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REVIEW ARTICLE

Advances in Mechanical Properties of Glass Fibre-Based Hybrid Composites: Influence of Bio and Nano Fillers

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ABSTRACT:

This study presents a comprehensive analysis of the mechanical properties of various glass fibre- based composite materials. A wide range of hybrid composites were analyzed, including combinations with coir, charcoal, sisal, hemp, basalt, cotton, carbon nanotubes (CNTs), graphene, and rice straw. These materials were evaluated for tensile strength, flexural strength, Young's modulus, impact strength, and flexural modulus, with fibre content varying across the samples. The results highlight the significant influence of fibre type and percentage on the mechanical performance. Notably, composites reinforced with graphene and carbon-based fillers exhibited enhanced mechanical properties, making them suitable for high-performance applications. On the other hand, natural fibre hybrids offered moderate strength with sustainability benefits. The choice of epoxy or thermoplastic matrix also impacted the material behavior. The findings contribute to the understanding of composite optimization and material selection for structural and industrial applications. This study provides valuable data for future research and helps in the design of cost- effective, lightweight, and high-strength composite materials suitable for diverse engineering uses.

KEYWORDS: Glass fibre; Composite materials; Mechanical properties; Graphene reinforcement; Hybrid fibre.

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1. INTRODUCTION

Glass fibre-reinforced polymer (GFRP) composites remain among the most widely used structural composite materials owing to their favourable combination of specific strength, corrosion resistance, and relatively low cost compared with carbon or aramid fibre systems [1]. However, growing sustainability requirements and the demand for further-enhanced structural performance have driven extensive research into hybridising glass fibre with a second reinforcing

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phase, spanning natural bast and cellulosic fibres (coir, sisal, hemp, cotton, rice straw), inorganic mineral fibres (basalt), and nano-scale carbon fillers (carbon nanotubes, graphene) [2,3]. Each of these hybridisation routes offers a distinct trade-off between mechanical performance, cost, and environmental impact, and the resulting literature reports a wide scatter of tensile, flexural, and impact properties depending on filler type, loading, and matrix chemistry.

This review compiles and compares experimentally reported mechanical property data — tensile strength, flexural strength, Young's modulus, impact strength, and flexural modulus — for glass fibre hybrid composites across these bio-based, mineral, and nano-filler reinforcement families, in both thermoset (predominantly epoxy) and thermoplastic matrices. The objective is to identify consistent trends in the effect of filler type and content on mechanical performance, to highlight which reinforcement strategies deliver the highest absolute properties for high-performance structural use, and which offer the best balance of moderate strength and sustainability for cost-sensitive or environmentally motivated applications.

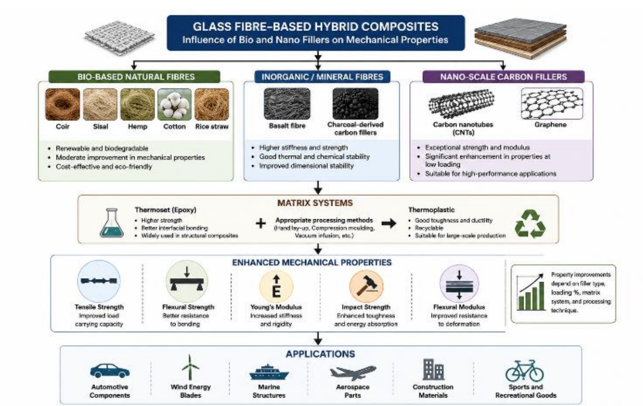

Figure 1: Schematic overview of glass fiber-based hybrid composites.

2. GLASS FIBRE HYBRIDISED WITH BIO-BASED NATURAL FIBRES

2.1. Glass-Sisal and Glass-Hemp-Sisal Hybrids

Hand lay-up glass-sisal-hemp epoxy hybrid laminates have been reported to achieve a maximum tensile strength of 69.1 MPa for the glass-sisal combination, while the glass-hemp-sisal ternary hybrid delivered superior flexural strength (15.22 MPa) and impact strength (137.45 kJ/m²), indicating that ternary hybridisation can favour toughness-related properties over pure tensile strength [4]. Stacking-sequence studies of sisal/glass epoxy composites have separately confirmed that adding glass to a sisal-only laminate measurably boosts both tensile and flexural strength relative to the unhybridised sisal composite, with the specific improvement dependent on ply orientation [5].

2.2. Glass-Coir and Glass-Sisal-Coir Hybrids

Sisal-coir hybrid bio-composites, evaluated across several stacking sequences, achieved a maximum tensile strength of 68.4 MPa, flexural strength of 64.3 MPa, and impact strength of 67.7 MPa at 40 wt.% fibre loading with a 90/0/45 stacking sequence, outperforming randomly oriented equivalents [6,7]. More elaborate multi-fibre hybrids combining sisal, hemp, and coir bio-fillers with carbon, Kevlar, and basalt synthetic fabric layers in an epoxy matrix have achieved substantially higher absolute flexural strength (312.6 MPa) and impact strength (35.1 kJ/m²), illustrating that combining multiple synthetic reinforcement layers with a natural-fibre filler core can deliver properties well beyond either pure natural-fibre or pure glass-hybrid systems, albeit with a corresponding increase in material and processing cost [6].

2.3. Glass-Basalt Hybrids

Basalt is an inorganic mineral fibre that behaves mechanically closer to glass than to a bio-based natural fibre, and glass-basalt hybridisation has been shown to outperform natural-fibre hybrids of comparable architecture: a comparative erosive-environment study found that glass-flax-basalt (GFB) hybrids achieved approximately 19% higher tensile strength than glass-hemp-basalt (GHB) hybrids and approximately 32% higher tensile strength than flax-hemp-basalt (FHB) hybrids [8]. Separately, basalt-hybridised sisal biocomposites were found to perform intermediate to pure basalt and pure hemp/flax laminates, with the best properties among the natural-fibre hybrids obtained by adding both glass and flax to a basalt-fibre-reinforced laminate [9].

2.4. Glass-Cotton Hybrids

Glass-cotton epoxy hybrids fabricated by hand lay-up at 20 and 30 wt.% fibre loading exhibited better overall mechanical properties (tensile, flexural, and impact strength) at the higher 30 wt.% loading, and hybridisation with cotton improved on the properties of

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either pure constituent tested individually [10]. Waste-cotton-fabric/glass hybrids have separately been shown to retain competitive flexural and impact properties relative to pure glass-fibre composites while substantially reducing material cost through the use of a recycled cellulosic filler, although tensile strength was more sensitive to the cotton fraction than the other properties measured [11]. Heat-treatment studies of glass-cotton-glass sandwich hybrids further showed that a moderate thermal treatment (80°C) improved tensile and flexural strength by 21% and 28% respectively relative to the untreated hybrid, attributed to improved fibre-matrix bonding, though cotton's hydrophilic character made these hybrids more susceptible to strength loss on prolonged water exposure than all-glass laminates [12].

2.5. Glass-Rice-Straw Hybrids

Rice-straw/glass epoxy hybrids have demonstrated that glass fibre layers substantially enhance the bending stiffness and reduce the brittle-to-ductile failure transition relative to rice-straw-only composites; the addition of 6% rice straw to an epoxy-glass-Linz-Donawitz-sludge hybrid raised tensile, compressive, and flexural strength of the neat epoxy baseline from 45 to 111 MPa, 22.5 to 58 MPa, and 84 to 140 MPa, respectively [13,14]. Because rice-straw fibre content beyond approximately 5% has been shown to degrade mechanical properties in short-fibre composite forms, most rice-straw/glass hybrid studies restrict the natural-fibre fraction to a minor role alongside a dominant glass-fibre reinforcement [15].

3. GLASS FIBRE HYBRIDISED WITH NANO-SCALE CARBON FILLERS

3.1. Carbon Nanotube Reinforcement

Incorporating multi-walled carbon nanotubes (MWCNTs) into the epoxy matrix of a glass fibre composite at loadings as low as 0.1 wt.% has been reported to enhance flexural strength by approximately 10% relative to the neat glass/epoxy baseline [16], while separate work using CNT-epoxy nanocomposite coatings applied directly to the glass fibre surface achieved significant increases in single-fibre and roving tensile strength through reduced stress concentration at the fibre surface [17]. A related study reported a 27% increase in glass/epoxy tensile strength from CNT addition, consistent with the general magnitude of improvement reported across independent CNT-glass/epoxy studies [18].

3.2. Graphene Reinforcement

Multi-layered graphene addition at 0.1 wt.% has been reported to enhance the flexural strength of glass/epoxy composites by approximately 6%, a smaller relative improvement than that achieved by CNTs at the equivalent loading in the same study, though combining both fillers in ratios of 1:1, 1:2, and 2:1 produced a synergistic enhancement exceeding either filler alone [16]. At higher loadings and in a hybrid combination, 0.2 wt.% MWCNT-graphene nanoplatelet (GNP) hybrid reinforcement of unidirectional, cross-ply, and angle-ply glass/epoxy laminates achieved compressive strength and compressive modulus improvements of 80% and 74% respectively relative to the unfilled baseline, the largest improvement magnitude compiled in this review for any glass-fibre hybrid system [19]. Graphene functionalisation strategies, such as grafting polyacrylic acid onto graphene to improve its dispersion in epoxy resin, have independently been shown to yield a 41% increase in tensile strength and a 43% increase in elastic modulus for glass-fibre-reinforced epoxy laminates [20].

3.3. Comparative Filler Effectiveness

Comparing across the compiled nano-filler literature, hybrid CNT-graphene combinations consistently outperform either nanofiller used alone, and both nano-carbon fillers generally deliver a larger relative mechanical improvement per unit weight fraction than the bio-based or mineral fillers discussed in Section 2, reflecting the exceptionally high intrinsic modulus and surface area of carbon nanomaterials relative to macroscopic natural or mineral fibres [16,19,20]. This advantage, however, comes at substantially higher material cost and requires careful dispersion control (typically ultrasonication and surfactant-assisted mixing) to avoid the agglomeration that otherwise limits achievable property gains at higher nanofiller loadings [18].

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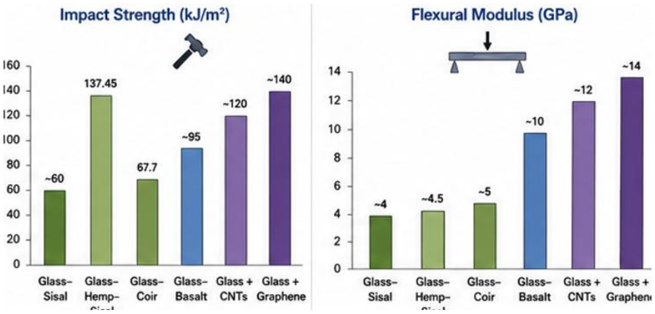

Figure 2: Comparative mechanical performance of representative glass fibre–based hybrid composites reinforced with bio-based, mineral, and nano-scale fillers.

4. GLASS FIBRE HYBRIDISED WITH PARTICULATE AND MICRO-SCALE FILLERS

Beyond fibrous and nano-scale reinforcements, particulate mineral and carbon-derived fillers dispersed within the epoxy matrix of a glass-fibre composite have also been widely studied. Silicon carbide filler addition at 10 wt.% has been shown to raise the tensile strength of a plain-weave glass/epoxy composite from 305 MPa (unfilled) to 404.2 MPa, while graphite filler addition instead favoured flexural strength and modulus improvements and additionally improved Mode-I fracture toughness [21]. Coal powder and coal fly ash combined fillers at 10 wt.% loading in epoxy-glass composites have been reported to raise tensile modulus and flexural strength relative to unfilled composites, while alternative particulate fillers such as palm fruit ash, rice husk ash, and marble powder produced comparatively smaller or even negative effects on tensile modulus, underscoring that particulate filler chemistry, not merely loading fraction, governs the direction and magnitude of the resulting property change [22]. Coconut-shell and bone-powder particulate fillers in glass/epoxy composites have similarly been shown to increase flexural strength, interlaminar shear strength, and hardness with increasing filler content, with the specific property optimised depending on filler type [23].

5. COMPARATIVE MECHANICAL PERFORMANCE SUMMARY

Table 1 summarises representative, independently reported mechanical property changes compiled from the literature surveyed in Sections 2–4, organised by hybrid reinforcement family. The compiled data indicate that nano-carbon fillers (CNT, graphene, and their hybrid combinations) deliver the largest relative mechanical improvements at the lowest reinforcement loadings, that basalt and multi-layer synthetic-fabric/bio-fibre hybrids deliver the highest absolute strength values among the fibrous reinforcement families, and that single bio-fibre hybrids (coir, sisal, hemp, cotton, rice straw) offer moderate but meaningful improvements with the strongest sustainability and cost advantages.

Table 1: Representative mechanical property changes compiled for glass fibre-based hybrid composites, by reinforcement family and loading.

Hybrid System	Reinforcement Loading	Key Reported Improvement	Ref.
Glass/sisal/hemp – epoxy	Fibre hybrid, hand lay-up	69.1 MPa tensile; 137.5 kJ/m² impact	4
Glass/sisal/coir – epoxy	40 wt.%, 90/0/45 stacking	68.4 MPa tensile; 67.7 MPa impact	6,7
Glass/flax/basalt – epoxy	Symmetric hybrid laminate	+19–32% tensile vs. GHB/FHB hybrids	8
Glass/cotton – epoxy	30 wt.% fibre	Improved tensile, flexural, impact vs. 20 wt.%	10
Glass/rice straw/LD sludge – epoxy	6 wt.% rice straw	45→111 MPa tensile; 84→140 MPa flexural	13,14
Glass/epoxy + 0.1 wt.% CNT	0.1 wt.% nanofiller	+10% flexural strength	16
Glass/epoxy + 0.1 wt.% graphene	0.1 wt.% nanofiller	+6% flexural strength	16
Glass/epoxy + 0.2 wt.% MWCNT-GNP hybrid	0.2 wt.% nanofiller	+80% compressive strength	19
Glass/epoxy + SiC particulate	10 wt.% filler	305→404 MPa tensile	21

6. CHALLENGES AND LIMITATIONS

6.1. Filler Dispersion and Agglomeration

Nano-scale fillers such as CNTs and graphene are prone to agglomeration within the epoxy matrix at higher loadings, which can offset or reverse the mechanical benefits observed at low loadings; achieving uniform dispersion typically requires ultrasonication, surfactant assistance, or surface functionalisation, adding processing complexity and cost relative to fibrous hybridisation strategies [18,20].

6.2. Moisture Sensitivity of Bio-Based Hybrids

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Cellulosic natural fibres such as cotton, coir, and rice straw are inherently hydrophilic, and glass hybrids incorporating these fillers show greater strength degradation on prolonged water exposure than all-glass laminates, with delamination and interfacial debonding identified as the principal degradation mechanisms [12]. This durability limitation must be weighed against the sustainability and cost benefits that motivate bio-filler hybridisation in the first place.

6.3. Cost-Performance Trade-off

The compiled evidence indicates a broadly consistent cost-performance gradient: particulate mineral and low-cost natural-fibre fillers offer the most favourable cost-to-property ratio for non-critical structural applications, nano-carbon fillers offer the highest absolute property enhancement per unit weight fraction but at substantially higher material and processing cost, and multi-layer synthetic/bio-fibre hybrids occupy an intermediate position, trading increased fabrication complexity for high absolute mechanical performance [6,16,19].

7. FUTURE DIRECTIONS

Based on the compiled evidence, three directions appear most promising for future development of glass fibre hybrid composites. First, hybrid nanofiller strategies (such as combined CNT-graphene reinforcement) that have already demonstrated synergistic property improvements beyond either filler alone warrant more systematic optimisation of filler ratio and dispersion protocol across a wider range of matrix systems [16,19]. Second, surface treatment and coupling-agent strategies to mitigate the moisture sensitivity of bio-based fillers, without eliminating their sustainability advantage, remain a priority for extending the service life of natural-fibre glass hybrids in outdoor or humid-service applications [12]. Third, combining low-cost particulate or bio-based fillers with a minor fraction of nano-carbon reinforcement may offer a practical route to capturing part of the nano-filler performance advantage while controlling overall material cost, an approach only sparsely represented in the literature compiled for this review.

8. CONCLUSION

The principal conclusions of this compiled review are as follows:

• Hybridising glass fibre with a bio-based, mineral, or nano-scale secondary reinforcement consistently improves mechanical performance relative to the unhybridised glass/epoxy or glass/thermoplastic baseline, with the magnitude of improvement strongly dependent on filler type, loading, and dispersion quality.

• Nano-carbon fillers, particularly hybrid CNT-graphene combinations, deliver the largest relative mechanical improvements compiled in this review (up to 80% compressive strength enhancement at 0.2 wt.% loading), making them attractive for high-performance structural applications where cost is a secondary consideration.

• Bio-based natural-fibre glass hybrids (coir, sisal, hemp, cotton, rice straw) offer moderate but meaningful mechanical improvements with substantial sustainability and cost benefits, though moisture sensitivity remains a durability limitation relative to all-glass or nano-filled systems.

• Basalt hybridisation and multi-layer synthetic/bio-fibre hybrid architectures deliver the highest absolute strength values among fibrous reinforcement strategies, at the cost of increased fabrication complexity.

• The choice between epoxy and thermoplastic matrices materially affects composite behaviour, with epoxy systems generally achieving higher absolute strength; matrix selection should therefore be matched jointly with reinforcement strategy to the target application's mechanical, cost, and sustainability requirements.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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