# Effect of Coconut Coir Loading on the Mechanical Performance of Glass Fiber–Epoxy Hybrid Composites: Experimental and Statistical Evaluation

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## ABSTRACT

Hybridisation of renewable lignocellulosic fillers with glass fibre-epoxy systems offers a route to reduce synthetic material content while retaining useful engineering performance. This study evaluated the effect of coconut coir powder addition on the tensile, flexural and impact responses of glass fiber epoxy hybrid composites produced by hand layup. Five formulations containing 0, 5, 10, 15 and 20 g of coir powder were tested. Tensile strength and Young's modulus were determined under uniaxial loading, maximum flexural load was measured in bending, and absorbed energy was obtained from impact testing. The data were analysed using one way analysis of variance followed by Tukey's test at $\alpha = 0.05$. A 5 g coir addition produced the highest tensile strength (45.97 MPa), maximum flexural load (0.15852 kN) and absorbed impact energy (2.20 ft·lbf), corresponding to increases of 5.1%, 13.2% and 2.8%, respectively, relative to the unfilled control. The impact-energy difference between the control and 5 g formulation was not statistically significant. Increasing the coir addition from 0 to 20 g raised Young's modulus from 0.735 to 1.267 GPa (72.4%) but reduced tensile strength, flexural load and impact energy beyond 5 g. ANOVA confirmed a significant formulation effect for all four responses ($p < 0.001$). The results reveal a composition dependent, stiffness strength, toughness trade off: low coir loading improves the balanced response, whereas higher loading produces a stiffer but weaker and less impact-tolerant composite. Within the range investigated, the 5 g formulation provides the most favourable overall mechanical balance for lightweight, nonprimary structural components.

**Keywords**: coconut coir; glass fiber; epoxy; hybrid composite; mechanical properties; ANOVA; sustainable materials

## INTRODUCTION

Natural fibre polymer composites have attracted sustained interest because renewable reinforcements can reduce dependence on mineral or petroleum derived constituents, lower density and support the valorisation of agricultural residues. Their engineering adoption, however, is constrained by variability, moisture affinity and imperfect interfacial adhesion with hydrophobic polymer matrices [1–4]. Hybridisation with glass fibre is therefore attractive: glass reinforcement supplies reproducible load-bearing capacity, while a natural phase can reduce synthetic content and introduce a circular material pathway [5–7].

Coconut coir is a lignocellulosic residue obtained from the husk of Cocos nucifera. Its relatively high lignin content differentiates it from many bast fibres and contributes to toughness and durability, but hydroxyl rich surfaces can limit compatibility with epoxy. Processing route, fibre or particle size, surface condition, dispersion and loading consequently govern whether coir acts as an effective stress transfer phase or as a defect generating inclusion [4,8,11–13]. Hamzah et al. demonstrated that the coconut coir/epoxy ratio

significantly affects tensile and impact responses, with their lowest investigated coir fraction producing the strongest overall mechanical behaviour [8]. Their related work on sawdust epoxy composites similarly identified a composition-dependent optimum through mechanical testing and statistical analysis [9].

Hybridising a renewable phase with glass fibre can mitigate some of the variability of all natural composites. Hamzah et al. showed that glass fibre skins improved the tensile response of plywood sandwich laminates and used ANOVA and microscopy to relate laminate configuration to performance [10]. More broadly, recent coir glass studies show that controlled hybrid architectures can improve mechanical performance, whereas excessive filler, weak wetting or agglomeration can promote voids, debonding and premature cracking [5,8,11–15]. Recent research has increasingly treated natural or synthetic hybridisation as a property tailoring strategy rather than simply a replacement of synthetic reinforcement. Premnath et al. [16] concluded that the mechanical response of hybrid composites depends on reinforcement fraction, orientation, stacking sequence and interface quality, with glass fibre frequently compensating for the lower and more variable load bearing capacity of natural fibres. This concept is especially relevant to epoxy systems because the crosslinked matrix offers good adhesion and dimensional stability but is intrinsically brittle. A properly designed natural fibre phase can introduce crack deflection, fibre bridging and frictional energy dissipation, whereas the glass phase can maintain stiffness and load transfer. The benefits are therefore synergistic only within an appropriate composition and architecture; an arbitrary increase in natural material does not necessarily produce a stronger or tougher composite.

The mechanical role of coir also varies with its physical form. Long, aligned fibres can sustain and transfer axial load, while chopped fibres and powders behave more like discontinuous reinforcements or fillers whose effectiveness is controlled by aspect ratio, surface area and dispersion. Tasgin et al. [17] compared several natural fibres in epoxy and demonstrated that coir offered distinctive thermal-insulation behaviour but lower tensile performance than some alternative fibres, illustrating that a material advantageous for one function may be suboptimal for another. Venkatesh [18] further showed that alkali processing modifies the characteristics of coir/epoxy composites by altering the fibre surface and interface. These findings reinforce the need to distinguish between untreated and treated coir, fibre and powder forms, and high and low additions when comparing results across studies.

Interfacial compatibility is central to this distinction. Hydrophilic lignocellulosic surfaces contain accessible hydroxyl groups, whereas cured epoxy is comparatively hydrophobic. Poor wetting can leave interfacial gaps that reduce the effective stress transfer area; moisture associated with the natural phase may also encourage porosity during curing. Surface treatment can remove waxes and portions of hemicellulose or lignin, increase roughness and expose reactive sites, although overly severe treatment may damage the reinforcing structure [11–13,18]. In a glass fibre hybrid, the consequences of poor coir epoxy bonding are not necessarily eliminated by the synthetic reinforcement. Instead, local debonding or agglomeration around coir particles can create stress concentrations from which cracks propagate through the matrix toward the glass fibre interface.

Filler loading consequently tends to produce a nonlinear response. At low concentration, well dispersed particles can occupy free volume, restrict matrix chain mobility and redistribute local stresses. At higher concentration, the available resin may become insufficient to wet the enlarged particle surface; particle to particle contact, agglomeration and trapped air then become more influential than reinforcement. Patil et al. [19] reported an optimum bio filler concentration of 5 wt.% for simultaneous tensile, impact and toughness improvement in an epoxy nanocomposite, while higher concentrations did not retain the same benefit. Although the filler chemistry and scale differ from coir powder, the study demonstrates the broader principle that bio filler performance is governed by an optimum concentration rather than a monotonic rule. This principle provides a useful framework for interpreting a formulation that becomes progressively stiffer while losing strength and energy absorption.

Recent agricultural residue composites also show why multiple response variables are required. Chinnasamy et al. [20] evaluated tensile, flexural, impact and vibration behaviour in epoxy composites containing natural fibres and coconut husk or bagasse fillers, finding that the preferred configuration depended on the target response. Seal et al. [21] extended bio filled epoxy evaluation to fatigue, creep and tribological performance,

highlighting that short term tensile data alone cannot establish application readiness. Likewise, the recent coconut S-glass study [14] demonstrated that hybrid constituents influence both mechanical and thermal properties. Collectively, these studies support a multi response approach in which tensile strength, modules, bending resistance and impact energy absorption are considered together before a composition is recommended. Hamzah et al. [22] reported a similar response-dependent optimum in tea bagasse/banana peel epoxy biocomposites containing a fixed total residue content of 40 wt.%. Among the residue filled formulations, banana peel alone provided the highest tensile strength, the equal ratio blend gave the highest flexural strength, and the 10:30 tea bagasse/banana peel blend achieved the highest absorbed impact energy. These findings provide further evidence that a preferred hybrid composition depends on the loading mode, although that particulate system differs from the glass fibre reinforced system investigated here.

Despite this progress, three gaps remain. First, much of the coir epoxy literature examines high natural fibre fractions, chemically treated continuous fibres or laminate stacking sequences, whereas relatively few studies isolate incremental coir powder addition within an established glass fiber epoxy system. Second, many studies report property maxima without explicitly examining the stiffness, strength and toughness trade off created by increasing filler content. Third, visual trends are often discussed without inferential statistics capable of separating genuine formulation effects from within-group experimental variation. A statistically supported comparison across several loading levels is therefore needed to establish whether a small coir addition provides a reproducible balanced improvement and to identify the point at which increased rigidity is accompanied by unacceptable losses in strength or impact tolerance. Most published work focuses on continuous coir fibres, treated fibres or stacked natural/synthetic fabrics. Comparatively less attention has been given to the response trade-offs created by progressively adding coir powder to an existing glass fiber epoxy system. This distinction matters because particulate coir may restrict polymer chain mobility and increase stiffness while simultaneously reducing strength and impact tolerance when interfacial defects dominate. Evaluating only a single property can therefore lead to a misleading formulation choice.

Accordingly, the present study investigates five coconut coir additions in a glass fiber epoxy hybrid composite and integrates tensile strength, Young's modulus, bending resistance, impact energy absorption and inferential statistics. The novelty lies in interpreting the four mechanical responses as a coupled design problem and distinguishing numerical improvements from statistically supported differences. The objectives were to (i) quantify the effect of coir addition on each mechanical response, (ii) establish statistically distinct formulation groups using one-way ANOVA and Tukey comparisons, (iii) identify the formulation offering the best overall balance rather than the maximum value of only one response, and (iv) clarify the practical trade-off between increased stiffness and reduced failure resistance at higher coir additions.

## MATERIALS AND METHODS

### Constituents and experimental design

The composite system comprised room temperature, curing epoxy resin and hardener, glass fibre reinforcement and processed coconut coir powder. The resin and hardener were mixed at a 2:1 ratio following the supplier's recommendation. Five formulations were fabricated; the specimen code denotes the coir addition in grams. The original project formulation record is reproduced in Table 1. Because the entries combine mass (g) and percentages and do not state the total batch mass, they should be treated as nominal batch formulations rather than converted to coir weight fraction. This preserves the traceability of the experimental record without introducing an unsupported conversion.

Table 1. Nominal formulations recorded in the experimental report.

| Code | Coconut coir addition (g) | Epoxy resin (%) | Glass fiber (%) |
|---|---|---|---|
| **EFGCC$_0$** | 0 | 60 | 40 |
| **EFGCC$_5$** | 5 | 57 | 38 |

| | | | |
|---|---|---|---|
| **EFGCC$_{10}$** | 10 | 54 | 36 |
| **EFGCC$_{15}$** | 15 | 51 | 34 |
| **EFGCC$_{20}$** | 20 | 48 | 32 |

Note: The percentages and coir masses are reported exactly as recorded. Total constituent masses and the basis of the percentage calculation must be confirmed before journal submission.

**Coir preparation and composite fabrication**

The coir was cleaned, dried, reduced to powder and graded before incorporation. Epoxy and hardener were mixed thoroughly, followed by gradual addition of the coir powder to promote dispersion. Glass reinforcement was positioned in the mould, the resin mixture was applied by hand layup, and the laminate was consolidated manually to remove entrapped air. Two mould geometries were used: 323 × 233 × 4 mm for tensile and flexural specimens and 200 × 150 × 5 mm for impact specimens. After ambient curing, specimens were cut to the required dimensions using a CNC router. All formulations were fabricated using the same sequence to minimize processing related variation.

**Mechanical testing**

Tensile testing was performed using a universal testing machine on 250 × 25 × 4 mm specimens, following the project's ASTM D3039 based procedure [23]. The reported outputs were ultimate tensile strength and Young's modulus. Flexural testing used 128 × 13 × 4 mm specimens in accordance with the project's ASTM D7264 based procedure [24]; because support span and load deflection details were unavailable, the directly recorded maximum load is reported rather than an unverified calculated flexural strength. Impact specimens measured 150 × 100 × 5 mm.

The project identifies ASTM D7136 and reports absorbed energy in ft·lbf [25]. The exact impact configuration, impactor mass, drop height and incident energy require confirmation; accordingly, the present paper reports the measured absorbed energy values without claiming a fully reproducible D7136 protocol.

**Table 2. Mechanical tests and reported response variables.**

| Test | Nominal specimen size (mm) | Response used in this paper | Replicates |
|---|---|---|---|
| **Tensile** | 250 × 25 × 4 | Strength (MPa); Young's modules (GPa) | 3 per formulation |
| **Flexural** | 128 × 13 × 4 | Maximum load (kN) | 3 per formulation |
| **Impact** | 150 × 100 × 5 | Absorbed energy (ft·lbf) | Confirm from raw log |

**Statistical analysis**

For each response, formulation means were compared using one way ANOVA at $\alpha = 0.05$. Where the omnibus test was significant, Tukey's honestly significant difference procedure was used for pairwise grouping at 95% confidence. The null hypothesis stated that all formulation means were equal. Effect direction and percentage change relative to EFGCC$_0$ were additionally used to interpret engineering significance. Statistical outputs were taken from the verified analysis tables in the project dataset.

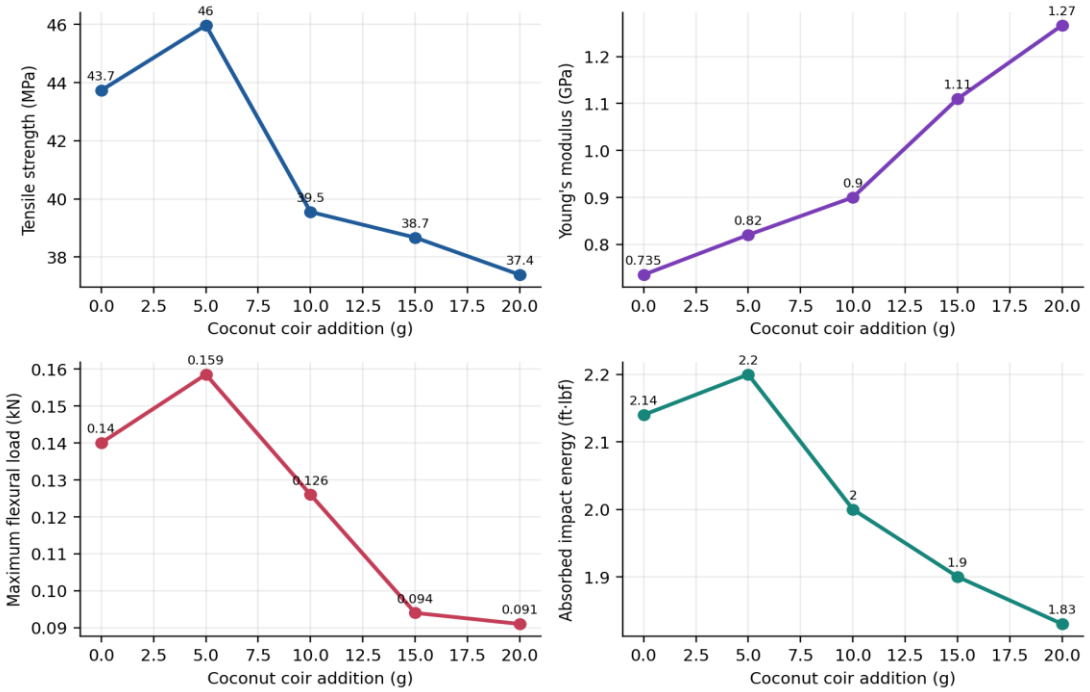
# RESULTS AND DISCUSSION

## Overall mechanical response

**Table 3. Mean mechanical responses of the five formulations.**

| Code | Tensile strength (MPa) | Young's modulus (GPa) | Maximum flexural load (kN) | Absorbed energy (ft·lbf) |
|---|---|---|---|---|
| **EFGCC$_0$** | 43.73 | 0.735 | 0.14000 | 2.14 |
| **EFGCC$_5$** | 45.97 | 0.820 | 0.15852 | 2.20 |
| **EFGCC$_{10}$** | 39.55 | 0.900 | 0.12600 | 2.00 |
| **EFGCC$_{15}$** | 38.67 | 1.110 | 0.09400 | 1.90 |
| **EFGCC$_{20}$** | 37.39 | 1.267 | 0.09100 | 1.83 |

**Figure 1. Effect of coconut coir addition on the mean tensile, stiffness, flexural-load and impact-energy responses.**




The four responses show two distinct behaviours. Tensile strength, maximum flexural load and absorbed impact energy increased from 0 to 5 g and then decreased with further additional coir. By contrast, Young's modulus rose monotonically throughout the investigated range. EFGCC$_5$ therefore represents a local optimum for strength and energy absorption, whereas EFGCC$_{20}$ maximises stiffness. This divergence confirms that formulation selection should be based on the intended failure mode and service requirement rather than on a single mechanical metric.

## Tensile strength and stiffness

EFGCC$_5$ achieved the highest tensile strength (45.97 MPa), a 5.1% increase relative to EFGCC$_0$ (43.73 MPa). At higher additions, tensile strength fell to 39.55, 38.67 and 37.39 MPa for EFGCC$_{10}$, EFGCC$_{15}$ and EFGCC$_{20}$, respectively. The 20 g formulation was 14.5% below the control and 18.7% below the 5 g maximum. ANOVA

showed a significant formulation effect ($F = 34.44$, $p = 8.04 \times 10^{-6}$). Tukey comparisons distinguished $EFGCC_5$ from the higher loading groups, while the 10–20 g formulations were mutually similar. The low addition plausibly improves packing or local stress redistribution; at larger additions, incomplete wetting, particle clustering and interfacial discontinuities become increasingly likely. The decline at high coir loading agrees with Hamzah et al. [8], who found that increasing the coir fraction beyond their best-performing composition reduced tensile and impact performance. Comparable composition sensitive behaviour was also reported for sawdust epoxy composites [9]. These mechanisms remain hypotheses here because fracture-surface microscopy was not performed [4,11–14]. Young's modulus increased from 0.735 GPa for $EFGCC_0$ to 1.267 GPa for $EFGCC_{20}$, a 72.4% gain. The ANOVA result was highly significant ($F = 211.13$, $p = 1.3 \times 10^{-9}$), and Tukey grouping separated all five formulations. Rigid coir particles can restrict matrix deformation even when their interfaces are insufficient to sustain high stress. Consequently, increasing coir addition stiffened the composite but did not preserve its ultimate tensile capacity. This stiffness strength decoupling is a central design outcome of the study.

**Flexural response**

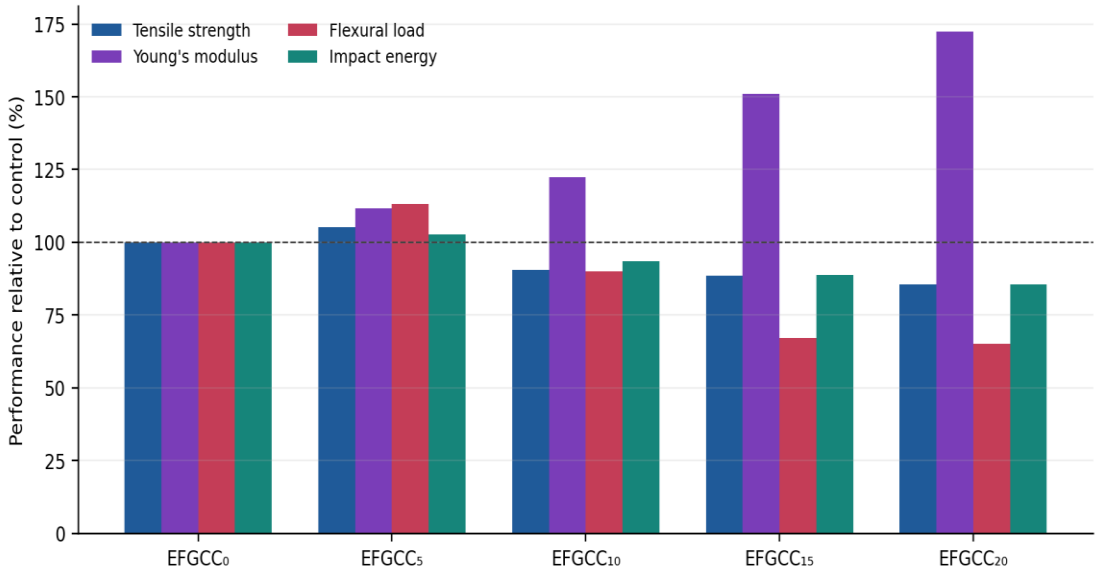
Maximum flexural load increased from 0.140 kN for $EFGCC_0$ to 0.15852 kN for $EFGCC_5$ (+13.2%), then decreased to 0.126, 0.094 and 0.091 kN. ANOVA confirmed significant differences ($F = 104.16$, $p = 4.16 \times 10^{-8}$). Tukey grouping placed $EFGCC_5$ alone in the highest group; $EFGCC_0$ and $EFGCC_{10}$ formed an intermediate group, and $EFGCC_{15}$ and $EFGCC_{20}$ formed the lowest group. Bending loads create simultaneous tensile and compressive stress and are sensitive to voids and weak interfaces. The sharp loss beyond 10 g is therefore consistent with a formulation in which increased solid loading no longer produces efficient stress transfer. Since the raw span and deflection records were unavailable, maximum load not flexural strength is the appropriate auditable response for this manuscript.

**Impact-energy absorption**

The highest mean absorbed energy was recorded for $EFGCC_5$ (2.20 ft·lbf), compared with 2.14 ft·lbf for the control. Despite the numerical increase of 2.8%, Tukey grouping placed both formulations in the same group, so the improvement was not statistically significant. $EFGCC_{10}$, $EFGCC_{15}$ and $EFGCC_{20}$ formed successively lower groups, with $EFGCC_{20}$ reaching 1.83 ft·lbf (14.5% below the control). ANOVA nevertheless confirmed an overall formulation effect ($F = 145.89$, $p = 8.03 \times 10^{-9}$). The progressive reduction beyond 5 g, together with the rising modules, indicates increasing brittleness and reduced capacity for energy dissipating deformation.

**Multi response interpretation**

**Figure 2. Mechanical responses normalised to the unfilled $EFGCC_0$ control (100%).**



Normalisation clarifies the engineering trade-off. $EFGCC_5$ exceeds the control for every measured mean and is the only formulation to improve strength, bending resistance and impact-energy absorption simultaneously. Higher coir additions deliver progressively greater stiffness, but that benefit is accompanied by losses in the other three responses. $EFGCC_{20}$ is therefore appropriate only where elastic rigidity dominates, and lower failure resistance is acceptable. For a general lightweight panel or nonprimary structural component exposed to mixed loading, $EFGCC_5$ provides the most defensible balanced formulation within the tested design space. This multi response interpretation is consistent with the different tensile, flexural and impact optima reported by Hamzah et al. [22] for tea bagasse/banana peel epoxy biocomposites. Their results support selecting formulations according to the required mechanical response. Direct comparison of optimum filler contents or property magnitudes is inappropriate because their study used 40 wt.% total residues without glass fibre reinforcement, whereas the present study reports coir additions in grams within a glass fibre epoxy system; the flexural and impact test configurations also differ.

**Limitations and reproducibility requirements**

Three limitations constrain interpretation. First, coir was recorded in grams while resin and glass fibre were recorded as percentages; total batch mass is required to express all formulations as weight fractions. Second, the flexural dataset provides maximum load but not the support span and full load deflection curves needed to calculate flexural stress and modulus. Third, the impact method requires confirmation of the machine configuration and incident energy parameters. These limitations do not alter the reported between-formulation trends, but they must be resolved from laboratory records before submission to a journal requiring complete methodological replication. Fractographic SEM, density/void fraction and moisture conditioning data would also strengthen the mechanistic explanation.

## CONCLUSIONS

- Coconut coir addition significantly affected tensile strength, Young's modulus, maximum flexural load and absorbed impact energy (all ANOVA $p < 0.001$).
- A 5 g coir addition produced the best-balanced response: 45.97 MPa tensile strength, 0.15852 kN maximum flexural load and 2.20 ft·lbf absorbed energy. The improvements over control were 5.1%, 13.2% and 2.8%, respectively, although the impact energy increase was not statistically significant.
- Young's modulus increased monotonically from 0.735 to 1.267 GPa as coir addition rose from 0 to 20 g, demonstrating a 72.4% stiffness gain.
- Beyond 5 g, higher coir addition produced a stiffer but weaker and less impact tolerant composite, revealing a clear stiffness strength toughness trades off.
- Within the tested range, $EFGCC_5$ is recommended for balanced lightweight, nonprimary structural applications. Intermediate additions around 2.5–7.5 g should be studied to refine the optimum.

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