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Sustainable Development and Mechanical Performance of Natural Fiber–Reinforced Polymer Composites: Comprehensive Analysis, Methodologies, and Future Directions

Alistair J. Finch
School of Computing, National University of Singapore (NUS), Singapore

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ABSTRACT

Background: Natural fiber–reinforced polymer composites have emerged as compelling alternatives to conventional synthetic-fiber composites because of their favorable environmental profile, low density, renewability, and competitive mechanical properties in many applications (Rowell, Young & Rowell, 2002; Hu & Lim, 2007). Despite notable progress in processing and characterization, widespread adoption remains challenged by variability in fiber properties, interfacial compatibility, moisture sensitivity, and the need for robust predictive modelling frameworks (Hornsby, Hinrichson & Trivedi, 1997; Peng et al., 2018).

Objectives: This research-synthesis article aims to construct a detailed, publication-ready synthesis that integrates classical experimental studies of natural fiber composites with contemporary advances in characterization, hybridization strategies, compatibilization, and machine-learning-based property prediction. The objective is to provide a unified conceptual and methodological framework for researchers and engineers to design, process, and evaluate natural fiber composites for engineering applications.

Methods: The manuscript synthesizes experimental findings, fiber preparation techniques, composite processing routes, dynamic and static mechanical testing protocols, and analytical frameworks described across the provided literature. It constructs a methodical approach that aligns fiber extraction/pretreatment, matrix selection, interfacial modification, and comprehensive mechanical and thermal characterization, and situates recent machine-learning modelling approaches as complementary tools for optimization and uncertainty quantification (Mulenga, Rangappa & Siengchin, 2025; Liang et al., 2025).

Results: A convergent picture emerges: (1) alkali and coupling-agent treatments systematically enhance fiber–matrix adhesion and mechanical performance across many plant fibers (Yan et al., 2016; Yang et al., 2007); (2) hybridization with short glass or synthetic fibers improves strength and modulus while balancing cost and sustainability trade-offs (Reddy et al., 2018); (3) processing parameters, particularly fiber length distribution, dispersion, and composite microstructure, dominate composite performance and variability (Hornsby, Hinrichson & Trivedi, 1997; Harriette, Jorg & Martie, 2006); and (4) supervised machine-learning models, when trained on diverse, high-quality datasets, show strong promise in predicting flexural and tensile properties and directing experimental design (Hamzat et al., 2025; Mulenga, Ude & Vivekanandhan, 2021).

Conclusions: Natural fiber composites represent an adaptable, lower-carbon alternative to synthetic composites when designed with attention to fiber selection, surface chemistry, and microstructural control. Integrating careful experimental protocols with modern data-driven modelling can accelerate materials discovery and industrial translation, but standardized datasets, clear protocols for moisture conditioning, and deeper mechanistic models of interfacial physics are needed to reduce performance uncertainty.

KEYWORDS

natural fiber composites, fiber–matrix interface, compatibilization, hybridization, mechanical characterization, machine learning.

Introduction

The accelerating global imperative to reduce carbon footprints and develop materials with improved end-of-life profiles has brought natural fiber–reinforced composites into sharp focus as a sustainable materials class for structural and semi-structural applications (Rowell, Young & Rowell, 2002; Hu & Lim, 2007). Natural fibers such as flax, jute, hemp, bamboo, coir, and agricultural residues (rice husk, wheat straw) have been studied extensively as reinforcement phases for thermoplastic and thermoset matrices because they combine low density, renewability, and a favorable specific stiffness-to-weight ratio when appropriately processed (Jiang & Hinrichsen, 1999; Hornsby, Hinrichson & Trivedi, 1997; Panthapulakkal, Zereshkian & Sain, 2006).

However, the transition from small-scale laboratory demonstrations to reliable engineering components requires resolving several interrelated scientific and technological challenges. First, natural fibers are heterogeneous and anisotropic at multiple scales: their chemical composition (cellulose, hemicellulose, lignin), microfibrillar angle, lumen content, and diameter distributions vary by species, growing conditions, and extraction method, producing wide property distributions (Rowell, Young & Rowell, 2002; Panthapulakkal, Zereshkian & Sain, 2006). Second, the hydrophilic nature of cellulosic fibers contrasts with the hydrophobic organic polymer matrices typically used, leading to poor interfacial adhesion, moisture uptake, interfacial degradation, and poor composite durability without deliberate surface treatments or compatibilizers (Yan et al., 2016; Yang et al., 2007). Third, processing protocols—fiber length, aspect ratio, dispersion, and compounding routes—critically determine micromechanical stress transfer and composite failure modes, making reproducible, high-performance processing a nontrivial engineering task (Harriette, Jorg & Martie, 2006; Hornsby, Hinrichson & Trivedi, 1997).

The literature provides a diverse body of experimental work addressing these issues. Studies of flax and cotton in biodegradable polyester amide matrices emphasize fiber compatibility with degradable matrices (Jiang & Hinrichsen, 1999). Investigations into rice husk and wheat straw underscore the potential of agro-waste as reinforcement in thermoplastics, contingent on particle sizing and compatibilization (Yang et al., 2004; Panthapulakkal, Zereshkian & Sain, 2006). Short-fiber jute and sisal composites processed by injection molding reveal how fiber orientation and matrix crystallization interplay to dictate mechanical behavior (Karmaker & Youngquist, 1996; Joseph et al., 2003). Hybrid composite studies position combinations of natural fibers and synthetic reinforcements as pragmatic routes to balance sustainability and mechanical requirements (Reddy et al., 2018).

Despite these advances, three critical literature gaps remain. First, there is limited consensus on standardized fiber preparation and conditioning protocols that yield reproducible composite properties across laboratories (Rowell, Young & Rowell, 2002). Second, while many compatibilizers and treatments have shown benefits, systematic mechanistic studies that relate chemical modification levels to interfacial mechanics and long-term durability under hygrothermal cycling are sparse (Yan et al., 2016). Third, although machine learning has begun to be applied to predict composite properties, comprehensive frameworks that integrate experimental design, uncertainty quantification, and interpretability remain nascent (Mulenga, Rangappa & Siengchin, 2025; Liang et al., 2025).

This article addresses these gaps by synthesizing classical and contemporary approaches into a coherent research strategy for designing, characterizing, and modelling natural fiber composites. It emphasizes mechanistic understanding of interfacial physics, rigorous processing control, and the judicious integration of data-driven modeling to guide experiments. The remainder of the manuscript presents detailed methodological guidance, a descriptive analysis of typical results and performance trends, an interpretive discussion of limitations and opportunities, and a forward-looking conclusion that prioritizes reproducibility, cross-disciplinary collaboration, and standardization.

Methodology

This article adopts a research-integration methodology: it consolidates and extrapolates methods reported in the literature to construct a reproducible, stepwise experimental and analytical framework for natural fiber composites. The methodology is descriptive and prescriptive rather than empirical: it synthesizes reported extraction, treatment, processing, and characterization techniques and proposes rigorous protocols that researchers can implement to generate high-quality data and to integrate with machine-learning models.

Fiber selection and characterization. The first methodological pillar is systematic fiber selection followed by multi-scale characterization. Fiber sources include bast fibers (flax, jute, hemp), leaf fibers (sisal), agricultural residues (wheat straw, rice husk), and industrial by-products (bamboo particulates) (Jiang & Hinrichsen, 1999; Hornsby, Hinrichson & Trivedi, 1997; Yang et al., 2004). For each fiber type, characterization should include chemical composition (cellulose, lignin, hemicellulose percentages), density, moisture content at equilibrium in controlled humidity, fiber diameter distribution (using optical microscopy or SEM), microfibrillar angle estimation where possible, and single-fiber tensile testing to establish baseline mechanical properties and variability (Rowell, Young & Rowell, 2002; Panthapulakkal, Zereshkian & Sain, 2006).

Fiber extraction and pretreatment. Natural fibers can be obtained by retting, mechanical decortication, or chemical pulping. The method chosen affects fiber integrity and surface chemistry (Rowell, Young & Rowell, 2002). For bast fibers like flax and jute, controlled retting or mechanical extraction minimizes fiber damage. Alkali treatment (mercerization) with NaOH is a common first-line approach to remove surface impurities, waxes, and portions of hemicellulose and lignin, increasing surface roughness and exposing cellulose fibrils to improve mechanical interlocking and chemical bonding with matrices (Yan et al., 2016; Yang et al., 2007). Detailed protocols must specify concentration, temperature, and exposure time to avoid excessive fiber degradation. For agro-residues such as rice husk, grinding to produce flour with controlled particle size distributions is essential, and subsequent silane or coupling agent treatments can be used to modify surface chemistry and hydrophobicity (Yang et al., 2004; Peng et al., 2018).

Compatibilization strategies. The hydrophilic/hydrophobic mismatch is managed by coupling agents (maleic anhydride grafted polymers), silanes, isocyanates, and polymeric compatibilizers that can form chemical bonds with cellulose or physically entangle with the matrix (Yang et al., 2007; Peng et al., 2018). The methodology prescribes systematic screening of compatibilizer types and loadings using small factorial experimental designs. Each treatment variation must be followed by spectroscopic or surface-chemical characterization (FTIR, XPS) to confirm the presence of functional groups, and by contact-angle or moisture uptake tests to quantify surface hydrophobicity changes.

Composite processing. Processing routes include extrusion compounding and injection molding for thermoplastic matrices and hand lay-up or resin transfer molding for thermosets. Processing variables that strongly influence composite microstructure include screw speed, temperature profile, residence time, fiber feed rate, and die geometry in extrusion; and mold temperature, pressure, and cooling rate in injection molding (Karmaker & Youngquist, 1996; Harriette, Jorg & Martie, 2006). The methodology stresses controlled experiments where one variable is changed at a time to isolate effects, supplemented by design-of-experiments (DOE) methods when exploring interactions. For particulate fillers like rice husk flour, particle-size distribution control and dispersive mixing are critical to avoid agglomeration (Yang et al., 2004).

Specimen conditioning and environmental control. Given the sensitivity of natural fibers to moisture, precise conditioning protocols are mandatory. Specimens should be equilibrated at prescribed relative humidity levels (e.g., 50% RH, 23 °C) for standardized testing or subjected to defined hygrothermal cycles for aging studies (Rowell, Young & Rowell, 2002). Procedures should document equilibrium times, mass changes, and dimensional stability.

Mechanical testing protocols. Standardized tensile, flexural, and impact testing should be conducted following widely recognized standards adapted for composite specimens (e.g., ASTM analogues) with careful reporting of specimen geometry, testing speed, and gripping strategies to avoid premature failures. For dynamic mechanical analysis, temperature sweeps across the glass transition and storage/loss modulus measurements give insight into damping behavior and matrix crystallization influenced by fibers (Rana, Mitra & Banerjee, 1999; Joseph et al., 2003). The methodology recommends testing both dry and conditioned specimens to separate intrinsic mechanical properties from moisture-induced effects.

Microstructural analysis. Fractography using SEM, optical microscopy for fiber distribution and orientation, and micro-CT for three-dimensional structure analysis where resources allow, provide the necessary link between processing, microstructure, and properties (Hornsby, Hinrichson & Trivedi, 1997; Harriette, Jorg & Martie, 2006). The methodology emphasizes correlative analysis: linking observed failure modes (fiber pull-out, matrix cracking, fiber fracture) to measured mechanical responses.

Hybridization approaches. Combining natural fibers with synthetic fibers (e.g., glass) or mixing different natural fibers (e.g., jute + pineapple leaf fiber) can be used to tailor stiffness, strength, and toughness while preserving weight and cost advantages (Reddy et al., 2018). The methodology outlines hierarchies for hybrid designs: sequential laminates, random short-fiber blends, and graded distributions, and prescribes experimental matrices to evaluate the trade-offs in mechanical performance, environmental impact, and processability.

Data handling and machine-learning integration. To exploit modern modelling approaches, the methodology prescribes rigorous experimental metadata capture: fiber provenance, chemical assay results, process parameters, environmental conditioning, and full mechanical response data. With curated datasets, supervised learning algorithms (regression trees, support vector machines, neural networks) can be trained to predict target properties (tensile strength, flexural modulus) and to identify key drivers among input variables (Mulenga, Rangappa & Siengchin, 2025; Hamzat et al., 2025). The methodology recommends cross-validation, hold-out test sets, and uncertainty quantification techniques to avoid overfitting and to provide interpretable models that can guide experimental designs and material selection.

Sustainability assessment. Life-cycle considerations form an integral methodological pillar. Data on fiber cultivation, processing energy, matrix selection (biodegradable vs conventional polymers), and end-of-life scenarios should be compiled to compare environmental impacts quantitatively and qualitatively (Rowell, Young & Rowell, 2002; Hu & Lim, 2007).

Ethical and reproducibility considerations. The methodology mandates detailed reporting of all experimental conditions and encourages deposition of datasets in public repositories to enable cross-laboratory comparisons and to support robust machine-learning model training.

Results

The following descriptive analysis synthesizes experimental trends and outcome patterns reported across the literature and projected from the methodological framework. As this manuscript is a synthesis rather than a primary-data experimental report, the results are interpretive and structured around emergent themes: fiber characterization and variability, effects of pretreatment and compatibilization, processing–microstructure–property relationships, hybridization outcomes, dynamic mechanical behavior, moisture effects and durability, and machine-learning model performance.

Fiber characterization and variability. Across multiple studies, natural fibers show broad distributions of single-fiber tensile strength and modulus; for example, bast fibers like flax exhibit higher stiffness and strength than many leaf fibers, but the spread in values can be substantial due to extraction and retting variability (Jiang & Hinrichsen, 1999; Rowell, Young & Rowell, 2002). Baseline characterization typically reveals cellulose contents in bast fibers above 60% with appreciable lignin and hemicellulose contents that influence water uptake and dimensional stability (Rowell, Young & Rowell, 2002). The practical outcome is that composite designers must treat fiber properties statistically: mean values alone are insufficient, and process tolerance windows must account for property spread.

Effects of pretreatment and compatibilization. Alkali treatment (NaOH) consistently improves fiber–matrix bonding by cleaning the fiber surface and increasing roughness, typically leading to higher tensile and flexural strengths in polypropylene and other thermoplastic matrices (Yang et al., 2007; Yan et al., 2016). Studies on rice husk flour demonstrate that compatibilizing agents, such as maleic-anhydride-grafted polymers, reduce particle agglomeration and increase interfacial adhesion, yielding higher composite strength and better dispersion (Yang et al., 2004; Yang et al., 2007). More specialized chemical treatments, including silanization and isocyanate coupling, provide stronger chemical linkage potential but require careful control of reaction conditions to prevent fiber degradation (Peng et al., 2018).

Processing–microstructure–property relationships. Multiple investigations underscore the primacy of microstructure—fiber orientation, aspect ratio, and dispersion—over theoretical fiber strength in determining composite mechanical properties (Karmaker & Youngquist, 1996; Harriette, Jorg & Martie, 2006). Injection molding of short fibers, for example, often leads to orientation gradients through the specimen thickness and local fiber breakage that together produce anisotropic properties and complex failure modes. Microstructural characterization shows that for particulate-filled systems (rice husk flour), fine particle size and good matrix wetting result in more homogeneous stress transfer and improved stiffness, whereas large particles introduce stress concentrators (Yang et al., 2004).

Hybridization outcomes. Hybrid composites combining natural and glass fibers or mixing different natural fibers demonstrate an ability to tune mechanical behavior. Reddy et al. (2018) show that incorporating small fractions of glass fibers into jute or pineapple leaf fiber composites increases tensile strength and modulus while increasing density modestly, presenting a pragmatic engineering trade-off. The literature reveals that sequential layering (e.g., natural-fiber skins over synthetic-fiber cores) can maximize surface sustainability while retaining load-bearing capacity.

Dynamic mechanical behavior and damping. Dynamic mechanical analysis reveals that natural fibers alter matrix viscoelastic properties, often increasing storage modulus below the glass transition due to reinforcement and affecting damping characteristics due to interfacial friction and fiber bending losses (Rana, Mitra & Banerjee, 1999; Joseph et al., 2003). The presence of natural fibers can broaden transition regions and introduce additional energy-dissipation mechanisms, which is advantageous in applications requiring high damping.

Moisture effects and durability. A recurrent observation across studies is that moisture uptake reduces composite stiffness and strength due to fiber swelling, interfacial debonding, and hydrolytic degradation in some matrices (Rowell, Young & Rowell, 2002; Yan et al., 2016). Conditioning protocols produce variable equilibrium moisture contents depending on fiber type and treatment; alkali-treated fibers often show reduced equilibrium uptake relative to untreated fibers but remain more hygroscopic than synthetic reinforcements. Long-term hygrothermal aging studies highlight progressive property decline and the need for protective matrix barriers or hydrophobic surface modifications for structural applications.

Machine-learning model performance. Recent works demonstrate that machine-learning models can predict composite flexural and tensile properties with acceptable accuracy when trained on extensive, diverse datasets that include processing and conditioning metadata (Hamzat et al., 2025; Mulenga, Rangappa & Siengchin, 2025). Model interpretability tools reveal that fiber volume fraction, fiber length distribution, and compatibilizer loading are often the most influential variables. However, model generalization is limited by dataset heterogeneity and the absence of standardization across experimental protocols; models trained on curated, standardized data perform markedly better.

Sustainability and life-cycle perspectives. Comparative analyses show that the environmental footprint of natural fiber composites depends heavily on matrix choice and end-of-life handling: composites with biodegradable matrices and natural fibers can offer substantial advantages in end-of-life impact if biodegradable pathways are available and competition with agricultural land use is managed (Rowell, Young & Rowell, 2002; Hu & Lim, 2007). The literature also notes that using agricultural residues (rice husk, wheat straw) as fillers adds value to waste streams and reduces upstream environmental burdens (Yang et al., 2004; Panthapulakkal, Zereshkian & Sain, 2006).

Discussion

The preceding descriptive results underscore several convergent themes: the decisive role of interfacial engineering, the centrality of microstructural control during processing, the necessity of robust moisture management strategies, and the promising but datadependent role of machine learning. This discussion elaborates on these themes, interrogates their mechanistic foundations, explores counter-arguments, and identifies research priorities.

Interfacial engineering as the keystone. The interface between natural fibers and polymer matrices is the mechanical and chemical fulcrum on which composite performance pivots. Treatments that modify fiber surface chemistry—alkali, silanes, maleated polymers—act through multiple mechanisms: they remove surface contaminants that impede wetting, increase roughness for mechanical interlocking, introduce functional groups that can react with matrix polymers, and sometimes reduce hygroscopicity (Yang et al., 2007; Peng et al., 2018). Mechanistically, an effective interface reduces interfacial shear stress concentration and enables efficient load transfer from matrix to fiber. Yet, trade-offs exist: aggressive chemical treatments can strip cellulose and lower intrinsic fiber strength, while coupling agents may add cost and processing complexity. Consequently, a balanced approach that quantifies both chemical bonding and mechanical interlocking effects via spectroscopic, micromechanical testing, and fracture-surface analysis is required. The field lacks standardized interfacial characterization metrics, which inhibits cross-study comparability; establishing agreed protocols for fiber surface analytics and single-fiber pull-out or microbond testing would substantially advance mechanistic understanding and reproducibility.

Processing–microstructure–property mapping. Multiple studies highlight that fiber orientation, distribution, and length are more predictive of composite mechanical response than nominal single-fiber strength (Karmaker & Youngquist, 1996; Harriette, Jorg & Martie, 2006). This observation aligns with micromechanical models: stress transfer efficiency depends on aspect ratio and orientation distribution functions that are set during compounding and molding. From a processing standpoint, this implies that investments in dispersion control, controlled feeding systems, and optimized screw designs can yield more reliable performance improvements than marginal gains in fiber procurement quality. Counter-arguments emphasizing superior fiber properties miss the point that these properties cannot be realized without microstructural control. Future work should emphasize in-line, non-destructive microstructure monitoring (for example, ultrasound or optical-sensing technologies) to provide real-time quality control.

Moisture management and durability strategies. The hydrophilicity of natural fibers is often portrayed as an intrinsic limitation; however, it is also an opportunity for innovative engineering solutions. Approaches range from matrix selection—using hydrophobic matrices or barrier layers—to fiber surface modifications and the incorporation of hydrophobic coatings or microencapsulated moisture scavengers. It is essential to articulate application-specific acceptance criteria: for many automotive interior parts, moderate moisture sensitivity may be tolerable, whereas for load-bearing exterior components, stringent hygrothermal stability is non-negotiable (Yan et al., 2016). The literature suggests that combining chemical treatments with physical barriers and design-for-protection approaches offers the best route to durability. Still, long-term accelerated aging protocols that correlate laboratory conditioning to field performance are insufficiently developed; establishing validated accelerated-testing-to-field-performance correlations is a high-priority need.

Hybridization: balancing sustainability and performance. Hybrid composites are pragmatically appealing because they allow designers to preserve sustainability in non-critical regions while employing synthetic reinforcements where needed for load-bearing functionality (Reddy et al., 2018). However, hybridization complicates recycling and end-of-life pathways; mixed-material composites are more challenging to recycle mechanically or chemically. An integrated design-for-recycling perspective should accompany hybridization strategies, considering modular structures, detachable assemblies, or reversible bonding chemistries to preserve circularity. Additionally, life-cycle assessments must be performed to ensure that performance gains do not overshadow environmental costs.

Machine learning as an accelerator and its limitations. Machine-learning models have shown notable predictive capability for mechanical properties when sufficient, high-quality data exists (Hamzat et al., 2025; Mulenga, Rangappa & Siengchin, 2025). These models excel at detecting non-obvious interactions between processing parameters and material properties and can direct experimental campaigns toward fruitful parameter regions. However, the models are only as reliable as the data: inconsistent experimental reporting, lack of metadata (e.g., conditioning history), and small dataset sizes lead to overfitting and poor external validity. Model interpretability is also crucial for adoption in materials engineering; black-box models without mechanistic insight will face skepticism. Therefore, hybrid modeling frameworks that integrate physics-based micromechanical constraints with data-driven components offer a promising compromise, enabling both accuracy and interpretability.

Standardization, reproducibility, and open data. A recurring obstacle in the field is the heterogeneity of experimental protocols, which makes cross-study synthesis and meta-analysis difficult. Advancing the field requires community-level agreements on standardized specimen conditioning, fiber pretreatment reporting, and dataset schemas for experiment metadata. Encouragingly, recent literature emphasizes the creation of shared datasets and benchmarking problems, but coordinated efforts and incentives (e.g., journals requiring dataset deposition) are still needed.

Limitations of the current synthesis. As a literature-driven synthesis, this article integrates diverse experimental findings but does not present new empirical data. The generalizations made should be tested by carefully controlled, multi-laboratory round-robin studies that examine the reproducibility of key findings such as the quantitative benefits of specific compatibilizers or the durability performance under standard hygrothermal cycles.

Future research directions. Building on this synthesis, priority research areas include: (1) developing rigorous interfacial characterization standards and micromechanical tests; (2) creating curated, open experimental databases with rich metadata to power robust machine-learning models; (3) designing reversible or monomaterial composite architectures to simplify recycling; (4) mapping accelerated aging tests to field performance through well-designed validation campaigns; and (5) developing in-line process monitoring technologies to control microstructure during manufacturing.

Conclusion

Natural fiber–reinforced polymer composites hold substantial promise as sustainable, low-density materials for a range of engineering applications. The literature reviewed demonstrates that when fiber selection, pretreatment, compatibilization, and processing are carefully controlled, these composites can achieve competitive mechanical performance and advantageous environmental profiles (Jiang & Hinrichsen, 1999; Rowell, Young & Rowell, 2002; Reddy et al., 2018). Nonetheless, persistent challenges—fiber variability, moisture sensitivity, and the fragmentation of experimental protocols—limit broader industrial adoption. Addressing these issues requires interdisciplinary efforts that combine rigorous experimental methods, life-cycle thinking, and modern data-driven modeling approaches. Machine learning offers powerful tools to accelerate materials discovery and to optimize processing but must be grounded in standardized, high-quality data and interpreted through a physics-informed lens (Mulenga, Rangappa & Siengchin, 2025; Liang et al., 2025). Ultimately, success will come from aligning materials science, processing engineering, environmental assessment, and data science to create natural fiber composites that are not only performant but also reliable, durable, and circular.

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