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Mechanical Characterization of Eco-Friendly Composites: Green Epoxy Resin Reinforced with Coir Fibers

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Abstract

The increasing demand for sustainable materials has fostered the development of natural fiber-reinforced composites as eco-friendly alternatives to petroleum-based systems. This work investigates the mechanical performance of GreenPoxy resin reinforced with coir fibers through a comprehensive experimental program. Fiber properties were first characterized by density and tensile tests, while the resin was evaluated under tensile and flexural loading. Composite laminates were then fabricated by hand lay-up using 3% and 6% fiber volume fractions, with both untreated and retted fibers. Mechanical behavior was analyzed using Taguchi design and ANOVA to assess the effects of fiber treatment and content. Untreated fibers displayed slightly higher intrinsic strength, while mercerization enhanced fiber–matrix adhesion, particularly at higher fractions. The composites exhibited promising properties, confirming the potential of coir/GreenPoxy systems for sustainable structural applications.

Keywords: Sustainable composites; Coir fibers; GreenPoxy; Taguchi; Mechanical characterization

1. Introduction

Composite materials are vital in aerospace, automotive, civil, and marine engineering for their strength-to-weight ratio, corrosion resistance, and design flexibility. Increasing concern over climate change and resource dependence is prompting the search for sustainable alternatives. (Faruk et al., 2012a; Mohanty et al., 2002; Pickering et al., 2016).

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Natural fibers such as flax, hemp, jute, sisal, and coir are increasingly recognized as promising reinforcements for sustainable composites. These fibers are renewable, low-cost, biodegradable, and exhibit adequate mechanical performance for semi-structural applications (Dinkar & Kumar, 2025; Jawaid & Abdul Khalil, 2011; John & Thomas, 2008; Rangappa et al., 2022). Among them, coir fibers, derived from coconut husks, are particularly abundant in tropical regions and feature a high lignin content, which enhances their durability and resistance to microbial degradation (Satyanarayana et al., 2007). Despite their relatively lower stiffness compared to bast fibers, coir fibers offer good toughness, high elongation at break, and potential for use in lightweight, eco-friendly composites (Hasan et al., 2021).

Parallel to reinforcement development, the choice of a suitable polymer matrix is crucial. Polymer matrix composites (PMCs) are classified mainly by the type of polymer used as matrix. Thermosetting resins such as epoxies, unsaturated polyesters, vinyl esters, phenolics, dominate structural applications because of their excellent adhesion, dimensional stability, and thermal/chemical resistance, though they are brittle and non-recyclable (Álvarez et al., 2025). Thermoplastic matrices including polypropylene (PP), polyethylene (PE), polyamide (PA), among others, are tougher, impact-resistant, and recyclable, but their higher viscosity complicates fiber impregnation; biodegradable thermoplastics like PLA further expand their use in green composites (Biron, 2018). Elastomeric matrices are used where high elasticity (Ribeiro et al., 2019), damping, and energy absorption are required, as in vibration isolators, tires, and flexible seals (Mandlekar et al., 2022). More recently, bio-based polymers such as GreenPoxy, polylactic acid (PLA), polyhydroxyalkanoates (PHA), and lignin- or starch-based resins have emerged as sustainable alternatives, reducing dependence on fossil resources while enabling partially or fully renewable composites. Conventional epoxies provide excellent mechanical and thermal performance, but their petroleum origin poses sustainability challenges. GreenPoxy resins, developed by Sicomin, are partially bio-based epoxies that incorporate renewable carbon content while maintaining the mechanical and processing characteristics required for structural composites (Sicomin Composites, 2023).

A major challenge in natural fiber composites lies in achieving strong and durable fiber–matrix adhesion. Lignocellulosic fibers such as coir, flax, or jute are inherently hydrophilic, owing to their high cellulose, hemicellulose, and lignin content, whereas most polymer matrices, particularly the thermosetting and thermoplastic resins are hydrophobic (Jawaid et al., 2017). This mismatch at the interface often leads to poor stress transfer, void formation, moisture absorption, and ultimately reduced mechanical performance of the composite (Faruk et al., 2012b; John & Thomas, 2008; Mohanty et al., 2002). To mitigate these issues, a variety of surface treatments have been explored to modify the fiber chemistry and morphology. Among them, alkali retting (NaOH treatment) is one of the most common approaches, as it effectively removes hemicellulose, pectin, waxes, and other amorphous constituents, exposing more crystalline cellulose and increasing surface roughness (Błędzki & Gassan, 1999; Satyanarayana et al., 2007; Varma & Chandran, 2025). These changes promote mechanical interlocking and enhance chemical compatibility with the resin. In addition, retting reduces fiber diameter and increases aspect ratio, both of which contribute to better stress transfer. However, the treatment parameters (concentration, temperature, duration) must be carefully controlled, since excessive alkali exposure can damage cellulose chains and degrade intrinsic fiber strength (Goyat et al., 2025). Equally important is the optimization of fiber content (volume fraction), as too low reinforcement fails to improve stiffness or strength, while too high content can cause fiber agglomeration, poor wetting, and processing difficulties (Lacerda & Ferreira, 2021; Montgomery, 2017).

This study characterizes the tensile and flexural properties of hand lay-up fabricated GreenPoxy composites reinforced with untreated and retted coir fibers at varying volume fractions, employing Taguchi and ANOVA to optimize parameters and assess the impact of treatment on the sustainable composite's performance.

2. Materials and Methods

2.1. Design of Experiments

The mechanical performance of natural fiber–reinforced polymer composites is highly dependent on processing parameters, particularly fiber content and interfacial adhesion. Among these, fiber volume fraction and surface

treatment play a decisive role in balancing reinforcement efficiency with processability. Accordingly, these two factors were selected as control variables in this study, with their respective levels detailed in Table 1.

Table 1 – Control variables considered in the composite fabrication.

Table 1. Control variables considered in composite fabrication.

Symbol	Parameter	Level 1	Level 2
A	Fiber surface treatment	NaOH treatment	Without treatment
B	Fiber volume fraction	3%	6%

Based on the defined control variables and their respective levels, the experimental design was structured using a Taguchi L_4 orthogonal array. This approach enables a systematic evaluation of the influence of each factor on the composite properties while minimizing the number of required experiments.

2.2. Retting treatment

Approximately 60 g of fibers were immersed in a 3% NaOH solution for 24 h at room temperature. After treatment, the fibers were washed with acetic acid at a concentration of 0.1 mol and rinsed with distilled water until the pH was neutralized, maintaining it between 6 and 7. Subsequently, the fibers were dried for 22 h at 50 °C. Figure 1 illustrates the fibers before and after the surface treatment.

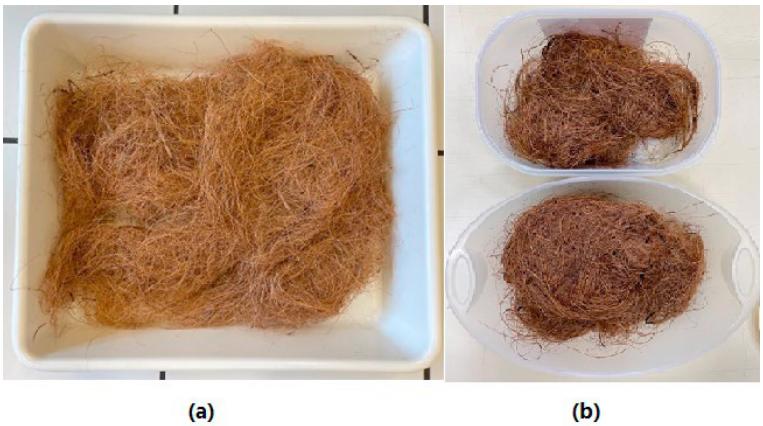

Fig. 1. (a) Untreated fibers; (b) fibers after surface treatment.

2.3. Specimens preparation

2.3.1 Resin specimens

Resin specimens for tensile and flexural tests were prepared according to ASTM D638 (Type I) and ISO 178 (Class I, three-point bending), respectively, with a uniform thickness of 4 mm. Aluminum molds were machined to the dimensions and geometry specified by the standards for specimen fabrication.

Using SR GreenPoxy 56 resin and SD Surf Clear hardener (Sicomin), resin specimens were prepared with a 100:45 resin-to-hardener ratio. The mixture was cast into the mold cavities Curing was conducted in a WTC Binder oven according to the manufacturer's specified cycle, which included sequential stages of 24 h at 23 °C, 24 h at 40 °C, and 16 h at 60 °C. Following the curing process, the specimens were demolded, subjected to quality evaluation, and conditioned for mechanical testing.

2.3.2 Composites specimens

Composites were fabricated with and without fiber retting, employing fiber volume fractions of approximately 3% and 6%. These fractions were selected after preliminary trials with 5 – 15%, in which higher fiber contents (⩾10%) produced plates with poor surface finish, defects, and inconsistencies, making them unsuitable for reliable specimen preparation within the scope of this study.

Composites were fabricated by hand lay-up in an open mold using GreenPoxy resin. Fiber contents of 3 g (≈3 vol%) and 6 g (≈6 vol%) were employed, with fibers cut to 30 – 50 mm lengths. The mold was cleaned and treated with five layers of wax release agent, after which fibers were randomly distributed and impregnated with resin in two layers using a roller to ensure uniform wetting. After lay-up, the mold was pressed with a hydraulic jack for 30 min, after which the load was replaced by weights to maintain minimal pressure. The specimens were then cured in an oven following the manufacturer's cycle: 24 h at 23 °C, 24 h at 40 °C, and 16 h at 60 °C. After fabrication, the composite plates with different fiber treatments and volume fractions were cut using an OUPLAN CNC milling machine, model STEEL PRO 2515. Following cutting, the specimens in their final configuration are illustrated in Figure 2.

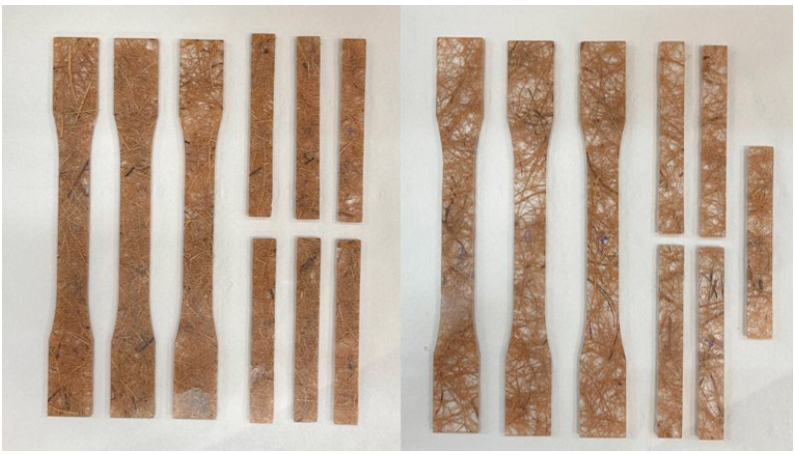

Fig. 2. Machined composite specimens with 6% and 3% fiber volume fractions.

2.*4 Mechanical tests*

2.4.1 Mechanical Characterization of Greenpoxy Resin

Mechanical characterization was performed to evaluate whether reinforcement with coconut fibers enhances the performance of the composite relative to the neat GreenPoxy resin, thereby clarifying the influence of fiber addition on material properties. Accordingly, six specimens were tested under identical laboratory conditions using a Shimadzu Autograph AGS-X universal testing machine (10 kN capacity), following ASTM D638. A crosshead speed of 5 mm/min was applied, leading to specimen failure within approximately five minutes. In addition, six specimens were subjected to flexural testing using a Shimadzu Autograph AGS-X universal testing machine (10 kN capacity), in accordance with ISO 178. Tests were performed with a support span of 64 mm, after measuring specimen thickness and width in the central region.

2.4.2 Mechanical Characterization of Composites

Tensile tests were performed on three specimens per condition using a Shimadzu Autograph AGS-X 10 kN universal testing machine, in accordance with the standard test speed of 5 mm/min to ensure failure within ~5 min. Specimen thickness and width were measured at the narrow section before testing. Force–displacement data were used to calculate mean values and standard deviations of the main mechanical properties.

Flexural tests were conducted on five specimens using a Shimadzu Autograph AGS-X 10 kN universal testing machine, with a support span of 64 mm and a crosshead speed of 2 mm/min, in accordance with the standard. Force–deflection data were used to calculate mean values and standard deviations of the main mechanical properties.

3. Results and Discussion

3.1 Mechanical Characterization of Greenpoxy Resin

3.1.1 Analysis of the Tensile Test Results

Six valid specimens were tested. Thickness was measured at four points due to variations arising from limited pressure control during open-mold fabrication, a typical characteristic of this process. Based on the tensile test results, the stress–strain curve was derived and is presented in Figure 3.

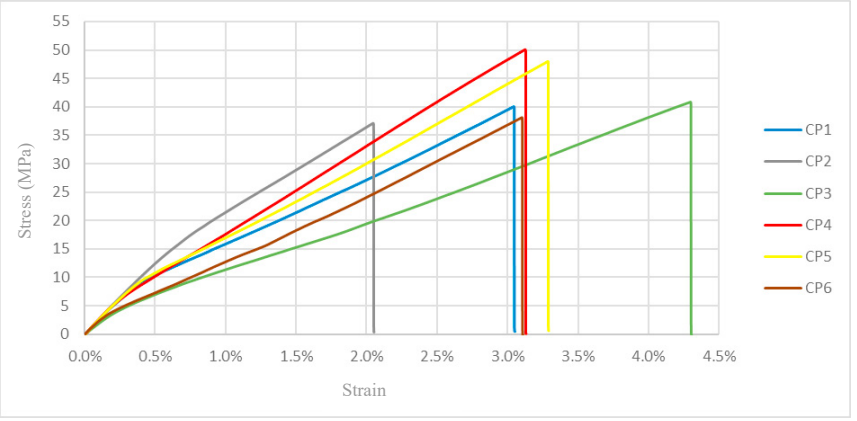

Fig. 3. Stress–strain curve obtained from the tensile test of Greenpoxy resin.

The tensile strength obtained (37 – 50 MPa; avg. 42.37 MPa) was consistent with the manufacturer's reference (49 – 51 MPa). In contrast, the average maximum strain (3.2%) was nearly twice the reported value (≈1.6%), likely due to differences in testing conditions and standards.

3.1.2 Analysis of the Flexural Test Results

Six valid specimens were tested, with width and thickness measured before testing. The resulting flexural stress–strain curve is shown in Figure 4.

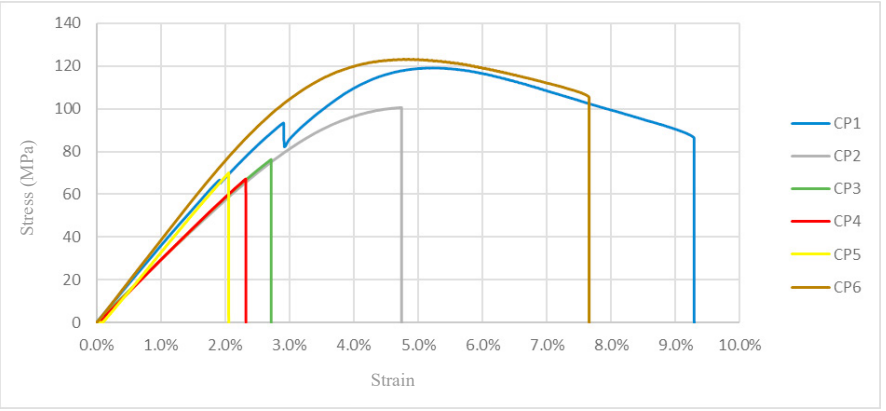

Fig. 4. Stress–strain curve obtained from the flexural test of Greenpoxy resin.

Flexural strength ranged from 67 to 123 MPa (avg. 92.77 MPa), lower than the manufacturer's reference (114–123 MPa). Maximum strain averaged 4.8%, consistent with the reported 4.5–5.5%, though a 3% standard deviation indicated high variability among specimens.

3.2 Mechanical Characterization of Composite

3.2.1 Analysis of the Tensile Test Results

Three valid specimens were tested for each combination of parameters and levels described in Table 1 and the L_4 orthogonal array. Before testing, the width and thickness of each specimen were measured. Based on the tensile test data, the stress–strain curve was calculated and is presented in Figure 5.

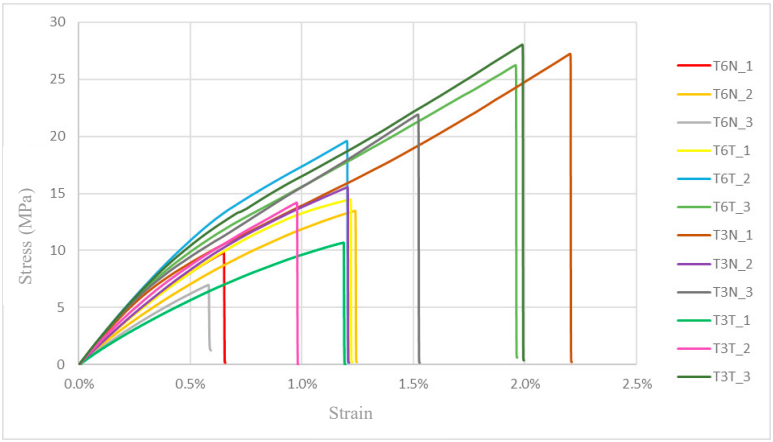

Fig. 5. Stress–strain curve obtained from the tensile test of composites.

Tensile strength averaged between 10 and 22 MPa, with a maximum of 28.08 MPa for the 3% treated-fiber composite, though this batch also showed the highest variability due to non-uniform plate quality. Maximum strain ranged from 0.83% to 1.65%, with the lowest value observed for the 6% untreated-fiber composite.

3.2.2 Analysis of the Flexural Test Results

Five valid specimens were tested for each combination of parameters and levels described in Table 1 and the L_4 orthogonal array. Before testing, the width and thickness of each specimen were measured. Based on the flexural test data, the stress–strain curve was calculated and is presented in Figure 6.

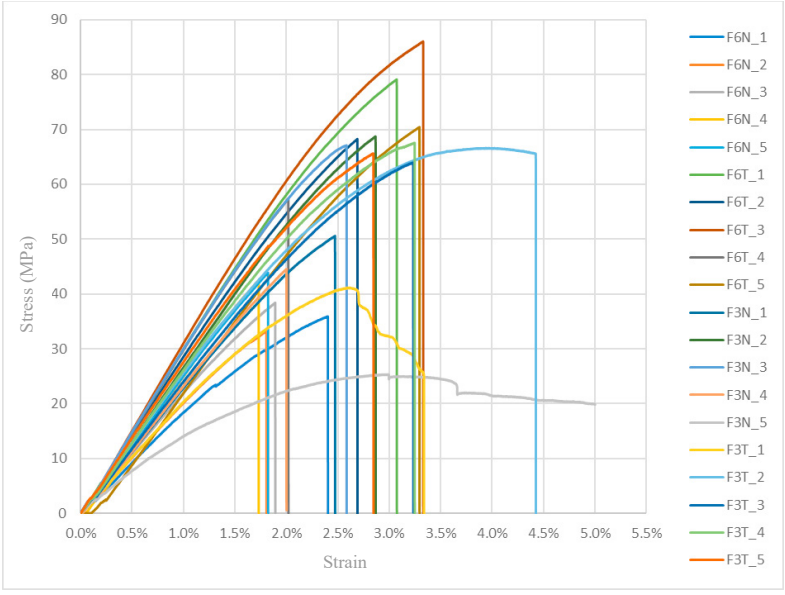

Fig. 6. Stress–strain curve obtained from the flexural test of the composites.

Flexural strength averaged 38–72 MPa, with a maximum of 86.08 MPa for the 6% treated-fiber composite, which also showed the highest mean despite large variability. Maximum strain ranged from 1.93% to 3.42%, with the best performance observed for the 3% treated-fiber composite.

3.2.3 ANOVA Analysis

ANOVA was performed using Excel® to evaluate the influence of each parameter on tensile and flexural strength. Results are summarized in Table 2 (tensile) and Table 3 (flexural).

Table 2 – ANOVA for Tensile Test.

Source	DF	SS (Aj.)	MS (Aj.)	F-Value	P-Value	% of Influence
Treatment	1	2.50	2.50	0.12	0.79	8.83%
volume fraction	1	5.09	5.09	0.25	0.71	17.94%
Error	1	20.77	20.77			73.23%
Total	3	28.37				100.00%

Table 3 – ANOVA for Flexural Test.

Source	DF	SS (Aj.)	MS (Aj.)	F-Value	P-Value	% of Influence
Treatment	1	16.42	16.42	10.67	0.19	90.23%
volume fraction	1	0.24	0.24	0.16	0.76	1.32%
Error	1	1.54	1.54			8.45%
Total	3	18.19				100.00%

DF = Degrees of Freedom; SS = Sum of Squares; MS = Mean Square; F- and P-values indicate the parameters with the greatest influence on the studied quality characteristic.

ANOVA results showed that in tensile tests, fiber volume fraction (≈18%) and fiber treatment (≈9%) were the main factors, while residual error was high (≈73%) due to variability among specimens, particularly in combination 6N. In flexural tests, fiber treatment dominated (≈90%), with minor contributions from residual error (≈8%) and fiber volume fraction (≈1%), indicating that surface treatment significantly improved fiber‑matrix adhesion and mechanical performance.

4. 4. Conclusions

As for the main conclusions, we can state:

- Coir fibers demonstrated suitable mechanical performance, although retting resulted in a slight reduction in intrinsic tensile strength.
- GreenPoxy resin exhibited tensile and flexural properties consistent with the manufacturer's specifications.
- The composite behavior was strongly influenced by fiber volume fraction and surface treatment.
- Optimal conditions were identified as 3% treated fibers for tensile performance and 6% treated fibers for flexural performance.
- Overall, Coir/GreenPoxy composites present promising potential as sustainable material alternatives.

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