packaging.

From microscopic observations through a scanning electron microscope, we were able to record the presence of internal and superficial air bubbles in some specimens before and after rupture (Figure 8a–e). We also noted the presence of superficial cracks in one specimen (Figure 8d) and that there are sometimes fragments of PLA that are not completely melted in another specimen (Figure 8e).

### *Tensile test of PLA/DPFs*

In order to characterize our new PLA/DPFs bio-composite, a series of tensile tests were carried out on test specimens in accordance with the ISO 527 standard (Figure 9). These tests resulted in fractures in different parts of the test specimen

Figure 10 shows the behaviour of the bio-composite with 10% date palm fibers fabric. The improvement in mechanical properties of PLA/

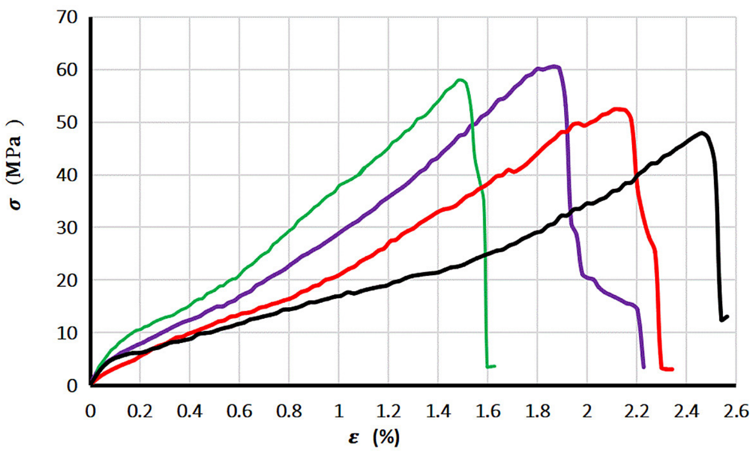


**Figure 7.** Tensile curves of PLA

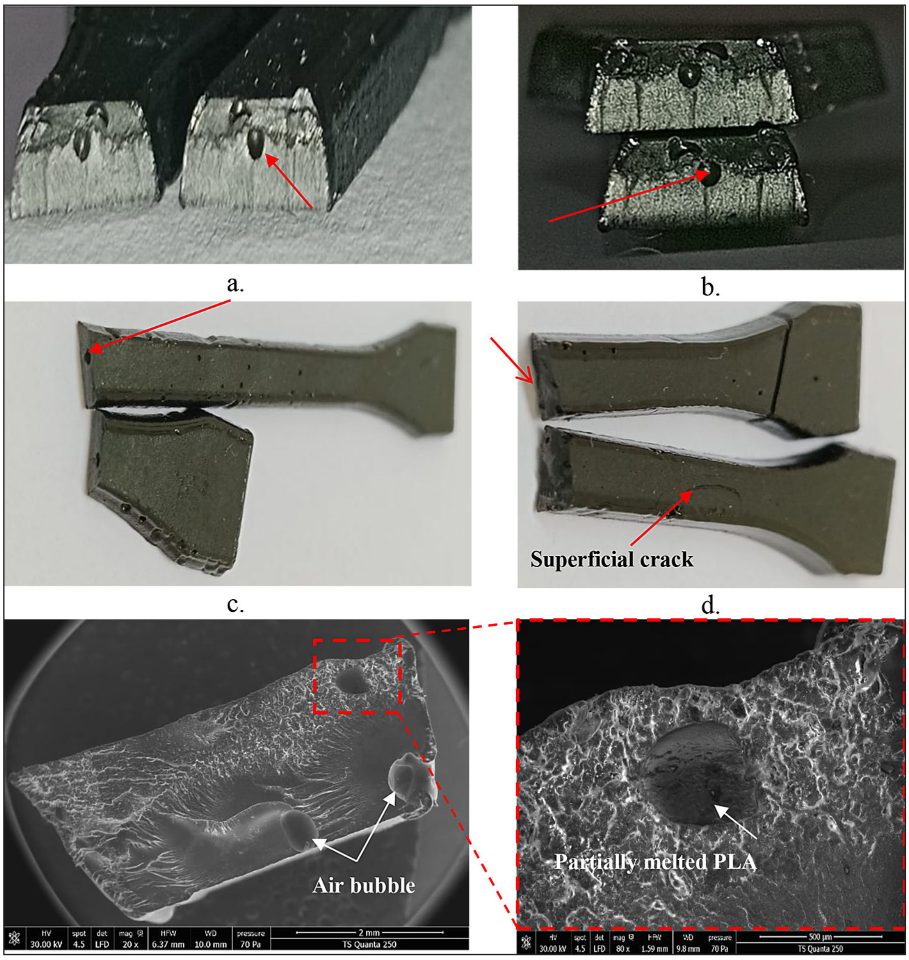


**Figure 8.** SEM observation: morphology of PLA presence of air bubbles (a), zoom of air bubbles (b), presence of air bubbles (c), presence of air bubbles and presence of superficial crack (d), (e) presence of air bubbles and presence of partially melted PLA (e), zoom of partially melted PLA (f)

**Figure 9.** Specimens before and after tensile tests

DPF composites with increasing fiber content (5 to 10%) can be explained by the reinforcement principles of polymer composites. The increase in tensile strength (60 to 80 MPa) and Young's modulus (3.96 to 4.20 GPa) aligns with the rule of mixtures, where rigid fibers (such as DPFs) transfer stress to the PLA matrix, enhanced by the cellulose in the fibers and interfacial adhesion [23–24]. The unexpected increase in elongation at break (2.6 to 3.2%) may result from energy dissipation mechanisms, such as fiber-matrix debonding or fiber pull-out, typical of natural fiber composites [25]. The moderate density decrease (1160 to 1080 kg/m³) reflects the slightly higher density of DPFs compared to PLA, a phenomenon consistent with natural fiber composites [26]. The variability in results (±20 MPa for PLA-DPF10%) is attributed to material loss during melding (PLA thermal degradation) and non-uniform matrix distribution, exacerbated by manual placement of PLA fragments, creating heterogeneous zones. The mechanical superiority of PLA/DPFs-10 (Young's modulus +24%, tensile strength +31% vs. pure

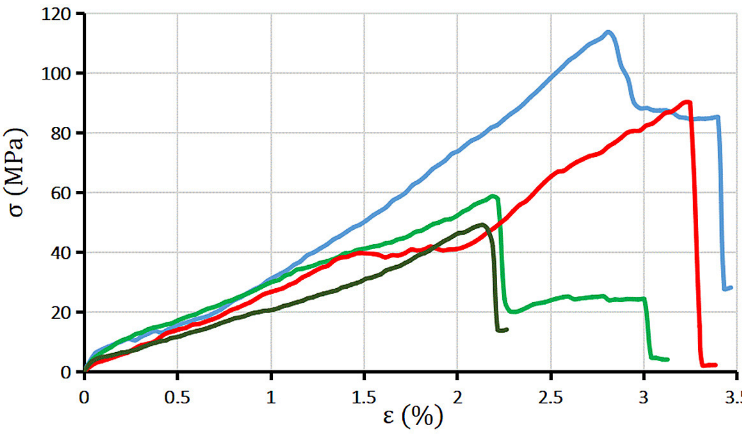


**Figure 10.** Tensile curves for samples of 10% natural DPFs

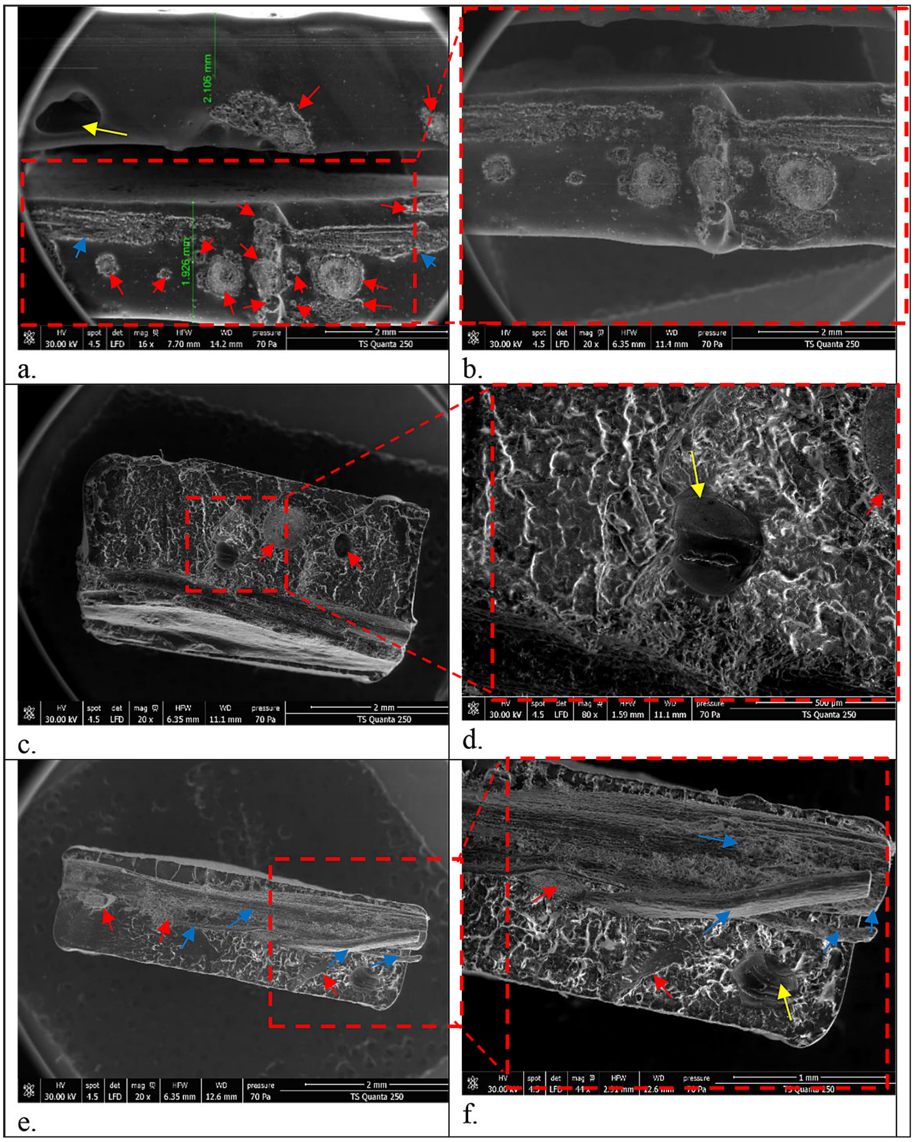


**Figure 11.** SEM image of some PLA/DPFs structures: (a) presence of partially melted PLA fragments, (b) zoom on the cut fiber, (c) presence of cut fiber and presence of partially melted PLA fragments, (d) zoom on the presence of partially melted PLA fragments, (e) presence of partially melted PLA fragments, presence of cut fiber and presence of transverse fiber, (f) zoom on the presence of partially melted PLA fragments, zoom on the cut fiber and zoom on transverse fiber

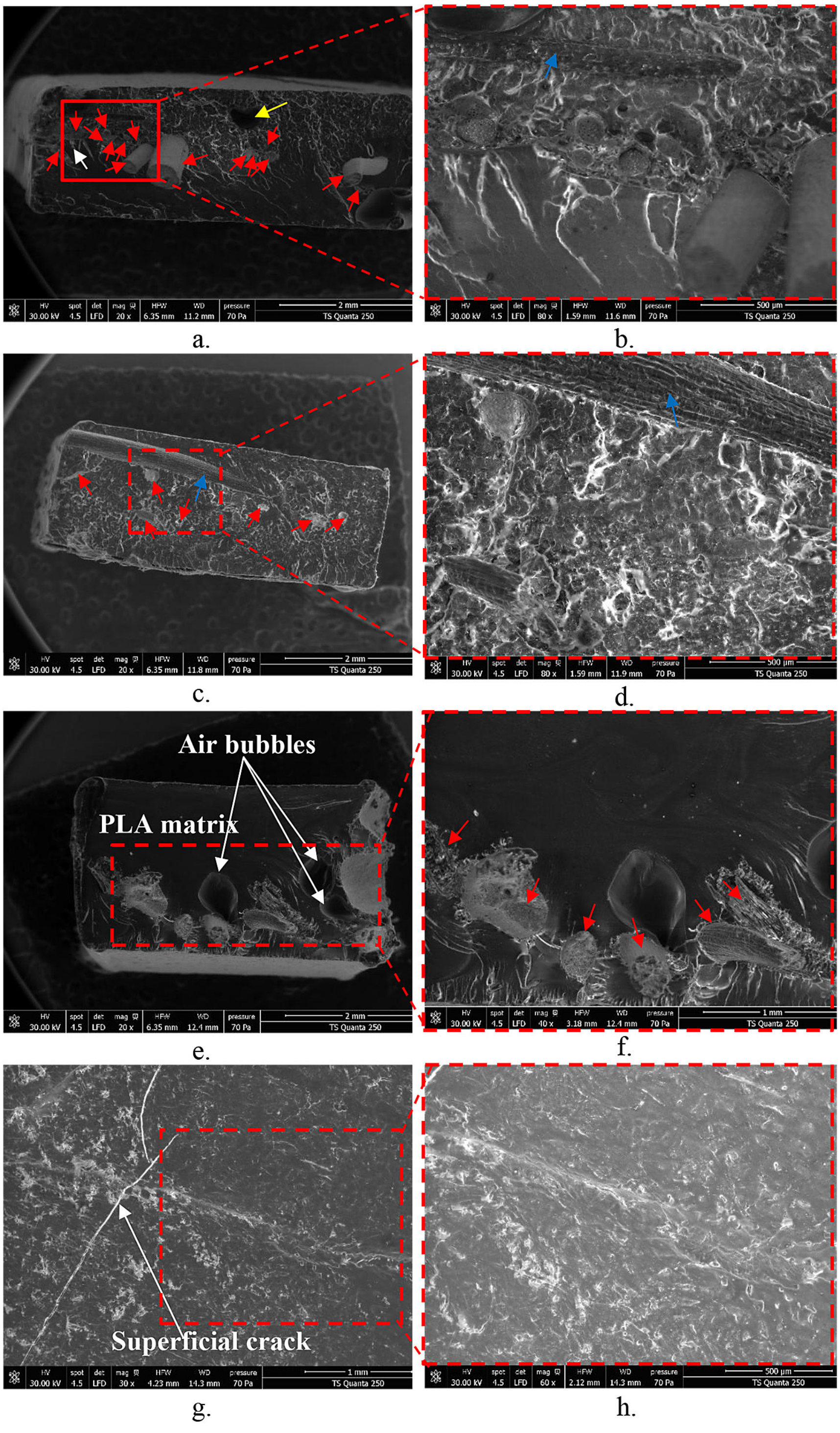


**Figure 12.** SEM images of PLA/DPFs samples: (a) presence of cut fiber and presence of partially melted PLA fragments, (b) zoom on transverse fiber, (c) presence of cut fiber and presence of transverse fiber, (d) zoom on transverse fiber, e. Presence of air bubbles, (f) zoom on the cut fiber and zoom on the presence of air bubbles, (g) presence of superficial crack, (h) zoom of crack

PLA) corresponds to optimal fiber loading, avoiding agglomeration while maximizing reinforcement. These results, while consistent with the literature, underscore the importance of optimizing manufacturing processes to reduce variability.

## Scanning electron microscopy

In addition, an analysis of the fracture surfaces of specimens broken in tension revealed good adhesion between the fibers and the matrix in the majority of specimens. Figures (11a, d and f) show that in some samples we recorded the presence of partially melted PLA fragments, especially in the case of thick plates, which can have a negative impact on the resistance of the structure. This defect is mainly due to insufficient PLA melting temperature or insufficient pressure force. It should be noted that the bio-composite plates obtained do not have the same thicknesses. For example, Figure 11a shows two samples of different thicknesses. The presence of holes (Figures 12e, 12f) is caused by air entrapment in the PLA during hot compression, while the presence of surface cracks (Figure 11g) is essentially caused by the non-compliance with the adequate cooling rate of the structure. The presence of broken fibers is, on the contrary, a sign of efficient force transfers between matrix and fiber thanks to good adhesion at the interface, whereas the presence of unbroken transverse fibers (Figures 11a–f and Figures 12a–f) proves that these fibers have not participated directly in the longitudinal resistance of the bio-composite specimens, but they do participate directly in its transverse resistance.

## CONCLUSIONS

This study successfully developed an innovative biocomposite based on PLA reinforced with untreated date palm fiber fabric using a digitally controlled hot compression method. Key findings revealed significant improvements in mechanical properties: a 24% increase in Young's modulus (4.20 GPa vs. 3.72 GPa for pure PLA) and a 31% enhancement in tensile strength (80 MPa vs. 55 MPa) with 10% fiber content. These improvements are attributed to optimal fiber-matrix interfacial adhesion, validated by SEM analysis, and the three-dimensional fiber structure, which promotes energy dissipation. The absence of fiber pretreatment reduces production costs and environmental impact while preserving the material's biodegradability.

However, defects such as air bubbles, superficial cracks, and partially melted PLA fragments were identified, primarily linked to compression parameters (temperature, pressure) and uneven cooling. These observations highlight the need to optimize manufacturing conditions to enhance composite homogeneity.

Future research directions include:

1. Industrial optimization of compression parameters (pressure, temperature, duration) to minimize defects and standardize processes.
2. Exploring fiber content beyond 10% to evaluate the trade-off between mechanical reinforcement and agglomeration risks.
3. Automating fiber distribution to reduce property variability and enable large-scale production.
4. Applying the biocomposite in sectors requiring lightweight and durable materials, such as eco-friendly packaging, lightweight construction elements, or biodegradable automotive components.

In conclusion, this work demonstrates the potential of untreated date palm fibers as competitive reinforcements for biocomposites, paving the way for sustainable and economically viable solutions for industry. The identified challenges offer concrete avenues for future research, advancing the adoption of these materials in a circular economic framework.

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