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APPLICATION OF NATURAL FIBER COMPOSITES AS CONSTRUCTION MATERIALS: A CRITICAL ANALYSIS OF CURRENT SITUATION AND FUTURE OPPORTUNITIES

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ABSTRACT

The construction sector, responsible for nearly 39% of global carbon emissions, faces a critical need to transition toward low-carbon and sustainable material systems. Natural fiber composites (NFCs), composed of plant-based fibers such as jute, flax, hemp, coir, and sisal embedded in polymeric or cementitious matrices, have emerged as viable eco-efficient alternatives to conventional synthetic composites. This study presents a comprehensive critical review of NFC applications in construction, focusing on their material composition, mechanical behavior, durability, environmental performance, and socioeconomic potential. A systematic literature review of peer-reviewed articles during 2015 to 2025 reveals that NFCs can enhance tensile and flexural strength by up to 55% compared to unreinforced matrices, owing to efficient stress transfer mechanisms and improved interfacial bonding. Advances in chemical modification, nano-hybridization, and geopolymer-based matrices have significantly improved moisture resistance and long-term durability, achieving up to 90% property retention under accelerated aging. Life Cycle Assessment (LCA) studies further demonstrate embodied energy reductions of 35–50% and carbon savings of 2.2 kg CO_2 eq/m² relative to glass fiber composites. Beyond environmental benefits, NFC utilization offers socioeconomic advantages through rural industrialization and agricultural waste valorization, particularly in resource-rich regions such as Indonesia, India, and Brazil. However, challenges remain regarding standardization, large-scale processing, and long-term reliability. Future progress will depend on interdisciplinary collaboration linking material optimization, predictive durability modeling, and policy standardization to establish NFCs as mainstream construction materials by 2035.

Keyword

Natural fiber composites,
Sustainable construction,
Mechanical performance,
Durability,
Life cycle assessment,
Circular economy

1. INTRODUCTION

The construction industry, which accounts for approximately 39% of global carbon dioxide emissions, is under increasing pressure to transition toward low-carbon and environmentally sustainable material systems (International Energy Agency, 2023). Traditional construction materials, such as cement, steel, and synthetic composites, are energy-intensive to produce and contribute significantly to greenhouse gas emissions throughout their entire life cycle. Consequently, the development of renewable and resource-efficient materials that can meet structural performance requirements while reducing environmental impacts has become a key research priority. In this context, natural fiber composites (NFCs) - engineered materials reinforced with plant-derived fibers such as jute, flax, hemp, kenaf, sisal, bamboo, and coir-have gained increasing attention as sustainable alternatives to conventional composites. These fibers are primarily composed of cellulose, hemicellulose, and lignin, which together provide high specific strength and stiffness relative to their density (Faruk et al., 2012; Siouta et al., 2024). Natural fibers are not only renewable and biodegradable but are also widely available, often as agricultural byproducts. Their integration into construction materials supports waste valorization, rural economic development, and the circular bioeconomy (Ramesh et al., 2017).

Several studies have demonstrated that NFCs can deliver competitive mechanical performance compared with synthetic fiber composites, particularly in tensile and flexural properties, while exhibiting superior environmental profiles and reduced embodied energy (Kamarudin et al., 2022; Pickering et al., 2016). Despite these advantages, the practical implementation of NFCs in construction remains constrained. Major challenges include the hydrophilic nature of lignocellulosic fibers, which leads to poor interfacial bonding with hydrophobic matrices, variability in mechanical behavior due to natural heterogeneity, and degradation in alkaline or humid environments typical of cementitious systems (Ghavami et al., 2022). Additionally, the absence of standardized design codes, limited scalability of industrial processing, and a lack of long-term durability data continue to hinder widespread adoption. Therefore, this study provides a comprehensive critical analysis of the current state of NFC applications in construction materials. It examines their mechanical and durability performance, technological challenges, and the potential pathways for scaling up NFCs toward broader industrial utilization in sustainable construction practices.

2. LITERATURE REVIEW

2.1. Composition and Characteristics of Natural Fibers

Natural fibers primarily consist of three major components-cellulose, hemicellulose, and lignin-with smaller proportions of pectin, waxes, and extractives. Typically, cellulose constitutes 40-70% of the fiber mass, hemicellulose 10-20%, and lignin 10-30%, depending on botanical origin and growth conditions (John and Thomas, 2008). The cellulose fraction is widely reported to govern tensile strength and stiffness due to its semi-crystalline molecular structure and hydrogen-bonded microfibrils, whereas lignin contributes to fibre rigidity and enhanced resistance to environmental and biological degradation (John and Thomas, 2008; Pickering et al., 2016). The ratio of these components largely determines the mechanical and moisture resistance behavior of the resulting composites. The representative physical and mechanical properties of selected natural fibers compared with E-glass fiber are summarized in Table 1. Although natural fibers exhibit lower absolute strength than synthetic fibers, their specific strength (strength-to-weight ratio) is favorable for lightweight structural applications.

Natural fibres exhibit substantial variability in their physical and mechanical properties owing to differences in botanical origin, fibre morphology, extraction methods, and testing conditions. In general, the mechanical performance of natural fibre–reinforced composites is governed by key fibre parameters such as density, tensile strength, elastic modulus, and elongation at break. To facilitate a comparative understanding of commonly used natural fibres, representative ranges of these properties reported in the literature are summarised in Table X, with glass fibre included as a conventional benchmark (John and Thomas, 2008; Pickering et al., 2016).

Table 1. Typical physical and mechanical property ranges of selected natural fibres and glass fibre are reported in the literature for comparative purposes.

Fiber Type	Density (g/cm^3)	Tensile Strength (MPa)	Modulus Elasticity (GPa)	Elongation (%)
Jute	1.46	393–800	10–30	1.8
Flax	1.40	500–1500	50–70	2.7
Hemp	1.48	350–900	30–60	1.6
Sisal	1.33	400–700	9–20	3.0
Coir	1.15	175–220	4–6	15–25
Glass fiber	2.54	2000–3500	70	2.5

The values presented represent approximate ranges compiled from multiple literature sources. The reported properties of natural fibres vary widely depending on factors such as fibre species, geographical origin, extraction technique, surface treatment, and testing methodology. Accordingly, the data are intended to support comparative discussion rather than to represent definitive material constants. The combination of low density, moderate strength, and good energy absorption capacity makes natural fibers promising reinforcements for lightweight, sustainable construction elements.

2.2. Natural Fiber Composites (NFCs) in Polymer and Cementitious Matrices

Natural fiber composites (NFCs) are generally classified into polymer-based and cementitious-based systems. In polymer matrices, thermosetting resins such as epoxy, unsaturated polyester, and phenolic resins, as well as thermoplastics like polypropylene (PP) and polyethylene (PE), are commonly employed (Kamarudin et al., 2022). However, the hydrophilic nature of natural fibers causes weak interfacial bonding with hydrophobic polymers. To address this issue, surface treatments such as alkali ($NaOH$), silane coupling, acetylation, and graft copolymerization have been widely implemented. Such chemical modifications are widely reported to remove hemicellulose and surface waxes, increase fibre surface roughness, and enhance fibre–matrix interfacial adhesion (John and Thomas, 2008; Pickering et al., 2016).

In cementitious composites, natural fibers such as hemp, coir, sisal, and jute are often added in small volume fractions (0.5-3%) to enhance crack control, tensile strength, and post-cracking toughness. Their ability to bridge microcracks effectively delays crack propagation and improves ductility (de Andrade Silva et al., 2010; Ghavami et al., 2022). However, prolonged exposure to highly alkaline environments typical of Portland cement matrices can degrade the cellulose microstructure and reduce bonding efficiency. Strategies based on modifying the matrix composition, including the use of alternative binders and reduced-alkalinity systems, have been reported as effective approaches to mitigating fibre degradation and improving the durability of natural fibre–reinforced cementitious composites (Filho et al., 2010).

2.3. Applications in Construction

Applications of NFCs in the construction sector have expanded beyond experimental research to include a variety of practical and semi-structural uses. These include lightweight wall panels, façade claddings, insulation boards, partition systems, and fiber-reinforced mortars (Siouta et al., 2024). Recent developments also focus on hybrid cement–polymer composites and geopolymer-based NFCs for sustainable infrastructure (Nguyen et al., 2020).

Experimental studies reported in the literature indicate that NFCs can enhance both mechanical and functional performance, particularly in terms of flexural behaviour and crack control when compared with conventional matrices (Siouta et al., 2024). Similarly, kenaf and coir fibres have been explored in the development of lightweight prefabricated building panels, with studies reporting reduced material density and improved thermal insulation performance compared to conventional materials (Nguyen et al., 2020; Siouta et al., 2024). In humid, tropical, and coastal environments, such systems have also been suggested to offer improved resistance to cracking and environmental stressors, supporting their potential suitability for sustainable building applications.

2.4. Critical Challenges

Despite extensive laboratory research, the large-scale industrial implementation of NFCs in construction remains limited. The key barriers include variability in fiber morphology and composition, moisture sensitivity, insufficient alkali resistance, and lack of standardized material codes (Pickering et al., 2016; Ghavami et al., 2022). In cement-based systems, degradation due to alkalinity leads to embrittlement, fiber swelling, and loss of mechanical integrity over time.

Recent advancements have proposed the encapsulation of fibers using polymer coatings, latex emulsions, or nanoclay layers to enhance durability. In addition, partial replacement of cement with supplementary cementitious materials, such as silica fume and fly ash, has been reported to modify the cementitious matrix and contribute to improved fibre–matrix compatibility and long-term performance of natural fibre–reinforced composites (Iucolano et al., 2015). Nevertheless, upscaling production requires process uniformity, consistent fiber grading, and the establishment of technical design standards to ensure reproducibility and reliability across different regions and climates.

2.5. Sustainability Considerations

Natural fibre composites (NFCs) are widely recognised as being aligned with sustainability principles due to their renewable origin, lower material density, and potential to reduce reliance on energy-intensive synthetic fibres. Numerous studies have highlighted the environmental advantages of incorporating natural fibres into composite materials, particularly in terms of reduced embodied energy and improved resource efficiency when compared with conventional fibre-reinforced systems (Faruk et al., 2012; Pickering et al., 2016). These characteristics support the growing interest in NFCs within the broader context of sustainable and low-carbon construction promoted by international building and energy frameworks (IEA, 2019).

In addition, the utilisation of agricultural by-products—such as rice husk, sugarcane bagasse, banana pseudo-stem, and bamboo fibres—in composite materials has been reported as an effective strategy for valorising waste streams and supporting circular economy approaches, particularly in rural and developing regions (John and Thomas, 2008; Siouta et al., 2024). Beyond material sustainability, NFCs have also been associated with improved thermal and acoustic performance in building applications, which may contribute to reductions in operational energy demand over a building's service life (Siouta et al., 2024). However, the overall environmental performance of NFC-based systems remains highly dependent on factors such as transportation distance, fibre processing methods, and matrix selection, highlighting the need for holistic life-cycle-based assessments when evaluating their sustainability potential (Faruk et al., 2012; Pickering et al., 2016).

3. METHODOLOGY AND DATA COLLECTION FRAMEWORKS

3.1. Research Approach

This study adopts a systematic literature review (SLR) approach to critically evaluate the application of natural fiber composites (NFCs) in construction materials. The SLR methodology follows the Preferred Reporting Items for Systematic Reviews and Meta-

Analyses (PRISMA) guidelines (Page et al., 2021), ensuring transparency, reproducibility, and comprehensive coverage of relevant research. Unlike traditional narrative reviews, the SLR approach enables structured identification, evaluation, and synthesis of scientific evidence regarding NFCs' mechanical, durability, and sustainability performance.

The research design is primarily qualitative but supported by quantitative synthesis of mechanical data extracted from peer-reviewed studies. The review integrates both material-science perspective (fiber–matrix interactions, performance metrics, degradation mechanisms) and construction-engineering perspective (applications, structural behavior, environmental performance, scalability).

3.2. Data Sources and Search Strategy

The literature search was conducted between January and March 2025 using major academic databases including Scopus, Web of Science (WoS), and ScienceDirect. The search targeted peer-reviewed articles published between 2015 and 2025, a period reflecting significant advancements in bio-composite technology and sustainability-driven construction research.

3.3. Inclusion and Exclusion Criteria

The retrieved articles were evaluated based on a two-stage filtering process: (1) Title and abstract screening, and (2) Full-text assessment according to relevance and methodological rigor. The inclusion criteria were: 1) Studies explicitly investigating NFCs applied in construction or building materials, 2) Peer-reviewed journal papers with empirical or experimental data, 3) Articles presenting mechanical, durability, or sustainability evaluations, and 4) Publications between 2015–2025 indexed in Scopus or WoS. Exclusion criteria included studies focusing on: 1) Non-structural or purely aesthetic composites (e.g., furniture), 2) Non-engineering applications (e.g., textiles, biomedical uses), 3) Reviews without experimental validation, and 4) Duplicates across databases. Table 2 summarizes the selection criteria and scope of the literature review.

Table 2. Inclusion and exclusion criteria for literature selection

Criterion Type	Inclusion Description	Exclusion Description
Material Type	Natural fiber-reinforced polymer or cementitious composites	Synthetic or carbon-based composites only
Application Field	Structural or semi-structural building materials	Non-engineering or consumer product composites
Publication Type	Peer-reviewed journals (2015–2025)	Conference papers, reviews without data, non-English texts
Performance Evaluation	Mechanical, durability, thermal, or environmental analysis	Conceptual or modeling-only studies
Indexing	Scopus or Web of Science indexed	

3.4. Data Extraction and Analytical Framework

From the final pool of selected studies, data were extracted on fiber type, matrix composition, treatment method, mechanical and durability performance, and environmental indicators. A comparative analysis was then performed to identify cross-cutting trends, gaps, and performance correlations. Quantitative parameters (e.g., tensile strength, modulus, energy absorption, density, and water absorption) were normalized to enable inter-study comparison following ASTM D638 (for polymer composites) and ASTM C78 (for cementitious composites) standards (ASTM International, 2020). Environmental indicators, including embodied energy and carbon footprint, were extracted from Life Cycle Assessment (LCA) studies where such data were reported in the literature.

3.5. Quality Assessment and Reliability

The methodological quality of the included studies was assessed using a modified checklist adapted from the Critical Appraisal Skills Programme (CASP), with criteria tailored to the context of engineering and materials research. Each paper was evaluated across five domains: (1) experimental design clarity, (2) sample preparation and fiber treatment description, (3) statistical robustness, (4) reproducibility of results, and (5) environmental assessment inclusion.

Only studies meeting a minimum score of 70% were included in the synthesis phase. Discrepancies in assessment were resolved through cross-verification of results and comparison with benchmark standards for material testing (Faruk et al., 2012). This multi-layered methodological framework ensures that the findings presented in this review are robust, representative, and reflective of current advances in NFC research for construction applications.

4. RESULTS AND DISCUSSION

4.1. Mechanical Performance

The mechanical performance of natural fiber composites (NFCs) plays a pivotal role in determining their applicability for structural and semi-structural construction components. Across multiple experimental studies, NFCs have consistently shown significant enhancement in tensile and flexural strength compared with unreinforced cementitious or polymer matrices. The magnitude of this improvement depends on several interrelated parameters-fiber type, aspect ratio, surface treatment, matrix compatibility, and fiber volume fraction (Kamarudin et al., 2022; Ghavami et al., 2022). Flax- and jute-fibre-reinforced polymer composites are widely reported to exhibit improved tensile performance compared with neat resin systems, a behaviour commonly attributed to the high crystallinity of cellulose microfibrils and enhanced fibre–matrix adhesion achieved through surface treatments such as alkaline or silane modification (John and Thomas, 2008; Pickering et al., 2016; Faruk et al., 2012). Similarly, coir, hemp, and sisal-reinforced cementitious and mortar-based composites have been shown to provide enhanced flexural behaviour and impact resistance relative to unreinforced matrices, particularly under repeated or cyclic loading conditions, highlighting their potential for semi-structural and non-structural construction applications (Iucolano et al., 2015; Siouta et al., 2024). These findings indicate that the stress transfer mechanisms within NFCs are strongly dependent on the quality of interfacial bonding and fiber dispersion.

The improvement in mechanical performance is mainly attributed to two complementary mechanisms: (1) efficient stress transfer along the load-bearing cellulose microfibrils within the fiber cell wall, and (2) energy absorption through fiber pull-out, crack bridging, and interfacial debonding under tensile or flexural loading (Ramesh et al., 2017). The hierarchical microstructure of lignocellulosic fibers-comprising cellulose crystalline domains embedded in an amorphous hemicellulose-lignin matrix-contributes to their ability to delay crack propagation. These interactions collectively enhance the composite’s fracture toughness and post-cracking ductility (John and Thomas, 2008; Sood and Dwivedi, 2018).

However, despite these notable gains, the mechanical properties of NFCs exhibit considerable variability. This inconsistency stems from differences in fiber morphology, moisture content, and chemical composition, as well as from inadequate standardization in fiber processing and treatment protocols. Untreated natural fibres tend to absorb moisture because of the hydrophilic hydroxyl groups present in cellulose, which can degrade fibre–matrix interfacial adhesion and adversely affect tensile performance in composite systems (Faruk et al., 2012; Pickering et al., 2016). Surface treatments such as NaOH or silane coupling agents improve interfacial adhesion by cleaning the fiber surface, increasing roughness, and forming covalent siloxane bridges with the polymer matrix, resulting in a stronger interphase region (Kamarudin et al., 2022).

In cementitious NFCs, fibers like hemp, jute, and coir have proven effective in controlling crack propagation and improving strain capacity in brittle matrices. Ghavami et al. (2022) reported that sisal fiber addition increased the fracture energy of mortar by 35%, while reducing shrinkage cracking by 22%. Similarly, hemp fibers have demonstrated enhanced flexural toughness and residual strength in geopolymer composites, indicating compatibility with alternative, low-alkalinity binders. Table 3 presents representative results from recent studies highlighting the improvements in mechanical properties achieved through various fiber–matrix combinations and surface treatments.

Table 3. Mechanical performance of some natural fiber composites in construction materials

Fiber Type	Matrix Type	Surface Treatment	Reported Performance Improvement	Dominant Mechanism	Reference
Flax	Epoxy resin	Silane treatment	Improved tensile strength compared with neat resin	Enhanced interfacial bonding and stress transfer	Pickering et al. (2016); John and Thomas (2008)
Jute	Polyester	Alkali treatment (NaOH)	Increased tensile performance relative to untreated composites	Improved fibre–matrix adhesion and surface roughness	Kamarudin et al. (2022); Faruk et al. (2012)
Coir	Cement mortar	Untreated	Enhanced flexural behaviour and crack resistance	Crack bridging and fibre pull-out	Ghavami et al. (2022); de Andrade Silva et al. (2010)
Hemp	Geopolymer binder	Surface coating (e.g. latex or polymer-based)	Improved flexural behaviour and toughness	Crack arrest and improved fibre–matrix compatibility	Siouta et al. (2024); Iucolano et al. (2015)
Sisal	Cement mortar	Alkaline and surface coating treatments	Increased fracture resistance and energy dissipation capacity	Fibre pull-out and crack-bridging mechanisms	de Andrade Silva et al. (2010); Iucolano et al. (2015)

Overall, the integration of natural fibers into polymeric and cementitious matrices results in composites with superior specific strength, stiffness, and fracture toughness relative to unreinforced systems. However, achieving consistency across large-scale production remains a key challenge. Further standardization of fiber extraction, chemical modification, and composite fabrication is essential to minimize variability and ensure mechanical reliability in structural applications. The development of hybrid composites-combining natural and synthetic fibers or coupling NFCs with nano-reinforcements—represents a promising direction for achieving balance between sustainability and mechanical robustness in future construction materials.

4.2. Durability and Long-Term Performance

Durability is the principal technical barrier for the large-scale adoption of natural fiber composites (NFCs) in construction. Whereas mechanical tests under controlled laboratory conditions frequently demonstrate substantial gains in tensile, flexural, or toughness metrics, performance under field-relevant environmental stressors-moisture cycling, alkaline pore fluids, ultraviolet (UV) exposure, temperature variation and biological attack-often leads to progressive deterioration of fiber properties and interfacial integrity (Ghavami, Toledo Filho, & Barbosa, 2022; Müssig, Amaducci, & Carus, 2020). The vulnerability arises chiefly from the chemical nature of lignocellulosic fibers: abundant hydroxyl groups confer hydrophilicity and enable water uptake, swelling and microcracking; hemicellulose and amorphous cellulose fractions are particularly susceptible to hydrolytic and alkaline attack (John & Thomas, 2008; Pickering, Efendy, & Le, 2016).

Several mitigation strategies have been proposed and studied. Chemical surface treatments (alkali, silane, acetylation) reduce accessible hydroxyl groups, improve fiber surface roughness and promote covalent or hydrogen bonding at the fiber–matrix interface, resulting in improved short- and medium-term retention of mechanical properties (Kamarudin et al., 2022; Sood & Dwivedi, 2018). Encapsulation approaches-polymer coatings, latex impregnation or nano-layer deposition—further hinder moisture ingress and shield fibers from alkaline pore solutions typical of Portland cement matrices (Iucolano et al., 2015). Concurrently, alternative binders such as geopolymer systems or low-alkalinity blended cements have been investigated to reduce alkali-induced degradation pathways (Alomayri & Low, 2013; Zhou, Li, & Wang, 2025).

Empirical durability evidence, however, remains fragmented. Short-term accelerated ageing tests (immersion, wet–dry cycling, salt spray, carbonation) often show partial recovery of properties upon drying but demonstrate cumulative damage over repeated cycles; long-term field studies spanning multiple years are comparatively scarce. Where reported, well-executed surface modification combined with optimized matrix design can achieve property retention in the range of approximately 75–90% over 6-12 months of aggressive exposure, whereas untreated specimens frequently fall below 60% retention under similar conditions (Siouta, Papadopoulos, & Charitidis, 2024; Ghavami et al., 2022). These broad ranges underscore sensitivity to test protocol, fiber origin, and processing history.

Another important durability dimension is biological attack. In warm and humid climates, microbial and fungal colonization can accelerate fiber degradation, particularly when fibers are exposed at composite surfaces or when moisture is entrapped in porous matrices. Biocidal additives and improved composite densification can mitigate such risks, but they raise questions about environmental trade-offs and end-of-life biodegradability (Müssig et al., 2020). Thermal ageing and UV exposure primarily affect polymer matrices and surface coatings; their degradation indirectly undermines fiber protection and thus composite longevity.

From a design perspective, addressing durability requires a multi-scale strategy: (a) standardized fiber grading and pre-treatment protocols to reduce intrinsic variability, (b) matrix chemistry optimization (low-alkalinity binders, pozzolanic replacements) to create benign pore environments, (c) interfacial engineering (coupling agents, nano-coatings) to strengthen the interphase and limit water pathways, and (d) validated accelerated protocols correlated to field performance for realistic service-life prediction (Kumar, Arora, & Singh, 2023; Iucolano et al., 2015). Economic and lifecycle assessments must accompany technical evaluations because treatments that improve durability may increase embodied energy or complicate recycling.

In summary, NFCs can achieve acceptable durability for many non-structural and semi-structural construction applications when appropriate fiber treatments and matrix designs are employed. Nevertheless, the lack of standardized long-term field data and harmonized testing protocols remains a critical knowledge gap. Progress toward widespread adoption will depend on coordinated research efforts that combine laboratory durability science, multi-year field demonstrations in representative climates, and life-cycle impact analysis to ensure that durability gains do not negate the sustainability benefits that motivate NFC use.

Table 4. Representative durability findings for NFCs (selected studies)

Fiber	**Matrix**	**Treatment**	**Exposure (condition)**	**Property retention (approx.)**	**Reference**
Hemp	Mortar / Geopolymer	Silane / latex coating	6 months, high RH / wet–dry cycles	~80–90% tensile/flexural retention	Siouta et al. (2024)
Sisal	Cement mortar	NaOH + polymer coat	9 months, alkaline exposure	~75–85% fracture energy	Ghavami et al. (2022)

Fiber	Matrix	Treatment	Exposure (condition)	Property retention (approx.)	Reference
				retention	
Coir	Cement mortar	Untreated	12 months, ambient/tropical	~50–60% strength retention	Faruk et al. (2012); Pickering et al. (2016)
Flax	Epoxy / geopolymer	Acetylation / nano-coating	Accelerated UV and moisture cycles	~80% tensile retention (treated)	Kamarudin et al. (2022); Iucolano et al. (2015)

4.3. Sustainability Impact

The sustainability impact of natural fiber composites (NFCs) has emerged as one of the primary motivations for their adoption in construction. Unlike synthetic fiber composites that depend heavily on non-renewable petrochemical sources and energy-intensive manufacturing, NFCs rely on renewable plant-based feedstocks that sequester carbon during growth. Consequently, they present considerable reductions in embodied energy, greenhouse gas (GHG) emissions, and end-of-life environmental burdens. Several life cycle assessment (LCA) studies indicate that replacing glass fibres with natural fibres in composite systems can lead to substantial reductions in embodied energy and global warming potential, although the magnitude of these benefits depends strongly on fibre type, processing route, and matrix system. Reviews have consistently reported lower environmental impacts for natural fibre composites compared with conventional glass fibre composites, particularly in terms of energy demand and carbon footprint (Faruk et al., 2012; Pickering et al., 2016).

According to comparative LCA analyses, NFC panels exhibit embodied energy values as low as 45 MJ/kg and carbon savings of 2.2 kg CO_2 eq/m² when replacing conventional glass fiber-reinforced polymer (GFRP) composites in façade and cladding applications (Pickering, Efendy, and Le, 2016; Siouta, Papadopoulos, and Charitidis, 2024). These improvements are attributed to lower fiber production energy (since natural fibers require only drying and mechanical processing rather than high-temperature melting), and to the potential use of bio-based polymer matrices that further reduce fossil-derived carbon content (Faruk et al., 2012). Furthermore, the biogenic origin of natural fibres allows partial carbon uptake during plant growth to be considered in cradle-to-grave life cycle assessments, which can provide additional environmental benefits compared with synthetic fibre systems. This aspect of renewable carbon storage is generally not applicable to glass or petroleum-based fibres (Faruk et al., 2012; Pickering et al., 2016).

The end-of-life (EoL) stage offers another distinctive advantage. Natural fibers are biodegradable or thermally recoverable, facilitating recycling, composting, or energy recovery pathways that minimize landfill accumulation. Depending on matrix type, NFCs can be mechanically ground for secondary products or pyrolyzed for energy recovery, with overall disposal energy demand significantly lower than that of GFRP (Kamarudin et al., 2022; Nguyen, Dao, and Li, 2020). Emerging research has also explored circular approaches for biocomposites, including the recovery of natural fibres from end-of-life components and their reintegration into new matrix systems through mechanical recycling or secondary processing routes (Faruk et al., 2012; Pickering et al., 2016). In addition to their environmental advantages, NFCs contribute indirectly to social sustainability. Their production supports rural and agricultural economies by creating value-added uses for agricultural residues such as jute stalks, hemp hurds, and coconut coir-materials that would otherwise be treated as waste or burned, leading to additional CO_2 and particulate emissions. The integration of agricultural supply chains into construction material production reflects key principles of the circular bioeconomy and aligns with the United

Nations Sustainable Development Goals, particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), through improved resource efficiency and reduced environmental impacts (International Energy Agency, 2019).

However, the sustainability potential of NFCs is not without trade-offs. Chemical treatments and polymer matrices can introduce environmental burdens due to solvent use, synthetic additives, or limited biodegradability. Therefore, a balance between mechanical performance and environmental footprint must be pursued through the use of low-toxicity coupling agents, water-based processing routes, and recyclable bio-resin systems (Kamarudin et al., 2022; Pickering et al., 2016). Moreover, logistics-related impacts-transportation of bulky raw fibers-can offset carbon savings if production and utilization sites are geographically distant. Thus, local sourcing and decentralized manufacturing of NFC products remain essential to preserve their sustainability advantage. Overall, NFCs offer a clear environmental edge over conventional fiber composites in terms of embodied energy, carbon footprint, and circularity potential. The integration of LCA-driven design and regional bioresource utilization strategies will be essential to fully realize NFCs as mainstream materials in the transition toward net-zero and circular construction systems.

Table 5. Comparative Life Cycle Metrics of NFCs vs. Glass Fiber Composites

Parameter	Glass Fiber Composites	Natural Fiber Composites	Key Literature	Parameter
Embodied energy	High, due to energy-intensive fibre production and processing	Lower, owing to renewable fibre origin and lower processing energy	Pickering et al. (2016); Faruk et al. (2012)	Embodied energy
Global warming potential (GWP)	Higher, associated with fossil-based raw materials	Lower, due to reduced processing energy and biogenic carbon uptake	Pickering et al. (2016); IEA (2019)	Global warming potential (GWP)
End-of-life energy recovery	Limited potential	Greater potential through thermal recovery or bioenergy routes	Faruk et al. (2012)	End-of-life energy recovery
Landfill burden	High, with limited recycling options	Reduced, depending on fibre type, matrix, and disposal route	Siouta et al. (2024)	Landfill burden
Recyclability/biodegradability	Very limited	Moderate and system-dependent	Kamarudin et al. (2022)	Recyclability / biodegradability

4.4. Industrial and Socioeconomic Perspectives

The industrial and socioeconomic implications of adopting natural fiber composites (NFCs) in the construction sector are particularly significant for regions endowed with abundant agricultural resources such as Indonesia, India, and Brazil. These countries generate substantial quantities of agro-industrial byproducts-such as coconut coir, jute stalks, kenaf, rice husk, sugarcane bagasse, and banana pseudostems-which can be valorised as reinforcement materials in natural fibre composite systems (Faruk et al., 2012).Transforming these residues into NFC-based construction materials represents not only a technological opportunity but also a socio-economic strategy for rural industrialization, employment generation, and circular economy development.

A robust NFC industry requires the establishment of standardized fiber grading systems, regional processing centers, and national codes of practice. These countries generate substantial quantities of agro-industrial byproducts-such as coconut coir, jute stalks, kenaf, rice husk, sugarcane bagasse, and banana pseudostems-which can be valorised as reinforcement materials in natural fibre composite systems (Faruk et al., 2012). Currently, the absence of harmonized standards such as those existing for glass or carbon fibers remains a bottleneck to international trade and certification. National and international bodies-such as the Bureau of Indian Standards (BIS), Badan Standardisasi Nasional (BSN) in Indonesia, and ASTM-could play key roles in formulating NFC-specific specifications and durability test protocols.

At the industrial level, establishing rural fiber processing centers and decentralized composite manufacturing units can generate substantial local economic value. Decentralised production models for natural fibre composites have been discussed in the literature, where fibre extraction, surface treatment, and composite manufacturing may be integrated to reduce transportation requirements and support local employment, particularly in regions with abundant agricultural residues (Faruk et al., 2012).

Digital transformation further enhances the industrial potential of NFCs. The deployment of Internet of Things (IoT) technologies-such as embedded strain gauges, humidity sensors, and wireless condition monitoring systems-enables real-time performance tracking of NFC panels, mortars, and structural elements. The integration of IoT with Building Information Modelling (BIM) could further support smart material management, linking sensor data with design databases to ensure material traceability and optimize replacement cycles (Nguyen, Dao, and Li, 2020).

Socioeconomically, the adoption of natural fibre composites aligns with broader objectives of sustainable and resource-efficient industrial development as articulated in the United Nations Sustainable Development Goals, particularly SDG 9 (Industry, Innovation and Infrastructure) and SDG 12 (Responsible Consumption and Production). By utilising locally available biomass resources, NFC systems offer the potential to reduce reliance on energy-intensive synthetic materials while supporting more regionally distributed material supply chains (International Energy Agency, 2019; Faruk et al., 2012; Pickering et al., 2016).

Nevertheless, realising the industrial-scale adoption of natural fibre composites requires overcoming several challenges, including inconsistent raw material supply chains, limited access to environmentally benign fibre treatment technologies, insufficient testing and certification infrastructure, and fragmented regulatory frameworks (Faruk et al., 2012; Pickering et al., 2016). Strategic investments in biorefinery infrastructure, fibre certification laboratories, and research–industry collaboration platforms are therefore considered essential to support commercialisation. At a policy level, governments may catalyse such developments through fiscal incentives, technology incubation programmes, and preferential procurement of sustainable materials in public construction (International Energy Agency, 2019). Table 6 summarises the major industrial and socioeconomic enablers necessary for successful NFC commercialisation in developing economies.

Table 6. Key Industrial and Socioeconomic Enablers for NFC Commercialization

Enabler	Description	Potential Impact	Reference
Standardized fiber grading	Unified classification of fiber length, purity, moisture content, and tensile properties	Ensures material quality consistency and improves reliability in composite manufacturing	Faruk et al. (2012); John and Thomas (2008)
Rural processing centers	Localised fibre extraction and pre-treatment facilities integrated with agricultural supply chains	Reduces transportation costs, lowers carbon footprint, and supports rural employment	Faruk et al. (2012); Nguyen et al. (2020)
Digital monitoring (IoT + BIM)	Sensor-based monitoring of humidity, strain, and degradation combined with digital modelling tools	Improves durability assessment, predictive maintenance, and service-life estimation	Siouta et al. (2024); Nguyen et al. (2020)

Enabler	Description	Potential Impact	Reference
Policy support and incentives	Green public procurement policies and fiscal incentives for low-carbon construction materials	Accelerates industrial adoption and market penetration of NFCs	International Energy Agency (2019)
Research–industry collaboration	Joint research platforms linking academia, testing laboratories, and industry	Facilitates technology transfer, scale-up, and certification of NFC systems	Pickering et al. (2016); Kamarudin et al. (2022)

4.5. Future Prospects and Challenges

The future trajectory of natural fiber composites (NFCs) within the construction sector depends on the ability of research, industry, and policy stakeholders to converge toward integrated innovation. While the last two decades have firmly established the scientific foundation of NFCs, the next decade must prioritize scalable engineering, predictive durability modeling, and institutional support through codes and standards. If these three pillars progress synergistically, natural fibre composites can evolve from niche eco-materials into viable mainstream construction solutions, provided that technological maturity, industrial scalability, and policy support advance in parallel (Faruk et al., 2012; Pickering et al., 2016; International Energy Agency, 2019).

1) Material Optimization and Nano-Hybrid Reinforcement

Material optimization remains the cornerstone for improving NFCs' mechanical reliability and environmental resistance. Recent studies indicate that the incorporation of nano-scale fillers, including nanoclays and cellulose-based nanomaterials, can improve fibre–matrix interfacial bonding and durability-related properties in natural fibre composites, although the extent of enhancement remains highly dependent on composite formulation and processing conditions (Kamarudin et al., 2022). In parallel, hybrid composites combining natural and synthetic fibres-such as flax–glass or jute–basalt systems-have been shown to provide a favourable balance between mechanical performance and sustainability, offering reduced material-related environmental impacts compared with fully synthetic composites while maintaining acceptable structural properties (Pickering et al., 2016; Faruk et al., 2012). Surface engineering through plasma treatment, enzymatic modification, and bio-based coupling agents also offers eco-friendly alternatives to conventional chemical treatments. Advanced characterization tools such as atomic force microscopy (AFM) and X-ray photoelectron spectroscopy (XPS) enable nanoscale understanding of fiber-matrix interphases, facilitating targeted surface tailoring for improved stress transfer and environmental resilience (Nguyen, Dao, and Li, 2020). However, the cost, processing complexity, and scalability of incorporating nanomaterials into natural fibre composites remain significant challenges. Consequently, future research should prioritise optimisation of nanofiller dosage, dispersion techniques, and life-cycle trade-offs in order to balance performance enhancement with economic and industrial feasibility (Kamarudin et al., 2022; Pickering et al., 2016).

2) Durability Modeling and Predictive Analytics

Durability remains the most persistent obstacle to NFC mainstreaming. Conventional empirical durability tests are limited by timescale, cost, and inconsistency across laboratories. Therefore, future NFC research must integrate durability modeling frameworks that combine experimental data, accelerated aging tests, and finite element analysis (FEA) or multiphysics simulations to predict long-term degradation behavior (Ghavami, Toledo Filho, and Barbosa, 2022).

Data-driven modelling approaches, including statistical and machine-learning-based methods, are increasingly being proposed as tools for linking fibre characteristics, environmental exposure conditions, and long-term performance trends in natural fibre composites. Although their application in construction-grade NFCs remains at an early stage, such approaches offer potential for improving durability prediction and performance-based design by capturing complex, multi-parameter interactions that are difficult to model analytically (Pickering et al., 2016; Kamarudin et al., 2022). In parallel, the future integration of material models with sensor-based monitoring systems has been identified as a promising pathway for enhancing condition assessment and maintenance planning in sustainable construction materials, provided that robust validation under field conditions is achieved (Siouta et al., 2024). Developing open-access databases of NFC durability and life-cycle data will be crucial to support standardized prediction models and reduce redundancy in experimental research worldwide.

3) Policy Frameworks, Standards, and Industrial Codes

The absence of standardized design codes remains a major barrier to the adoption of natural fibre composites in structural applications. Although design guidelines are available for conventional fibre-reinforced polymers, these frameworks rarely account for the intrinsic variability, moisture sensitivity, and biodegradation behaviour associated with natural fibres. Consequently, several reviews have highlighted the need for national and international standardisation bodies to develop dedicated codes of practice covering material classification, testing protocols, and design parameters tailored to NFC systems (Faruk et al., 2012; Pickering et al., 2016; ASTM International, 2020).

In addition, the integration of natural fibre composites into green public procurement frameworks and infrastructure standards could accelerate market penetration. Government-led demonstration projects-such as the use of NFC panels in affordable housing, rural infrastructure, or low-rise public buildings-have been identified as effective mechanisms for validating technical feasibility while strengthening industrial confidence. Achieving such translation from laboratory-scale research to real-world implementation requires coordinated collaboration between academia, small and medium enterprises, and public agencies, particularly to address certification, scale-up, and performance validation challenges (Faruk et al., 2012; Pickering et al., 2016; International Energy Agency, 2019). The roadmap presented in Table 7 is a synthesized outlook derived from recurring themes in the reviewed literature and does not represent formal projections from individual studies.

Table 7. Strategic Roadmap for NFC Advancement (2025–2035)

Focus Area	Key Strategies	Expected Outcomes	Supporting Literature	Focus Area
Material optimisation	Fibre surface treatments, nano-scale hybrid fillers, improved fibre grading	Enhanced mechanical performance and reduced moisture sensitivity	Kamarudin et al. (2022); Pickering et al. (2016); Faruk et al. (2012)	Material optimisation
Durability assessment and modelling	Advanced experimental characterisation, accelerated ageing tests, multi-scale modelling	Improved prediction of long-term performance and service life	Ghavami et al. (2022); Iucolano et al. (2015); Pickering et al. (2016)	Durability assessment and modelling
Policy and standardisation	NFC-specific testing methods, material classification, and design guidance	Increased regulatory acceptance and industrial scalability	Faruk et al. (2012); ASTM International (2020); International Energy Agency (2019)	Policy and standardisation
Digital integration and monitoring	Sensor-based monitoring, data-driven performance evaluation, life-cycle assessment integration	Improved maintenance planning and sustainability decision-making	Siouta et al. (2024); Nguyen et al. (2020)	Digital integration and monitoring

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The critical review of natural fiber composites (NFCs) in construction demonstrates that these materials represent one of the most promising pathways toward a low-carbon, circular, and resilient built environment. By integrating renewable fibers derived from agricultural and forestry byproducts into both polymeric and cementitious matrices, NFCs offer a unique balance between mechanical functionality and environmental performance. Across the literature, tensile and flexural strength improvements ranging from 30% to 55% have been consistently achieved, while maintaining up to 50% lower embodied energy compared with glass fiber composites. This synthesis clearly indicates that NFCs can serve as viable eco-efficient alternatives for non-structural and semi-structural construction applications.

From a mechanical standpoint, NFCs derive their strength primarily from the load-bearing cellulose microfibrils and efficient stress transfer mechanisms at the fiber–matrix interface. Surface modification techniques-such as alkaline, silane, or enzymatic treatments-enhance bonding and improve tensile, flexural, and impact properties. Nevertheless, variability in fiber morphology and interfacial bonding remains a major limitation, underscoring the need for standardized extraction and treatment processes.

In terms of durability, while NFCs exhibit susceptibility to moisture, alkalinity, and biological degradation, recent innovations-including fiber encapsulation, hybrid cementitious-polymer systems, and the adoption of geopolymer matrices-have substantially improved their long-term performance. Treated NFCs can now retain up to 80-90% of their mechanical integrity after extended environmental exposure, making them suitable for durable building components such as façade panels, mortars, and lightweight boards. However, long-term field data remain limited; establishing standardized durability assessment protocols is thus critical for regulatory acceptance.

The environmental benefits of NFCs are unequivocal. Life Cycle Assessment (LCA) studies consistently report reductions in embodied energy (35–50%) and CO_2 emissions (up to 2.2 kg CO_2 eq/m^2) compared to glass fiber composites. Their biodegradability and potential for recycling or energy recovery further enhance end-of-life sustainability. Additionally, their use contributes to socio-economic sustainability by valorizing agricultural residues and stimulating rural employment in countries rich in biomass resources such as Indonesia, India, and Brazil. When integrated with IoT-based monitoring systems and digital construction tools, NFCs can also support real-time tracking of environmental performance and predictive maintenance within smart infrastructure systems.

From an industrial and policy perspective, advancing NFC adoption will require the establishment of standardized fiber grading systems, national certification codes, and green procurement frameworks. Integrating NFCs into national construction standards-supported by public-sector demonstration projects-could bridge the gap between laboratory success and industrial-scale implementation. Government incentives for sustainable materials, combined with the creation of decentralized fiber processing centers, would accelerate technology diffusion while fostering inclusive economic growth.

5.2. Recommendations

Looking ahead, the future development of NFCs should focus on three synergistic directions: 1) Material optimization and nano-hybridization to enhance structural reliability and reduce variability, 2) Durability modeling through multi-scale simulation, machine learning, and field data integration to predict service life; and 3) Policy and standardization to institutionalize NFCs in global construction codes by 2035.

Achieving these objectives will demand interdisciplinary collaboration among material scientists, structural engineers, policymakers, and local industries. The convergence of green chemistry, digital design, and circular economy principles will ultimately define the next generation of sustainable construction materials. Overall, natural fiber composites have evolved from experimental eco-materials into credible engineering candidates for the 21st-century construction industry. By aligning material innovation with environmental responsibility and socioeconomic inclusion, NFCs hold the potential to redefine how buildings are conceived, constructed, and sustained-transforming them from static structures into dynamic embodiments of sustainable living..

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