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Mechanical Properties of Pineapple Braided Fabric Reinforced Epoxy Matrix Composite Fabricated via Vacuum-Assisted Resin Infusion Moulding

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ABSTRACT

Fibres and fabrics obtained from lignocellulosic materials have attracted attention as reinforcements in polymer composites due to their competitive mechanical and ecological benefits. While the potential of randomly oriented pineapple leaves fibres (PALF) in composites have explored in previous studies, the mechanical behaviour of braided PALF fabric composites fabricated via vacuum-assisted resin infusion moulding (VARIM) remains relatively unexplored. In this study the tensile, compression and flexural strengths of epoxy-based composite containing 40 vol.% braided pineapple fabrics, fabricated using VARIM, for load carrying applications were investigated. The results revealed that the three-layered unbleached pineapple braided fabric composites exhibited a tensile strength of 845.1 MPa, the ones from bleached fabrics exhibited a higher tensile strength of up to 996.7 MPa, attributed to enhanced fibre-matrix adhesion resulting from the bleaching process. Additionally, the bleached fabric composites displayed a superior flexural strength of 55.6 MPa for the three-layered configurations, highlighting further the potential of both the bleaching and braiding processes for higher load carrying capacity applications. The results underline the potential of the layered braided pineapple fabric composites, especially the bleached variants, for engineering applications that demand a balance of strength, stiffness, and flexibility. This study not only advances the understanding of the braided PALF fabric composites but also highlights their viability as sustainable alternatives to synthetic fibre reinforcements. By exploiting the properties of pineapple fibre bundles and the VARIM fabrication technique, this research contributes to the endeavours to develop high-performance and eco-friendly composite materials for a diverse engineering application.

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INTRODUCTION

Sustainable development in a modern society partly has been closely linked to the adoption of natural-based materials in engineering applications, processes and in our daily lives. As the industrial and the socio-economic sectors focus on promoting transition towards greener alternatives, natural based-fibres are becoming an important focus, offering both ecological and financial benefits (Abera, 2024, Feng *et al.*, 2024, Prasad *et al.*, 2024). However, replacing conventionally used synthetic materials with natural based fibres poses new technological and environmental challenges, particularly in ensuring that these alternatives meet the performance requirements of various applications (Feng *et al.*, 2024; Elfaleh *et al.*, 2023; Kamarudin *et al.*, 2022; Sanjay *et al.*, 2016).

Natural fibres have been utilised for centuries in the production of basic items such as textiles, baskets, and roofing materials. Yet, toward the end of the 20th century, their role began to expand as they were recognized for their potential to replace man-made fibres, including glass and carbon, in polymer composites (Ahmad and Zhou, 2022; Mohammad, 2014). This shift has been driven by the increasing need to reduce waste accumulation and environmental impacts of such materials, which are often derived from non-renewable resources. Numerous review articles have highlighted the significant promise of natural based fibres for the reinforcement of polymer composites, particularly in applications requiring high strength and lightweight materials (Nagaraja *et al.*, 2024; Mahajan *et al.*, 2022; Thyavihalli Girijappa *et al.*, 2019).

Because of its abundance in cellulose, accessibility, and biodegradability, pineapple leaf fibre (PALF) has attracted particular attention among the natural based fibres. (Sethupathi *et al.*, 2024; Neto *et al.*, 2013). As a by-product of pineapple cultivation, PALF offers a sustainable, low-cost alternative to synthetic fibres, contributing to waste valorisation and resource efficiency. While these fibres have traditionally been overlooked, recent studies have demonstrated their potential in reinforcing polymer matrices, particularly in the fabrication of composite materials with high strength-to-weight ratios (Elfaleh *et al.*, 2023; Leão *et al.*, 2015).

In the fabrication of fibre-reinforced composites, the method of processing plays a critical role in determining the mechanical properties of the final product (Maiti *et al.*, 2022; Ho *et al.*, 2012).

Vacuum-Assisted Resin Infusion Moulding (VARIM) has emerged as an effective manufacturing technique that ensures uniform distribution of resin through the fibre network, minimizing void content, and enhancing the overall quality of the composite (Shen *et al.*, 2024; Agwa *et al.*, 2022). VARIM involves the use of a vacuum to draw the resin into a preformed fibre reinforcement, creating a high-fibre-volume composite with optimal adhesion between the fibre and the matrix (Sayam *et al.*, 2022). This method is particularly advantageous for large-scale production of composites due to its low cost, scalability, and ability to produce complex shapes with minimal waste (Zabihi *et al.*, 2018).

The presented study was aimed at investigating the mechanical properties of braided pineapple fabrics reinforced epoxy matrix composites fabricated via VARIM. By examining the tensile, flexural, and impact properties of the composite, this research seeks to evaluate the potential of the pineapple leaf fibres as a sustainable reinforcement material for production of high-performance composites.

METHODS AND MATERIALS

Materials

Vacuum-assisted resin infusion moulding, epoxy resin, hardener, and pineapple leaf fibres are the materials used to create the reinforced epoxy matrix composite for braided pineapple fabrics.

Methods Preparation of pineapple leaf fibres (PALF)

To ensure that the fibres maintained their full strength and structural integrity, pineapple leaf fibres were extracted using the decortication method without retting. Initially, pineapple leaves were disassembled using a mechanical decorticator to separate the raw fibres from the leaf material by removing non-fibrous components such as the parenchyma tissues and waxy cuticle. Following decortication, any leftover debris was manually removed from the fibres. Following the extraction of the fibres, a thorough wash was performed to eliminate any remaining sap or non-fibrous materials. To guarantee even drying and moisture removal, the fibres were first air-dried for 24 hours in an open environment before drying in an oven for 4 hours at 60 °C.

The fibres were spun into yarns followed by braiding into fabric as shown in Figure 1 using a 16-carrier braiding machine. For the best load transfer between the fibres and the matrix during composite manufacturing, the braid angle was fixed at 30° (Jang *et al.,* 2024). The braided fabric was then cut into 300 mm × 300 mm sections for use in the vacuum-assisted resin infusion moulding process to create composite panels.

Figure 1: Pineapple yarns and braided fabrics

Vacuum-assisted resin infusion moulding (VARIM)

A flat mould of size 300 mm × 300 mm was used. The mould was prepared by cleaning and treating the surface using a mould releasing agent. Multiple layers of the braided pineapple fabric (up to 3 layers) were stacked in the mould to create the composite laminate for investigating the effect of fabric content on mechanical properties. The stacked fabric layers were enclosed in a vacuum bagging film, and a resin inlet and vacuum outlet were attached. A peel ply and breather cloth were placed on top of the fabric layers to ensure uniform flow of resin and vacuum distribution. The resin-hardener ratio was 10:1 ratio. Degassing was done to remove air bubbles. Under vacuum pressure of 80 kPa, the resin was infused into the fabric stack until complete impregnation was achieved. The vacuum was maintained for an additional 30 minutes to remove excess resin and ensure minimal voids. The infused laminate was cured at room temperature in 24 hours. This was followed by post-curing at 80°C for 2 hours to enhance the cross-linking of the epoxy resin. The composite laminate was carefully demoulded and cut into test specimens as per ASTM standards.

Fibre characterization

The diameter of the pineapple leaf fibres was measured using a micrometre at five different points. Single fibre bundle tensile strength tests were conducted as per ASTM D3822.

Composite testing

Tensile test

Tensile test specimens were cut from the composite laminate according to ASTM D3039 dimensions (250 mm × 25 mm × laminate thickness). The test specimens were subjected to uniaxial tensile loading on a Universal Testing Machine (UTM) having a load cell of 10 kN (Zwick Roell, Z010). The crosshead speed was 2 mm/min. The strength, modulus, and elongation at fracture of each specimen were recorded.

Flexural test

The specimens for the flexural tests were prepared as per ASTM D790 (125 mm × 12.7 mm × laminate thickness). The tests were conducted using a three-point bend on a UTM (Zwick Roell, Z010) at a span-to-depth ratio of 16:1. The flexural strength and modulus of the specimens were calculated.

RESULTS AND DISCUSSION

Tensile properties of pineapple fibres, yarns and the braided fabrics

Table 1 shows the summary of the tensile properties of the pineapple fibres, yarns, and the braided fabrics, both the bleached and the unbleached ones. There is a clear indication of the influence of the fibre treatment process on the tensile properties. The results show that the unbleached pineapple fibres exhibited average tensile strength of 196.2 ± 17.0 MPa after fracture. In contrast, the bleaching process generally caused a decrease in the average tensile strength of the fibre bundles, while increasing the elongation after fracture by 1.56%. The changes observed in the tensile properties can be attributed to the elimination of the binding components of the fibre bundles, i.e. lignin and hemicellulose, during the bleaching process. The removal of the components lowered the fibre bundle's structural strength while increasing its flexibility (Abolore *et al*., 2023).

A similar pattern was seen when the fibre bundles were spun into yarns. The tensile strength and elongation after fracture of the unbleached fibre yarns were 334.2 ± 21.5 MPa and 4.9%, respectively while those of the bleached fibre yarn were 241.6 ± 28.3 MPa and 6.4%, respectively. Similarly, the braided fabrics also followed the same trend, whereby the bleaching process reduced the tensile strength by 31.8 MPa while increasing the elongation after fracture by 2.3%. Since the reduction in the tensile strength and the increase in elongation after fracture in the bleached fabrics are in consistence with those of the fibres and the yarns, it can be inferred that the observed changes are accredited to the elimination of lignin and hemicellulose during bleaching as also suggested previously (Alam *et al.*, 2014, Rayung *et al.*, 2014).

Tensile properties of the braided pineapple fabrics composite

The tensile strength of the braided pineapple fabric composites prepared from unbleached yarns, increased significantly with the increase in the number of layers as shown in Figure 1. A single-layered composite exhibited a tensile strength of around 289.1 MPa, which increased to 512.4 MPa with two layers, and 845.1 MPa with three layers, respectively. This progressive increase in the tensile strength is attributed to higher volume fractions of the fibre yarns in the multi-layered composites, which enhances the distribution of the load and subsequent mechanical reinforcement. The unbleached fibres maintained their natural structure, contributing to the composite's strength. However, failure in the unbleached composites primarily occurred through fibre pull-out, and matrix cracking as suggested previously (Wasik 2005). The fibre pull-out was more evident due to the presence of natural waxes and impurities, which weakened fibre-matrix bonding as more stress concentration points developed and the layers got separated under the load (Lin *et al*., 2023).

The results reveal further that the tensile strength of the braided pineapple fabric composites prepared from the bleached yarns also increased with the increase in the number of layers. However, their strengths had relatively higher values, with each layered composite having the tensile strength of 352.1 MPa, 643.5 MPa and 996.7 MPa, respectively. The resulting improvement in the tensile strength of the composites prepared from the bleached pineapple braided fabric can be attributed to enhanced adhesion between the bleached fibres and the epoxy matrix. Essentially, the bleaching process improved the fibre-matrix adhesion probably due to development of surface roughness.

A tensile strength of around 171.2 MPa has been reported for unbleached PALF-reinforced epoxy composites by Hoque *et al*. (2021), which is lower than 845.1 MPa obtained for the unbleached braided fabric in this study, cementing further the contribution of the braiding process.

Compressive strength of pineapple braided fabrics composite

The compression strength of the composites produced from bleached and unbleached pineapple braided fabrics are given in Figure 2. There is no significant difference observed between the compression strength of the composites made from the bleached fabrics (1901.1 MPa) and that of the unbleached fabrics (1879.2 MPa) for single-layered composites. However, as the number of layers were increased, the difference in the compression strength became more apparent. The compressive strength of the composites with respect to the bleaching of the fabrics increased by 413.4 MPa and 573.1 for two-layered and three-layered composites, respectively. Despite these remarkable changes being attributed to the increase in the rigidity of the composite due to the layers and thickness increase, the bleached fibres' flexibility and uniformity also contributed to better load distribution and transfer which enhanced the compression resistance in the composite as suggested in other studies (Wulandari *et al.*, 2023; Rayung *et al*., 2014).

Table 1: Summary of tensile properties of fibre bundles, yarn and braided fabric

Material Type	Treatment	Tensile Strength (MPa)	Elongation After Fracture (%)
Pineapple Fibre	Unbleached	196.2 ± 17.0	3.5
	Bleached	162.6 ± 21.1	5.1
Fibre Yarn	Unbleached	334.2 ± 21.5	4.9
	Bleached	241.6 ± 28.3	6.4
Braided Fabric	Unbleached	289.7 ± 18.4	6.1
	Bleached	257.9 ± 21.0	8.4

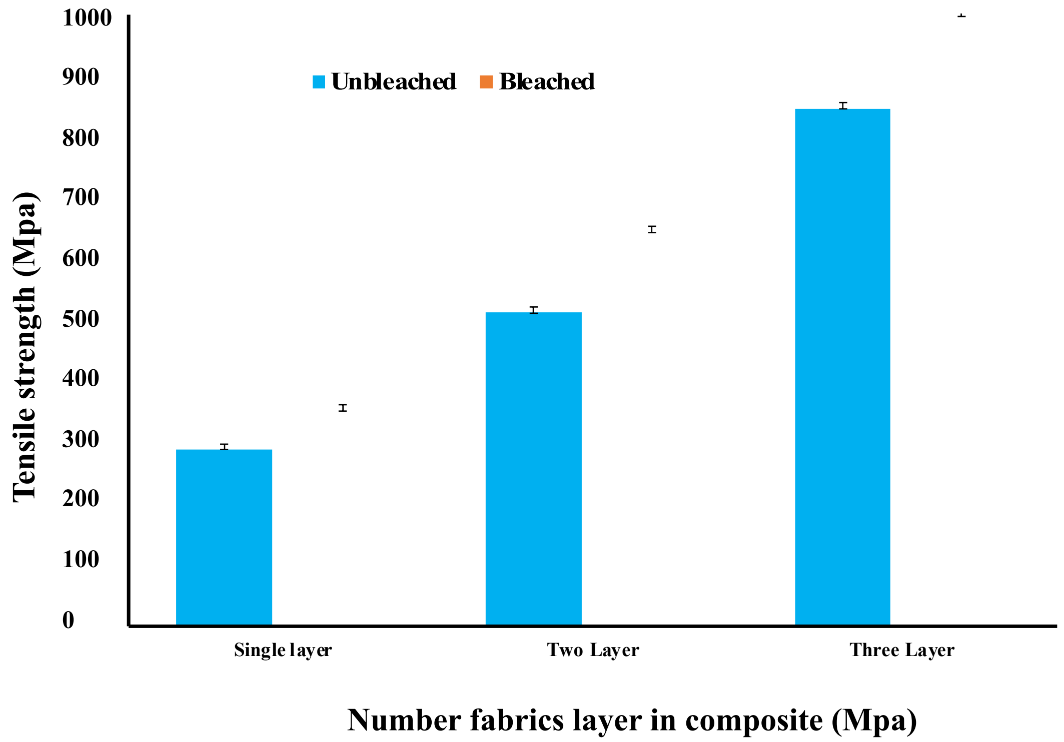

Figure 1: Tensile strength of pineapple braided fabric composite

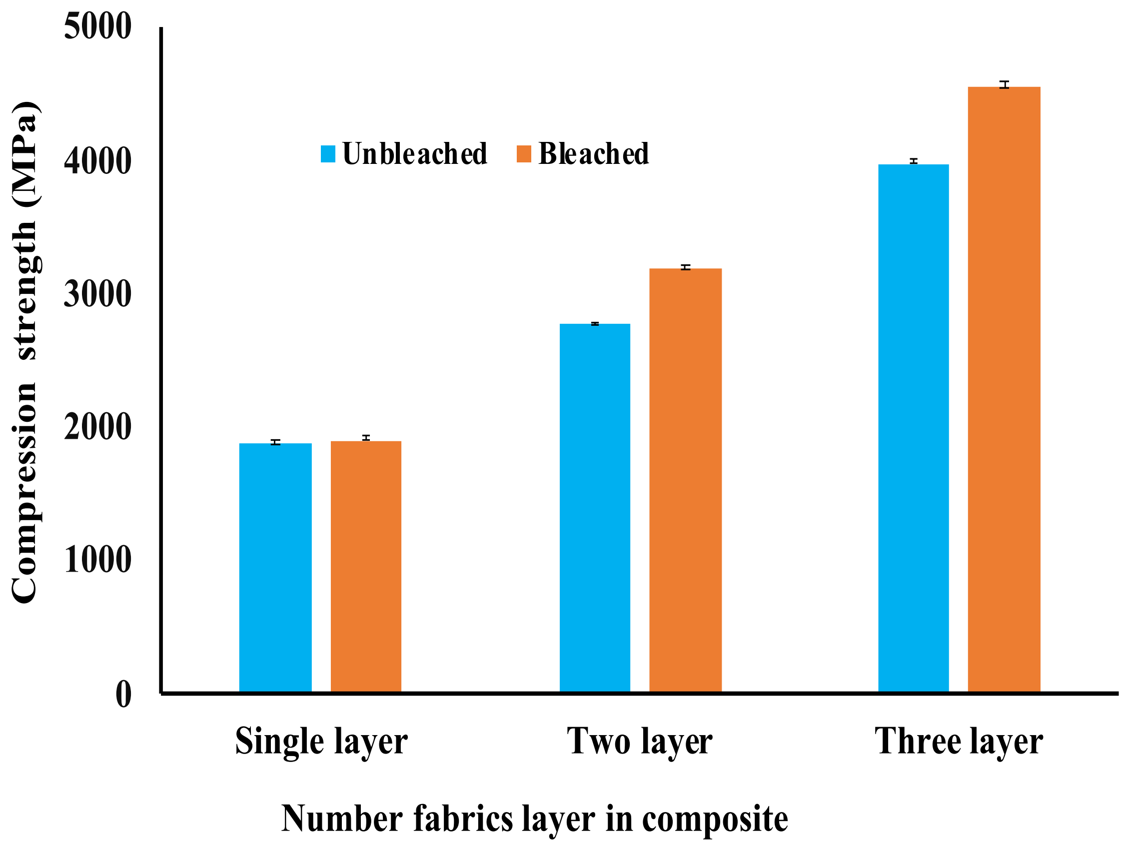

Figure 2: Compressive strength of pineapple braided fabric composite

Flexural strength of composite pineapple braided fabrics

The results of the flexural strength of the composites made from the unbleached and bleached pineapple braided fabrics given in Figure 3 demonstrates further a clear influence of the bleaching process on the mechanical properties. It is shown that the composites from the bleached fabrics had remarkably higher flexural strength at all layers. The remarkable difference was very clear for the three types, where the flexural strength due to the bleaching process was increased by 6.9 MPa, 7.6 MPa, 13.2 MPa for the single, double and triple layered composites, respectively. The flexural strength of the single layered composite produced from unbleached fabrics was 23.4 MPa**,** while the composite from the bleached fabrics exhibited a higher strength of 30.3 MPa**.** The corresponding flexural strengths of the double and triple layered composites obtained from the unbleached and bleached fabrics are 35.6 MPa and 43.2 MPa; and 42.4 MPa and 556.3 MPa, respectively**.**

The increase in the flexural strength of the bleached fabric composites can also be attributed to enhanced bonding between the breached fabrics and the epoxy matrix due to the removal of non-cellulosic components during the bleaching process. The treatment process likely improved the fibre-matrix interaction as also suggested in other studies (Hosseini *et al.*, 2023; Sawpan *et al.*, 2012).

The unbleached fabric composites, on the other hand, demonstrated greater rigidity, especially in the multiple layered configurations, despite their lower flexural strength. This makes them appropriate for applications that demand a balance between strength and environmental sustainability (Ismail *et al.*, 2022). The results demonstrate further that although the composites produced from the bleached fibres had higher flexural strength than those from the unbleached fabrics both products are still good. Their utilisation will rely on the particular mechanical needs of the intended application.

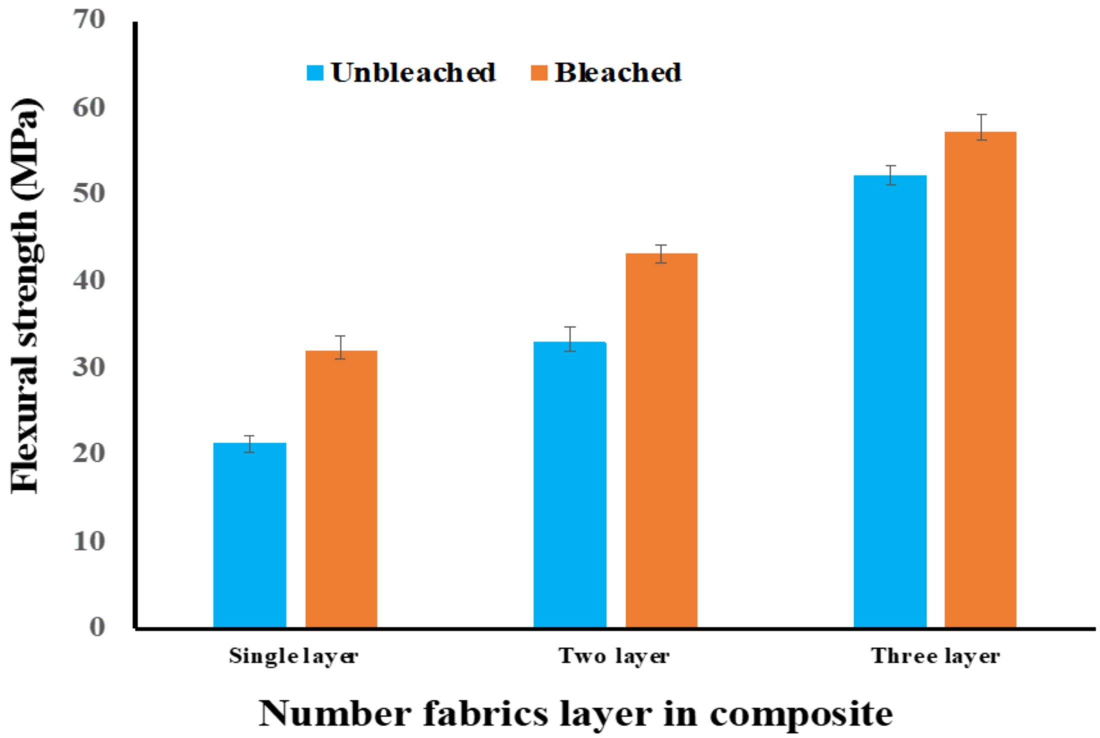

Figure 3: Flexural strength of pineapple braided fabric composite

This study found that three-layered composites from bleached fabrics had a significantly greater flexural strength of up to 55.6 MPa compared with 15 MPa reported previously in the work of Mohamed *et al*. (2021) for PALF composites. This is another demonstration that an optimised bleaching treatment improves fibre-matrix adhesion and when combined with the braiding process further increase in performance is achieved.

The works by Hadi *et al*. (2022) and Santulli *et al*. (2022) also have highlighted the potentials of PALF composites in applications where tensile and flexural properties are required. However, the results presented in these previous works are relatively less than those reported in our study. The observed improvement in mechanical strength of the composites reported in our work, suggest further the potential of the PLAF composites for high-performance applications.

CONCLUSIONS

This study has demonstrated that pineapple leaf fibres (PLF) can be extracted and processed into yarns and fabrics using conventional processes. Bleaching of the fibres improves the flexibility of the fibres. This was manifested by an increase in the elongation after fracture by 1.6%, 1.5% and 2.3% for fibre bundle, yarn and braided fabric, respectively. On the contrary the bleaching process reduces the tensile strength of the fibre bundle, yarn and the braided fabric by 33.6 MPa, 92.6 MPa and 31.8 MPa, respectively. The observed changes are attributed to the removal of lignin and hemicellulose which act as matrices to cellulose in the fibre bundle's cell wall. These changes also generally impacted the tensile, compression and flexural properties of the produced composites.

The tensile strength of the composites produced from the bleached fabrics increased to 352.1 MPa, 643.5 MPa and 996.7 MPa for the single layered, double layered and triple layered composites, respectively. This was an indication that the bleaching process strengthened the fibre-matrix interfacial bond enhancing the load transfer between them and the reinforcement potentials of the braided fabrics. The same trend was observed in the compression and the flexural strength.

The impact of the bleaching process on the compression strength was vivid only for the double layered and triple layered composites where the compression strength increased by 413.4 MPa and 573.1 MPa, respectively. On the flexural strength, the bleaching process improved the strength by 6.9 MPa, 7.6 MPa, 13.2 MPa for the single, double and triple layered composites, respectively.

Although the bleaching process reduces the strength of the fibre bundles due to losses of the cell wall binding matrices, its impact on the improved mechanical performance of the composites was quite evident in this study. We therefore recommend further exploration on the potential of the bleaching and the braiding processes for productions of epoxy-based composites for mechanical load-bearing applications.

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