INTERNATIONAL MULTI DISCIPLINARY JOURNAL FOR RESEARCH & DEVELOPMENT
eISSN 2394-6334 Impact factor: 7,854 Volume 12, issue 09 (2025)

Sustainable Transition in Structural Composites: Advanced Mechanical Characterization, Modeling, and Application Potential of Natural Fiber–Reinforced Polymer Composites

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Abstract:

Background: The accelerating demand for sustainable materials has revitalized interest in natural fiber–reinforced polymer composites (NFRPCs). Historically relegated to low-end applications because of variability, moisture sensitivity, and limited interfacial adhesion, natural fibers such as flax, jute, hemp, sisal, and tamarind shell particles are increasingly investigated as viable alternatives to synthetic fibers for structural and semi-structural applications. This paper synthesizes empirical findings and theoretical perspectives from diverse investigations—ranging from fundamental tensile and flexural property studies to machine-learning-assisted predictive modeling of advanced composite behavior—to present a comprehensive, publication-ready analysis of NFRPC performance, processing strategies, and potential to replace glass fibers in selected structural roles (Herrera-Franco, 2004; Wambua, 2003; Gassan & Bledzki, 1999).

Objective: This work aims to (1) integrate findings on mechanical behavior (tensile, flexural, impact, dynamic) across different natural fiber types and composite systems; (2) critically analyze processing, fiber treatment, and hybridization strategies that enhance performance; (3) present a conceptual, text-based methodology for systematic characterization and predictive modeling (including data-driven approaches recently applied to composite behavior); and (4) identify realistic application domains and roadmap obstacles to substituting conventional E-glass fibers with natural fibers in structural composites (Shlykov et al., 2022; Escalante-Tovar et al., 2025; Kumar et al., 2024; Elfaleh et al., 2023).

Methods: A rigorous narrative-method synthesis was performed that triangulates controlled experimental findings from mechanical testing literature, process–structure–property linkages derived from fiber-surface treatments and matrix selection studies, and contemporary machine-learning predictive frameworks used for tensile and flexural property modeling (Kumar et al., 2024; Escalante-Tovar et al., 2025). Emphasis is placed on mechanistic explanation: fiber geometry, microfibril angle, crystallinity, interfacial shear strength, and composite architecture are linked to macroscopic tensile and flexural responses.

Results: Across the literature, properly treated and optimized natural fiber composites demonstrate tensile moduli and specific stiffnesses competitive with low-end E-glass systems for selected layups and loading regimes (Herrera-Franco, 2004; Wambua, 2003; Shah, 2013). Impact and low-velocity response remain challenging but can be mitigated by hybridization and matrix toughening (Dhakal). Surface modification such as alkali or silane treatments systematically increases interfacial adhesion, raising tensile strength and strain-to-failure (Gassan & Bledzki, 1999; Rong et al., 2001). Machine-learning models trained on carefully curated experimental datasets yield accurate predictive tools for tensile and flexural properties and help identify sensitive process parameters (Kumar et al., 2024; Escalante-Tovar et al., 2025).

Conclusions: NFRPCs, when optimized via fiber selection, treatment, hybridization, and architecture design, can meaningfully replace glass fibers in select structural applications—particularly where weight savings, sustainability, and specific energy absorption are prioritized. However, life-cycle performance, environmental durability, reproducibility, and standardization of processing and characterization protocols remain significant barriers. A structured, multi-scale research agenda combining systematic experimentation with advanced data-driven modeling is recommended to accelerate industrial adoption (Rong et al., 2001; Elfaleh et al., 2023).

Keywords: natural fiber composites; tensile properties; interfacial adhesion; hybrid composites; machine learning; structural replacement.

Introduction

The global materials landscape is at an inflection point shaped by sustainability targets, regulatory pressures, and market demand for lower-carbon alternatives to conventional synthetic-fiber composites (Elfaleh et al., 2023). Natural fiber–reinforced polymer composites (NFRPCs) have resurfaced as promising candidates because they couple renewable, low-density reinforcements with established polymeric matrices, creating composites with favorable specific mechanical properties and reduced embodied energy compared to glass- or carbon-fiber composites (Wambua, 2003; Elfaleh et al., 2023). The potential for natural fibers—flax, hemp, jute, sisal, and other lignocellulosic materials—to supplant glass fibers in certain structural roles is not new, but improvements in processing, fiber treatment, composite architecture, and predictive modeling now offer a more nuanced assessment of feasibility (Herrera-Franco, 2004; Shah, 2013).

This article synthesizes an interdisciplinary body of work to articulate when and how natural fibers can approach or exceed the mechanical thresholds required for structural use, identify remaining gaps, and propose a research and development pathway for industrial deployment. The literature reveals several recurrent themes: natural fibers often provide high specific stiffness and low density, but their tensile strength and impact resistance can lag due to variability in fiber quality, poor matrix adhesion, and susceptibility to moisture (Rong et al., 2001; Rowel et al., 1997). Numerous studies demonstrate that targeted surface treatments and hybridization strategies can narrow the performance gap with glass fibers by addressing interfacial bonding and energy absorption behavior (Gassan & Bledzki, 1999; Wongsriraksa et al., 2013).

Concurrently, recent advances in computational modeling—particularly machine-learning approaches—enable the use of experimental datasets to predict composite properties, optimize process parameters, and quantify sensitivity to material variability (Kumar et al., 2024; Escalante-Tovar et al., 2025). These tools do not replace mechanistic understanding but augment it, helping prioritize experimental campaigns and accelerate material formulation. This integrated perspective aligns microstructural determinants (e.g., fiber morphology, cellulose crystallinity, microfibril angle) with macroscopic observables (tensile modulus, strength, flexural behavior, impact response), thereby offering a structured pathway for replacing E-glass in targeted applications (Herrera-Franco, 2004; Shlykov et al., 2022).

Problem Statement and Literature Gap

Despite encouraging progress, there remains fragmentation in the literature: experimental studies frequently use disparate processing conditions, fiber sources, fiber treatments, and test standards; data reporting lacks uniformity; and there is limited cross-validation of machine-learning models across independent datasets (Rowel et al., 1997; Elfaleh et al., 2023). Specifically, three gaps are apparent. First, a standardized, textually described methodology that integrates microstructural characterization, process control, mechanical testing, and data-driven predictive modeling is seldom articulated in a single, reproducible framework (Herrera-Franco, 2004; Kumar & Raja, 2021). Second, while numerous small-scale studies claim competitive specific properties relative to glass, comprehensive assessments that account for long-term durability, environmental exposure, and manufacturing scale-up are fewer and often inconclusive (Rong et al., 2001; Wambua, 2003). Third, machine-learning approaches have shown promise for specific manufacturing modalities (e.g., material extrusion-based additive manufacturing), but broad adoption is constrained by sparse, inconsistent datasets and limited interpretability of some models (Kumar et al., 2024; Escalante-Tovar et al., 2025).

Addressing these gaps requires an approach that is both deeply mechanistic and pragmatically experimental: a method that prescribes how to select fiber types, apply surface treatments, define composite architectures, and collect standardized datasets suitable for predictive modeling. This article aims to produce such a synthesis by drawing on established experimental outcomes and contemporary modeling studies, thereby offering researchers and practitioners a consolidated resource for advancing NFRPCs into structural roles.

Methodology

The methodology described here is intentionally text-based and fully reproducible by practitioners without specialized equipment beyond standard composite processing and characterization facilities. It integrates material selection, fiber treatment protocols, composite fabrication, mechanical evaluation, and data-handling for predictive modeling. Each step is accompanied by rationale and theoretical context drawn from the literature.

Material Selection and Characterization

The first step is rigorous selection and baseline characterization of fibers and matrices. Natural fibers differ widely in cell wall composition, lumen fraction, microfibril angle, and crystallinity—parameters that directly influence stiffness, strength, and failure modes (Herrera-Franco, 2004; Shlykov et al., 2022). The protocol requires:

1. Source documentation: Record botanical species, harvest season, geographical origin, and retting method. Such metadata are crucial because growth conditions significantly affect fiber mechanical properties (Rowel et al., 1997; Wongsriraksa et al., 2013).
2. Single-fiber tensile testing: Use standardized single-fiber tests to obtain Young's modulus, tensile strength, and strain-to-failure distributions. Single-fiber data help decouple fiber intrinsic variability from composite-level effects (Herrera-Franco, 2004).
3. Microstructural analysis: Employ optical microscopy and, where possible, scanning electron microscopy (SEM) to quantify fiber diameter distributions, lumen size, and surface topography. X-ray diffraction or similar techniques should be used to estimate cellulose crystallinity and infer effects on stiffness (Shlykov et al., 2022).
4. Hygroscopic assessment: Measure moisture uptake isotherms and dimensional changes under controlled humidity steps, since moisture influences interfacial adhesion and long-term properties (Rowel et al., 1997; Wambua, 2003).

Fiber Surface Treatment and Chemical Modification

Interfacial bonding between natural fibers and polymer matrices is a dominant factor determining composite strength and toughness. The literature documents alkali (NaOH) treatments, silane coupling agents, acetylation, and enzymatic treatments as commonly used strategies (Gassan & Bledzki, 1999; Rong et al., 2001; Wongsriraksa et al., 2013). The methodology includes:

1. Alkali treatment baseline: Immerse fibers in aqueous NaOH solutions of controlled molarity (for example, 2–10 wt%) for durations determined by preliminary trials; follow with neutralization and thorough washing. Alkali treatment cleans the surface and increases surface roughness, improving mechanical interlocking and exposing cellulose hydroxyls for subsequent coupling agent reactions (Gassan & Bledzki, 1999; Rong et al., 2001).
2. Coupling agent application: Apply silane or other coupling agents to alkali-treated fibers using controlled solvent systems; document concentration and curing conditions. Coupling agents form covalent or hydrogen-bonded bridges between fibers and thermosetting matrices, increasing interfacial shear strength (Wongsriraksa et al., 2013).
3. Comparative groups: Prepare untreated, alkali-only, coupling-only, and alkali+coupling groups to discern synergistic effects of combined treatments. Comparative analysis elucidates which combination best balances strength gain with process complexity (Gassan & Bledzki, 1999).

Composite Fabrication

Composite processing must be chosen to reflect intended application and to control fiber alignment and volume fraction precisely:

1. Matrix selection: Use representative thermosetting (e.g., epoxy, unsaturated polyester) and thermoplastic matrices (e.g., polypropylene, ABS variants) to examine matrix influence on stiffness, strength, and impact energy absorption (Shah, 2013; Kumar et al., 2024).
2. Layup configurations: Fabricate unidirectional, cross-ply, and woven fabric composites to capture architecture effects. Hybrid laminates combining natural fibers with glass fibers in strategic plies should be included to evaluate progressive substitution strategies (Herrera-Franco, 2004; Girisha, 2014).
3. Volume fraction control: Target a range of fiber volume fractions (10–50 vol%) to map property trends; ensure proper degassing and consolidation to minimize void content that significantly reduces composite strength (Wambua, 2003).

4. Processing parameters: For thermosets, maintain consistent cure schedules and post-cure treatments. For thermoplastics, document melt processing temperatures, residence times, and cooling rates, as these affect fiber–matrix wetting and crystallinity of the matrix (Wongsriraksa et al., 2013; Kumar et al., 2024).

Mechanical Testing Protocol

A standardized mechanical testing matrix is essential to produce datasets suitable for interpretation and modeling:

1. Tensile tests: Conduct tensile testing according to recognized standards, recording stress–strain curves to determine Young's modulus, ultimate tensile strength, and failure strain. Collect multiple replicates to characterize statistical variability (Herrera-Franco, 2004).
2. Flexural tests: Perform three-point and four-point bending tests to determine flexural stiffness and strength. Flexural failure modes often reveal interlaminar weaknesses and fiber/matrix debonding behavior (Escalante-Tovar et al., 2025).
3. Impact tests: Use low-velocity impact testing to determine energy absorption characteristics and damage tolerance. Report peak force, absorbed energy, and residual tensile/flexural properties after impact (Dhakal).
4. Dynamic mechanical analysis: Employ DMA to assess viscoelastic behavior and glass transition shifts related to fiber addition and treatments (Shlykov et al., 2022).
5. Fractography: After mechanical tests, use SEM fractography to identify failure mechanisms—fiber pull-out, fiber fracture, matrix cracking, or delamination—and relate them to interfacial quality and fiber morphology (Rong et al., 2001).

Data Handling and Machine-Learning Modeling

To harness the predictive power of data-driven approaches, the protocol outlines how to curate datasets and build interpretable models:

1. Dataset curation: Assemble a dataset that includes fiber properties (modulus, strength, diameter distribution), treatment metadata (chemical concentrations, durations), composite architecture (fiber volume fraction, layup), processing parameters, environmental conditioning, and mechanical test outputs. Ensure consistent units and missing-value handling (Kumar et al., 2024; Escalante-Tovar et al., 2025).
2. Feature engineering: Derive composite descriptors such as specific stiffness, aspect ratio distributions, and surface roughness indices from microstructural data. Include categorical encoding for treatment types and matrix family.
3. Model selection: Begin with interpretable regressors (linear regression, decision trees) to identify primary effectors of mechanical properties, then progress to ensemble methods (random forest, gradient boosting) and, where dataset size permits, to neural networks for non-linear interactions (Kumar et al., 2024; Escalante-Tovar et al., 2025).
4. Cross-validation and generalizability: Use k-fold cross-validation and holdout test sets to evaluate model robustness. Where possible, validate models on data from independent studies to ensure external validity (Escalante-Tovar et al., 2025).
5. Interpretability: Employ feature-importance analyses and partial-dependence plots to understand key drivers of composite performance, enabling mechanistic hypotheses to be tested experimentally.

Ethical and Sustainability Considerations

Beyond mechanical performance, environmental and social dimensions must be assessed. Life-cycle assessment (LCA) frameworks should be used to quantify cradle-to-gate environmental impacts relative to glass-fiber composites, accounting for agricultural inputs, fiber processing energy, and end-of-life scenarios (Elfaleh et al., 2023). Social factors—land use, local employment, and supply-chain stability—should be documented for scale-up feasibility (Rowel et al., 1997).

Results

The descriptive analysis synthesizes consistent trends and notable exceptions from the referenced body of work. Results are organized by property type and illustrate how fiber selection, treatment, architecture, and hybridization influence composite performance.

Tensile Properties and Specific Stiffness

Across multiple studies, natural-fiber composites exhibit a range of tensile moduli that are strongly dependent on fiber type, orientation, and volume fraction. For unidirectional layups with high fiber volume fractions and well-aligned fibers, tensile modulus values approach those of low-end glass-fiber composites on a specific basis (modulus per unit mass) because natural fibers have lower density (Herrera-Franco, 2004; Wambua, 2003). The mechanism underlying high specific stiffness is the relatively high cellulose content and oriented microfibrils in fibers such as flax and hemp, which contribute to longitudinal stiffness (Shlykov et al., 2022).

However, tensile strength results display larger scatter due to interfacial bonding limitations and intrinsic fiber defects (Herrera-Franco, 2004). Where alkali and silane treatments are applied in combination, multiple studies report systematic increases in tensile strength—often explained by improved interfacial shear strength and reduced fiber pull-out during failure (Gassan & Bledzki, 1999; Rong et al., 2001). The magnitude of improvement depends on treatment intensity—over-treatment can reduce strength by damaging the fiber cell wall—necessitating an optimization strategy (Gassan & Bledzki, 1999).

Impact and Low-Velocity Behavior

Low-velocity impact response is a critical metric for many structural applications, yet natural-fiber composites frequently underperform relative to glass-fiber systems in pure unhybridized configurations (Dhakal). Natural fibers tend to enable higher energy absorption through progressive damage—matrix cracking and fiber pull-out contribute to toughness—but peak load capacities and perforation resistance can be lower. Hybrid laminates that place tougher glass-fiber plies on impact-exposed surfaces while using natural-fiber plies internally can achieve favorable combinations of impact resistance and reduced weight, highlighting hybridization as a pragmatic pathway (Shah, 2013).

Flexural Behavior and Interlaminar Performance

Flexural testing reveals that natural fiber composites can attain respectable flexural stiffness and strength when fiber orientation is optimized. However, interlaminar shear strength and delamination resistance are recurrent concerns, particularly with non-woven or randomly oriented mats where resin-rich areas and weak fiber–matrix boundaries promote delamination under bending loads (Escalante-Tovar et al., 2025). Strategic use of through-thickness reinforcement, tougher matrices, or interleaving techniques mitigates these weaknesses.

Effects of Fiber Treatment and Surface Modification

A recurring result is that surface treatments significantly enhance composite performance by improving adhesion and reducing defects at the interface. Alkali treatment removes hemicellulose and surface impurities, increasing fiber surface roughness and facilitating mechanical interlocking, while silane agents form chemical bridges that improve load transfer (Gassan & Bledzki, 1999; Rong et al., 2001). The literature cautions against over-exposure to harsh chemical treatments, which can lead to fiber embrittlement and reduced tensile properties (Rong et al., 2001).

Hybridization Strategies

Hybridization combining natural fibers with glass fibers in a tailored laminate architecture consistently appears as an effective compromise—maintaining high surface performance, impact resistance, and stiffness where needed, while reducing overall composite density and embodied energy (Girisha, 2014; Shah, 2013). The literature reports that careful stacking sequence design, with glass oriented in high-stress or impact-facing plies and natural fibers used for core load-bearing or stiffness contributions, can capture many benefits of both fiber classes (Girisha, 2014).

Predictive Modeling Outcomes

Machine-learning models trained on representative datasets have demonstrated capacity to predict tensile and flexural properties within acceptable error margins, provided that feature selection encapsulates microstructural and processing influences (Kumar et al., 2024; Escalante-Tovar et al., 2025). Interpretable models reveal that fiber volume fraction, fiber tensile modulus, surface treatment type, and matrix family are among the most significant predictors for tensile modulus and strength. These models enable sensitivity analyses that direct experimentalists toward the most impactful variables for optimization.

Durability and Environmental Conditioning

Studies addressing moisture uptake and environmental conditioning underscore that water absorption decreases stiffness and strength through fiber swelling, microcracking at the interface, and hydrolysis of the matrix in some cases (Rowel et al., 1997; Wambua, 2003). Treatment strategies that reduce fiber hygroscopicity—acetylation or proper matrix encapsulation—improve retention of properties under humid conditions, but long-term durability data spanning service lifetimes remain limited in the literature.

Case Study Insights: Flax as a Glass Substitute in Small Wind Turbine Blades

A focused case study within the literature demonstrates the feasibility of substituting E-glass with flax in small wind turbine blades, contingent upon optimized laminate design and hybridization (Shah, 2013). Flax fibers, when organized into unidirectional plies with high fiber volume fractions and properly treated, provide sufficient stiffness to meet aeroelastic design constraints; however, fatigue life and moisture-induced degradation require mitigation strategies and further long-term testing.

Discussion

This section provides a deep interpretation of the results, exploring theoretical implications, reconciling conflicting findings, highlighting limitations, and outlining the future research trajectory.

Mechanistic Interpretation of Tensile and Flexural Behavior

The mechanical performance of NFRPCs emerges from the interplay between intrinsic fiber properties (modulus, tensile strength, density, microfibril angle), interfacial bonding, composite architecture, and matrix properties. The stiffness advantage on a specific basis is rooted in the favorable cellulose content and low density of certain fibers, enabling high specific modulus when fibers are aligned and fully load-bearing (Herrera-Franco, 2004; Shlykov et al., 2022). Strength outcomes hinge on efficient stress transfer across the interface; when that transfer is compromised by weak adhesion, failure localizes at the interface as fiber pull-out rather than fiber fracture, producing lower ultimate tensile strength (Gassan & Bledzki, 1999). Surface treatments that increase interfacial shear strength convert some pull-out-dominated failures to fiber-dominated failures, thereby increasing composite strength—yet the treatment must preserve fiber integrity to avoid paradoxical strength reductions (Rong et al., 2001).

Theoretical Implications for Composite Design

From a theoretical standpoint, the interplay between microstructure and macroscopic properties implies multiple optimization levers. The rule-of-mixtures provides a first-order estimate of modulus for unidirectional composites but fails to capture the influence of fiber waviness, imperfect bonding, and statistical distributions of fiber strength typical of natural fibers (Herrera-Franco, 2004). Consequently, composite designers must move beyond simplistic mixture rules and incorporate stochastic descriptors of fiber variability, interfacial scaling laws, and damage mechanics models that reflect progressive debonding and pull-out phenomena. Machine-learning models offer a pragmatic route to encapsulate these complex interactions by learning effective mappings from high-dimensional descriptors to property outputs (Kumar et al., 2024; Escalante-Tovar et al., 2025). However, maintaining physical interpretability is essential—models should be used to generate hypotheses and prioritize experiments rather than as black boxes for final acceptance without mechanistic validation.

Reconciling Conflicting Findings

Discrepancies in reported composite properties often trace back to differences in fiber source, processing parameters, experimentally uncontrolled humidity, and test protocols (Rowel et al., 1997; Elfaleh et al., 2023). To reconcile these findings, this article emphasizes transparency in metadata reporting and advocates standardized experimental protocols.

Comparative meta-analyses become feasible only when essential metadata—fiber origin, treatment details, volume fraction, void fraction, and environmental conditioning—are explicitly reported (Wongsriraksa et al., 2013).

Challenges and Limitations

Several enduring challenges temper enthusiasm for wholesale substitution of glass fibers with natural fibers. First is variability: biological fibers inherently show greater statistical dispersion in mechanical properties than manufactured glass fibers, complicating structural reliability assessments (Herrera-Franco, 2004). Second is environmental sensitivity: hygroscopicity and associated property degradation under humid or cyclic conditions limit service environments unless properly mitigated (Rowel et al., 1997). Third is long-term durability under fatigue loading and UV exposure—areas with sparse, long-duration data (Wambua, 2003). Fourth, manufacturing scale-up imposes supply-chain and processing consistency demands: agricultural feedstocks are subject to seasonal variation and require logistical frameworks distinct from petrochemical-based fibers (Elfaleh et al., 2023).

Opportunities and Strategic Pathways

Despite limitations, several strategic pathways can accelerate adoption:

1. Hybridization as transitional strategy: Hybrid laminates that strategically combine glass and natural fibers deliver early performance gains while substantially reducing weight and embodied energy, offering a pragmatic compromise for industries such as marine, automotive, and wind-energy components (Girisha, 2014; Shah, 2013).

2. Standardization and metadata reporting: Developing community standards for experimental reporting will enable better meta-analyses and model transferability (Escalante-Tovar et al., 2025).
3. Optimization via combined experimental–computational loops: Integrating carefully curated experimental datasets with interpretable machine-learning frameworks will identify the most impactful variables for experimental optimization and accelerate development cycles (Kumar et al., 2024).
4. Matrix innovation: Using tougher, low-permeability matrices or matrix modifications that limit water ingress (e.g., barrier coatings, low-free-volume thermosets) can mitigate durability concerns while preserving weight advantages (Wongsriraksa et al., 2013).
5. Lifecycle and circularity design: Optimizing for mechanical recyclability, biodegradability (where appropriate), or energy-efficient end-of-life processes enhances the overall sustainability case for natural fibers (Elfaleh et al., 2023).

Future Research Directions

The following research themes are prioritized:

1. Large-scale, multi-source datasets: Curate cross-laboratory datasets with harmonized metadata for model training and validation, enabling reliable predictive modeling across fiber types and manufacturing methods (Kumar et al., 2024; Escalante-Tovar et al., 2025).
2. Long-term environmental durability studies: Conduct multi-year field and accelerated aging tests that include fatigue, UV exposure, and cyclic humidity to quantify service-life expectations in real-world conditions (Rowel et al., 1997).
3. Mechanistic multiscale modeling: Develop models that bridge microfibrillar mechanics, interfacial debonding kinetics, and laminate-scale damage accumulation to inform robust design rules that account for variability (Shlykov et al., 2022).
4. Advanced fiber modification: Research environmentally benign treatment methods that reduce hygroscopicity and improve interfacial bonding without compromising fiber integrity—such as plasma treatments or bio-based coupling agents (Wongsriraksa et al., 2013).

5. Certification and standards development: Collaborate with standards bodies to develop qualification pathways for NFRPCs in specific industries, including automotive interior components, consumer goods, and certain wind-energy segments.

Conclusion

Natural fiber–reinforced polymer composites represent a compelling route toward more sustainable material systems in multiple application domains. The literature demonstrates that, through careful fiber selection, surface treatment, hybridization, and architecture design, NFRPCs can achieve competitive specific stiffnesses and, in many cases, acceptable strength and toughness for targeted structural applications (Herrera-Franco, 2004; Wambua, 2003; Gassan & Bledzki, 1999). Machine-learning approaches complement experimental studies by identifying high-leverage variables and enabling efficient exploration of large design spaces (Kumar et al., 2024; Escalante-Tovar et al., 2025).

However, definitive replacement of E-glass in general structural roles remains premature without solutions to variability, environmental durability, and supply-chain standardization. A staged approach—beginning with hybridization and progressing to full substitution in contexts where the advantages of lower density and lifecycle impacts outweigh the challenges—appears most feasible. The research agenda proposed here combines systematic experimentation, mechanistic modeling, and harmonized data practices to accelerate the maturation and industrial acceptance of NFRPCs (Rong et al., 2001; Elfaleh et al., 2023). By coupling scientific rigor with pragmatic engineering pathways, the field can progress from promising laboratory results to reliable, scalable, and sustainable material systems.

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