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Natural Fiber-Reinforced Composites in Precast Modular Construction: A Critical Review of Structural Viability and Durability Considerations for High-Rise Applications

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ABSTRACT

Natural Fiber-Reinforced Polymer Composites (NFRPCs), which utilize renewable lignocellulosic fibers, present a compelling, low-carbon alternative. These materials offer substantial environmental benefits. Furthermore, their low density and high specific stiffness (e.g. flax rivaling E-glass on a weight-normalized basis) make them structurally appealing for lightweight, prefabricated elements in high-rise applications. This critical review synthesized contemporary research on integrating NFRPCs into precast modular structures, rigorously assessing their structural viability, material variability, and long-term durability. The analysis confirmed that NFRPCs are immediately viable for high-performance, secondary applications, such as façade cladding and partition systems. In these roles, they exhibit intrinsically beneficial properties, including a very low thermal conductivity (~0.05–0.15 W/m K) and high acoustic absorption (~0.4–0.8), offering superior integrated thermal and acoustic performance compared to traditional inert materials. Durability is challenged by the hygroscopic nature of lignocellulosic fibers, leading to significant moisture absorption, interface weakening, and substantial mechanical degradation, with retained strength potentially dropping to 40–60% of initial values under severe hygrothermal or alkaline exposure. Compounding this, the high inherent variability of natural fibers results in a large coefficient of variation (~0.30–0.40), which necessitates the use of highly conservative material partial safety factors (~1.8–2.2) in reliability-based design, thereby severely limiting the material's usable load-bearing capacity.

摘要

利用可再生木质纤维素纤维的天然纤维增强聚合物复合材料 (NFRPC)是一种引人注目的低碳替代品. 这些材料具有巨大的环境效益. 此外，它们的低密度和高比刚度 (例如，亚麻在重量归一化的基础上可与e玻璃相媲美)使其在结构上对高层应用中的轻质预制构件具有吸引力. 这篇评论综合了将NFRPC集成到预制模块化结构中的当代研究，严格评估了它们的结构可行性、材料可变性和长期耐久性. 分析证实，NFRPC可立即用于高性能的二次应用，如外墙覆层和隔墙系统. 在这些角色中，它们表现出固有的有益特性，包括非常低的导热性 (~0.05-0.15 W/m K)和高声吸收率 (~0.4–0.8)，与传统的惰性材料相比，具有优异的综合热和声学性能. 木质纤维素纤维的吸湿性对耐久性提出了挑战，导致显著的吸湿性、界面弱化和实质性的机械降解，在严重的湿热或碱性暴露下，保持的强度可能会降至初始值的40-60%. 更糟糕的是，天然纤维的高固有变异性导致了较大的变异系数 (~0.30–0.40)，这需要在基于可靠性的设计中使用高度保守的材料部分安全系数 (~1.8–2.2)，从而严重限制了材料的可用承载能力.

KEYWORDS
Natural fiber-reinforced composites; structural viability; structural durability; modular precast construction; high-rise applications; sandwich panels

关键词
关键词; 天然纤维增强复合材料; 结构可行性; 结构耐久性; 模块化预制结构; 高层应用; 夹芯板

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Introduction

Rapid urbanization and stringent sustainability mandates have compelled the construction industry to improve resource efficiency and performance while cutting costs. In particular, clients and regulators demand lower embodied carbon, shorter schedules, and reduced onsite labor without sacrificing structural robustness or occupant safety (Loizou et al. 2021; Rojas-Herrera et al. 2025). Industrialized construction broadly encompassing prefabrication and modular building systems addresses these needs by shifting the fabrication of standardized components to controlled factory environments. Studies consistently show that factory production enables superior quality control, optimized material use, and waste minimization relative to conventional site-based methods (Rojas-Herrera et al. 2025; Zhang et al. 2024). In one analysis, modular concrete and steel systems generated roughly 46% and 87% less construction waste than traditional approaches (Table 1) (Loizou et al. 2021; Rojas-Herrera et al. 2025). Standardization and automation also reduce defects and improve productivity. Offsite assembly demands less labor and is faster, as well-fitting modules only need to be joined on-site under controlled conditions.

Notably, these process efficiencies translate into sizable schedule and cost savings (Table 1). Industry reports indicate that modular construction can shorten project timelines by approximately 20–50% and lower overall costs (including materials, labor, and overhead) by 20% or more (Blanco et al. 2023; Loizou et al. 2021). A McKinsey analysis, for example, found end-to-end build times cut by up to half for modular homes, along with commensurate cost reductions (Blanco et al. 2023). Many project-level studies similarly report at least 20% faster completion and substantial labor-hour savings when factories fabricate major elements in parallel with onsite work. Quality improvements are also documented, with precision production, prefabrication can enhance design quality and reduce rework compared to traditional methods. For instance, one review noted that standardizing components in factory conditions cut steel usage by up to 30% through tailored load designs, while slashing manufacturing time and onsite assembly work (Blanco et al. 2023; Rojas-Herrera et al. 2025).

Beyond process improvements, material innovations within modular construction promise further gains. Conventional high-rise precast systems typically utilize steel-reinforced concrete frames and glass- or carbon-fiber-reinforced polymer (FRP) panels (Huang et al. 2024; Wang et al. 2023; Wei et al. 2018). Cement-based concrete is especially carbon-intensive: global cement production generates on the order of 1.6 billion tonnes of CO_2 per year (roughly 7–8% of all anthropogenic emissions) (Purton 2024). Synthetic fibers like E-glass and Kevlar also require energy-intensive processing, contributing significantly to a component's embodied energy (Alrehaili, Nurdiawati, and Al-Ghamdi 2025; Hosseini et al. 2026; Hosseini, Gaff, Konvalinka, et al. 2025, 2025; Hosseini and Raji 2023; Zhang et al. 2024). NFRPCs offer an alternative. These composites combine renewable lignocellulosic fibers (e.g., flax, hemp, jute, sisal, coir, bamboo) with polymeric or cementitious matrices and can be manufactured using standard composite methods in a factory setting (Asif et al. 2025; Hosseini et al. 2023; Hosseini, Gaff, Hui, et al. 2025; Hosseini, Gaff, Wei, et al. 2025; Radwa et al. 2024, 2025). The fibers' low density and plant origin substantially reduce material weight and life-cycle emissions.

On a specific-strength basis, many natural fibers rival glass; for example, flax or hemp fibers have tensile strength and stiffness comparable to E-glass per unit weight (Ajayi et al. 2025; Formela, Saeb, and Klapiszewski 2022). Because they grow rapidly and are often agricultural byproducts, natural fibers typically incur significantly lower raw material costs than industrial fibers. Recent surveys indicate that a given kilogram of flax, jute, or hemp often costs only a fraction of the equivalent weight of glass fiber (Ahmad, Choi, and Park 2015; Ajayi et al. 2025; Formela, Saeb, and Klapiszewski 2022). In practical terms, natural

Table 1. Comparative impact of construction methodologies and material integration (Loizou et al. 2021).

Metric	Traditional Construction	Modular Construction	Reduction
Schedule	Baseline (100%)	~50%	~50%
Waste (Concrete)	Baseline (100%)	~54%	~46%
Waste (Steel)	Baseline (100%)	~13%	~87%
Embodied Carbon	Baseline (100%)	~66%	~34%
Material Cost	Baseline (100%)	~20%	~80%
Safety Incidents	Baseline (100%)	~20%	~80%
Noise	Baseline (100%)	~60%	~40%

fiber composites can have 40–50% lower embodied carbon in manufacturing than glass-fiber systems (Lopez-Arraiza et al. 2025; Nissar et al. 2025), while raw fiber costs are commonly 60–80% below those of E-glass (Ajayi et al. 2025; Formela, Saeb, and Klapiszewski 2022; Shahinur and Hasan 2020). These attributes, including high specific performance, renewability, low density, and cost, suggest that NFRPCs could enable lightweight, low-carbon structural and façade elements in modular buildings.

Nevertheless, the uptake of NFRPCs in tall-building construction has been limited by technical concerns. Lignocellulosic fibers naturally absorb moisture, which can weaken the fiber–matrix interface and lead to long-term degradation (Elfaleh et al. 2023). Unprotected natural composites may undergo fungal attack, hydrolysis, or dimensional changes in humid environments, which challenge their durability in building envelopes. In addition, natural fibers exhibit significant variability factors, such as plant species, soil nutrients, harvest timing, and processing, can cause wide scatter in tensile strength, stiffness, and fiber length (Imon 2024). This inconsistency complicates engineering design and quality assurance. Finally, purely plant-based composites may struggle with fire resistance, ultraviolet stability, and biodegradation (at the end of life) unless additives or protective treatments are used. Addressing these durability and variability issues is essential before natural-fiber systems can be confidently deployed in structural applications.

This review synthesizes contemporary research on integrating NFRPCs into precast modular construction, with emphasis on multistory building structures and enclosures. We survey recent studies (from 2010 to present) on fiber characterization and composite mechanical properties, including quantitative comparisons to synthetic-fiber analogs. We critically examine durability degradation mechanisms under environmental and hygrothermal exposure, and we consider design and analysis approaches (e.g., probabilistic modeling) that account for material variability and moisture sensitivity. The review also highlights emerging implementation examples and case studies of NFRPC elements in modular projects. Finally, we identify key research needs, such as improved fiber treatments, hybrid composite designs, and predictive service-life models, that will be crucial to advancing NFRPC technology from the laboratory into mainstream modular construction practice. Collectively, this evidence-based review aims to equip engineers and researchers with a thorough understanding of the prospects and challenges of natural-fiber composites for sustainable modular buildings.

Method

The literature search for this review was conducted using a suite of interdisciplinary and discipline-specific academic databases selected for their comprehensive coverage of civil engineering and mechanical engineering research. Primary databases included Google Scholar, Scopus, and Web of Science. The temporal scope of the review was limited to publications released between 2010 and 2025. This 15-year period was selected to capture recent advancements in natural fiber surface treatments, composite manufacturing technologies, including automation and additive manufacturing, and the development of advanced life-cycle assessment methodologies. The selected timeframe also corresponds to a period of intensified research activity driven by increasing regulatory and societal demand for sustainable, low-carbon alternatives to conventional synthetic composite materials in the construction sector.

The search strategy was designed to systematically intersect three core thematic domains: reinforcing materials, composite technologies, and construction applications. Boolean logic was employed to combine concept-centric and application-oriented keywords. Terms related to reinforcing materials included variations of natural fiber, lignocellulosic fiber, bast fiber, and specific fiber types such as flax, hemp, jute, bamboo, coir, and sisal. These were combined with composite-related terms, such as natural fiber-reinforced polymer, biocomposite, sandwich panel, fiber–matrix interface, and hybrid composite. Construction-related terms included modular construction, precast, prefabricated, façade cladding, high-rise, durability, and structural viability. Database-specific syntax and filters were applied as appropriate to refine the results and enhance relevance.

Eligibility criteria were established a priori to ensure the inclusion of technically rigorous and academically credible studies. Studies were included if they were peer-reviewed journal articles or reputable conference proceedings, focused explicitly on the mechanical performance, durability, or structural design of natural fiber-reinforced polymer composites within civil engineering or architectural applications, and provided empirical data, validated computational models, or quantitative meta-analytical results. Only publications written in English were considered to maintain consistency and accuracy in technical interpretation. Studies were excluded if they focused on dietary or purely textile-grade natural fibers without relevance to structural applications, originated from non-peer-reviewed sources, such as opinion pieces or editorials, relied solely on theoretical or numerical modeling without experimental validation, or addressed only traditional construction materials, such as steel or conventional concrete without reference to composite integration. These criteria ensured that the final body of literature reflected mature, application-oriented research capable of informing the engineering assessment of natural fiber-reinforced composites in modular and precast construction systems.

This critical review addresses a previously unexplored research niche at the intersection of composite materials engineering and building construction by integrating three largely disconnected domains NFRPCs, modular and precast construction systems, and durability of bio-based composites. While extensive literature exists in each area, prior studies have evolved in isolation, with NFRPC reviews focusing primarily on material characterization, modular construction research assuming conventional materials, and durability studies rarely contextualized within real building systems. This review constitutes the first application-driven synthesis that explicitly examines the feasibility of NFRPCs in high-rise precast modular construction, linking laboratory-scale material behavior to system-level structural performance, regulatory expectations, and long-term service conditions.

A key contribution of the review lies in translating material variability and durability degradation into structural design-relevant metrics. Although the high scatter in mechanical properties and environmental sensitivity of NFRPCs is well documented, these characteristics are seldom incorporated into reliability-based design frameworks. This review systematically consolidates reported coefficients of variation, characteristic strength reductions, and aging-related losses to evaluate their implications for partial safety factors and usable design strengths. By benchmarking these outcomes against established practices for synthetic fiber-reinforced polymers, the review demonstrates that the effective design capacity of NFRPCs is often substantially lower than their mean laboratory performance. This reliability-aware synthesis provides a quantitative basis for identifying applications where NFRPCs can meet structural requirements and distinguishing them from scenarios where variability and durability penalties render their use impractical.

The review further distinguishes itself by framing NFRPCs within the specific constraints and opportunities of modular and precast construction. Factory-controlled production environments offer improved quality control and repeatability, partially mitigating material variability, while modular systems impose strict demands on weight, standardization, transport, and connection detailing. Within this context, the review highlights the advantages of NFRPCs for lightweight façade and envelope components, particularly when configured as multifunctional sandwich panels capable of providing structural adequacy for non-load -bearing applications alongside thermal and acoustic performance. At the same time, the review moves beyond aspirational narratives by clearly identifying fundamental material limitations-such as hygroscopicity, thermal degradation thresholds, and inherent variability-that constrain certain structural uses despite advances in treatments and hybridization. By integrating performance, durability, reliability, and constructability considerations into a single analytical framework, this work offers a construction-oriented and design-relevant synthesis that delineates realistic pathways for the adoption of NFRPCs in high-rise precast modular buildings.

Lignocellulosic fiber characterization

Classification and botanical origins

Natural lignocellulosic fibers are categorized by the plant part and species from which they are derived (Eleutério et al. 2025). Prominent groups include bast fibers (stem phloem of dicots) such as flax (*Linum usitatissimum*), hemp (*Cannabis sativa*), jute, ramie, and kenaf (Ngo 2017); leaf fibers (sclerenchymatous bundles of monocot leaves) like sisal (Agave sisalana), abaca (Manila hemp, *Musa textilis*), banana, and pineapple leaf (Ngo 2017); seed fibers, such as cotton and kapok; and fruit fibers, notably coconut coir from the husk (mesocarp) of *Cocos nucifera*. Other fibers are derived from agricultural residues or grasses/wood, such as bamboo, wheat straw, and rice husk (grass/straw fibers), as well as softwood and hardwood pulps (Eleutério et al. 2025). Among these, bast fibers have attracted special interest for engineering composites because of their long, high-cellulose structures and favorable specific strength (Eleutério et al. 2025). In particular, flax and hemp are the most intensively studied reinforcements, reflecting their centuries-long use in textiles and construction, as well as the existence of robust supply chains for these temperate-region crops (Eleutério et al. 2025; Ngo 2017). The Figure 1 presents major types of natural fibers. Individual fiber tensile properties Natural bast fibres such as flax, hemp, jute, and sisal exhibit very high strength and stiffness, but with large scatters (Figure 2).

Chemical composition and microstructure

The functional properties of plant fibers derive from their hierarchical cell-wall structure. In general, lignocellulosic fibers are predominantly composed of cellulose (typically tens of percent of the dry mass) together with substantial amounts of hemicellulose and lignin (Suriani et al. 2021). Proportion ranges for natural fibers are roughly 30–80% cellulose, 7–40% hemicellulose, and 3–33% lignin by weight (Suriani et al. 2021), with minor constituents (pectins, waxes, ash) completing the composition. Cellulose molecules pack into semicrystalline microfibrils (roughly 10–200 nm in diameter) embedded in an amorphous matrix of hemicellulose and lignin (Eleutério et al. 2025; Suriani et al. 2021). These microfibrils alternate crystalline and amorphous segments, and their average orientation (the microfibril angle, MFA) to the fiber axis critically determines mechanics. Fibers with a low MFA (microfibrils nearly parallel to the axis) exhibit very high axial stiffness and strength, whereas a high MFA gives greater ductility and energy absorption (Eleutério et al. 2025). For example, ramie fibers have an extremely small MFA (on the order of 7–10°),

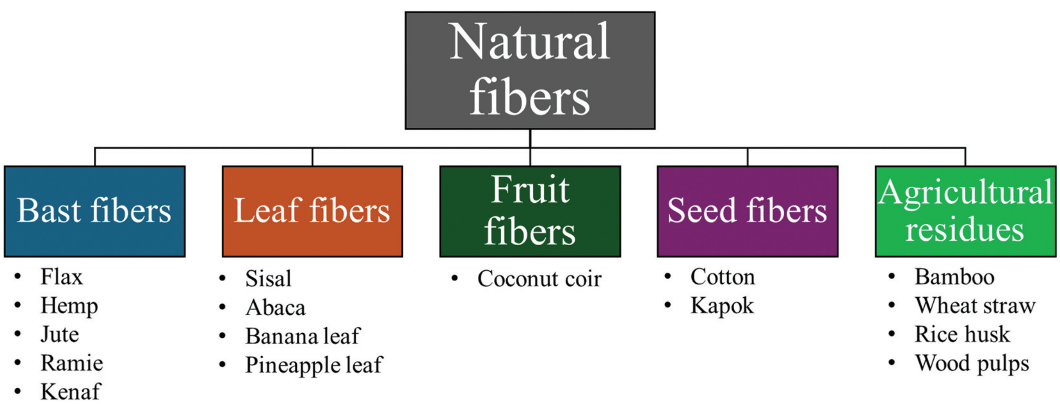

Figure 1. Major types of natural fibers.

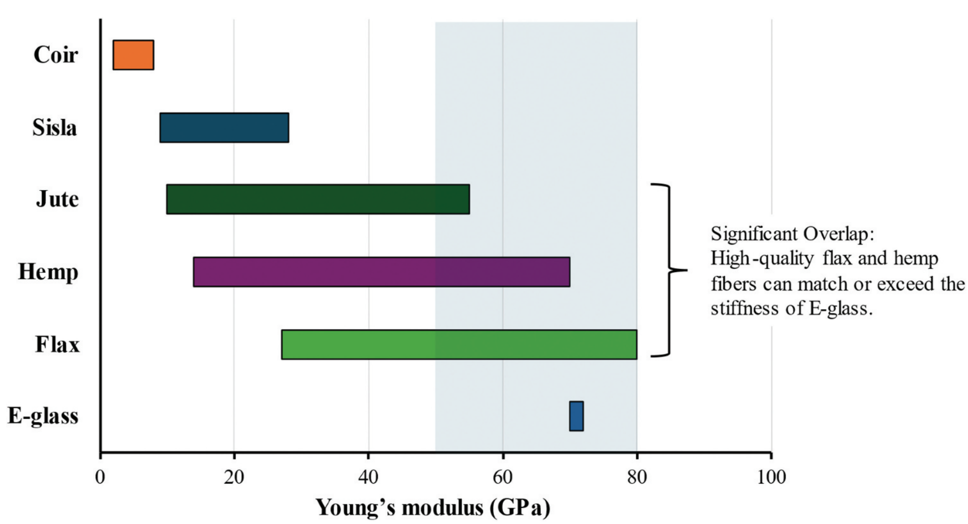

Figure 2. Stiffness comparison of natural and synthetic fibers.

Table 2. Compositional and microstructural properties of key natural fibers (Eleutério et al. 2025; Farag, Abou Taleb, and Hamouda 2025; Haugan and Holst 2013; Ilyas et al. 2022; Königsberger, Lukacevic, and Füssl 2023; Martinelli et al. 2024; Murodjon Musulmonqul Ogli Assistent 2025; Murugadoss et al. 2025; Raghul et al. 2023; J. K. Roy et al. 2014; Smole et al. 2013; Teshome Wagaye et al. 2024).

Fiber Type	Cellulose (%)	Hemicellulose (%)	Lignin (%)	MFA (°)	Modulus (GPa)	Elongation (%)
Cotton	75–92	2–6	0–1	20–30	5–13	7–8
Ramie	68–91	5–17	0.6–1	7–10	40–128	1.2–4
Flax	60–81	14–21	2–5	5–10	27–80	2.7–3.2
Hemp	57–90	14–22	3–6	6–10	30–70	1.6
Coir	32–43	0.15–0.25	40–45	41–45	4–6	15–40

which correlates with their exceptionally high Young's modulus (tens of GPa) (Eleutério et al. 2025). In contrast, coconut coir has an extensive MFA (~41–45° (Windyandari, Kurdi, and Tauviqirrahman 2019)), which yields a low modulus (~4–6 GPa) but a large elongation at break (15–40%) (Windyandari, Kurdi, and Tauviqirrahman 2019) (Table 2).

Performance variability and durability

Natural fibers display wide variability in composition and properties among species. Cotton fibers, for instance, are almost pure cellulose (about 75–92% cellulose (Eleutério et al. 2025)) with negligible lignin, whereas bast fibers like flax and hemp have moderately high cellulose (around 60–81% and 57–90%, respectively (Eleutério et al. 2025)) and low lignin. By contrast, coir contains only approximately 36–43% cellulose but a very high lignin content (~41–45%). These differences strongly affect fiber–matrix interactions and durability in composite materials. Highly cellulosic fibers tend to stiffen cementitious composites but can suffer from poor bonding or moisture uptake unless treated. In contrast, lignin- and hemicellulose-rich fibers (like coir) readily wet and bond to cement but derive their toughness and decay resistance from the lignin content; indeed, the unusually low hemicellulose (~0.15–0.25% in coir (Windyandari, Kurdi, and Tauviqirrahman 2019)) and high lignin make coir exceptionally durable in alkaline, wet environments (Windyandari, Kurdi, and Tauviqirrahman 2019). In practice, fibers with higher hemicellulose or lignin often require alkaline-stable modifications, since hemicellulose is the most vulnerable cell-wall component in high-pH cementitious pore fluids.

Mechanical property assessment and fiber-level performance

Individual fiber tensile properties

Natural bast fibers, such as flax, hemp, jute, and sisal, exhibit very high strength and stiffness, but with large scatters (Figure 1). Reported elementary-fiber tensile strengths span broad ranges flax fibers, for example, have been measured from roughly 345 up to 1830 MPa (Oksman 2001) (typical Young's modulus ~27–80 GPa (Oksman 2001)). Hemp fibers generally fall in the mid-hundreds of MPa (≈285–1110 MPa) with modulus ~14–70 GPa (Oksman 2001). Jute fibers are somewhat weaker (on the order of 100–800 MPa, modulus ~10–55 GPa), and sisal is similar or slightly higher than jute (tensile ~347–855 MPa, modulus ~9–28 GPa) (Oksman 2001). By contrast, coir (coconut) fiber – a seed/fruit fiber – is much weaker and more compliant, with reported tensile strength roughly 100–600 MPa (Hasan et al. 2021) and modulus only ~2–8 GPa (Hasan et al. 2021). (For comparison, synthetic E-glass fibers are on the order of 2–3 GPa tensile strength and ~70–72 GPa modulus.) When normalized by density, the specific stiffness of bast fibers approaches or even exceeds glass: for instance, flax fiber has a specific modulus of ~35 GPa cm^3/g versus ~29 for E-glass (Liu et al. 2022).

These wide property ranges reflect the natural variability of lignocellulosic fibers. Fiber diameter alone varies (flax: 12–30 μm, hemp: 15–28 μm) and is influenced by the extraction method, retting, harvest time, and storage conditions. Microstructural defects and non-uniform cell wall structures in plant fibers also contribute to scattering. Consequently, statistical studies report much larger coefficients of variation for natural fiber strength (often ~0.3–0.4) than for engineered fibers (typically <0.1). In practice, then, individual fiber tests consistently show large spreads in tensile strength and modulus (Hasan et al. 2021; Oksman 2001).

Composite-level mechanical performance

At the composite scale, NFRPCs derive their properties from multiscale interactions (fiber/matrix adhesion, fiber orientation and volume fraction, void content, cure conditions, etc.) and thus exhibit broad but generally consistent performance ranges. For example, high-quality flax/epoxy laminates with roughly 30–50% flax by volume typically achieve tensile strengths on the order of 200–300 MPa, with Young's modulus in the 8–15 GPa range (Oksman 2001). In one study, a 50/50 (by volume) Arctic flax/epoxy laminate exhibited a tensile strength of ~ 280 MPa and a stiffness of ~ 40 GPa (Imon 2024). Flax composites tend to have flexural strengths on the order of 100–180 MPa and moderate toughness (unnotched impact ~50–100 J/m^2 in reported tests). In contrast, flax/polyester composites are significantly weaker (often only ~50–100 MPa tensile) due to their weaker fiber/matrix bond. Hemp/epoxy laminates (at similar fiber fractions) exhibit comparable tensile strength (on the order of ~150–250 MPa) and flexural strength (~120–200 MPa), with reported modulus ~6–12 GPa; the higher intrinsic stiffness of hemp fibers often gives hemp composites slightly higher modulus than analogous flax laminates. Jute/epoxy systems have lower tensile strength (typically only a few tens of up to approximately 100 MPa) and modest stiffness (~5–10 GPa), but exhibit excellent impact resistance (~180–220 J/m^2 reported), making them useful where energy absorption is needed. Bamboo/epoxy laminates show intermediate performance: tensile strengths around 120–180 MPa, flexural ≈100–160 MPa, modulus ~4–8 GPa, and impact values (≈120–200 J/m^2) comparable to or higher than other natural composites. Bamboo composites benefit from the very high fiber strength (elementary bamboo fibers can approach ~1770 MPa), despite moderate composite stiffness, and are attractive for low-cost, renewable structures.

For reference, conventional 40 wt% E-glass/epoxy composites typically exhibit tensile strengths on the order of 300–400 MPa, flexural strengths of 300–450 MPa, and modulus ~35–45 GPa, significantly higher than the natural-fiber composites. However, because natural-fiber composites have much lower density and often fail by matrix-dominated mechanisms, the gap at the composite level is smaller. In practice, NFRPC laminates often reach 50–70% of the strength of equivalent glass composites, despite raw fiber strengths that are 7–15× lower. In high-rise construction, this level of performance is sufficient for façade systems, architectural panels, and other non-load-bearing components, where serviceability and self-weight govern design rather than ultimate strength. Importantly, the use of natural fibers can reduce dead load by approximately 35–40%, offering tangible benefits for tall buildings by lowering cumulative gravity loads on façades and supporting structures while improving overall sustainability (Liu et al. 2022). The Table 3. Presents composite-level mechanical properties of different fiber composites.

Table 3. Composite-level mechanical properties of different fiber composites (Lin et al. 2024; Oksman 2001; Rajole, Ravishankar, and Kulkarni 2020; B. S. Roy et al. 2025).

Composite System	Tensile Strength (MPa)	Young's Modulus (GPa)	Flexural Strength (MPa)	Impact Strength (J/m^2)	Key Characteristics
Arctic Flax/Epoxy (50% Vol)	~280	~40	–	–	Exceptional stiffness matching E-glass; RTM processing.
Flax/Epoxy	200–300	8–15	100–180	50–100	Balanced performance; industry standard for semi-structural NFRP.
Flax/Polyester	50–100	–	–	–	Weak interface limits strength; low cost.
Hemp/Epoxy	150–250	6–12	120–200	–	Comparable to flax; high intrinsic fibre stiffness.
Jute/Epoxy	<100	5–10	–	180–220	Excellent energy absorption; lower static strength.
Bamboo/Epoxy	120–180	4–8	100–160	120–200	Moderate stiffness; high elementary fibre strength (~1770 MPa).
E-Glass/Epoxy	300–400	35–45	300–450	–	High absolute strength and stiffness, with a high density.

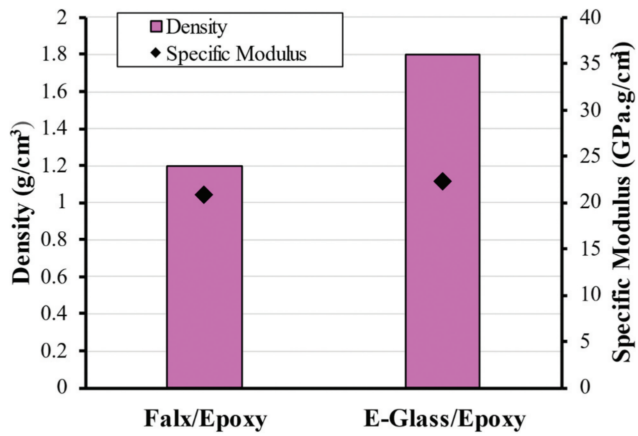

Figure 3. Specific modulus of natural vs synthetic fiber composites.

Density and weight-related performance metrics

A major benefit of lignocellulosic composites is their low density. Typical flax/epoxy and hemp/epoxy laminates have bulk densities of around 1.2–1.3 g/cm^3, while bamboo/epoxy systems have bulk densities of ~1.2–1.35 g/cm^3. In contrast, glass/epoxy systems typically have bulk densities of around 1.8–2.0 g/cm^3. This ~40% weight reduction translates directly into lower structural dead loads, which is particularly beneficial in tall buildings where cumulative gravity effects are significant. For example, replacing 1 m^2 of a 6 m-tall glass-fiber façade panel (at ~1.9 g/cm^3) with a natural-fiber panel could save on the order of 5–7 kg/m^2, which, cumulatively over many stories, allows for lighter framing and foundations.

From a specific property viewpoint, the advantages remain strong. For instance, the specific tensile strength of a flax/epoxy composite (strength divided by density) lies in the range of ~160–220 MPa cm^3/g, essentially overlapping the range for E-glass/epoxy (Liu et al. 2022). Likewise, the specific stiffness (Young's modulus divided by density) of flax composites is on the order of 6–11 GPa/cm^3/g, narrowing the gap with glass composites. In short, natural composites can match or exceed glass-fiber systems on a weight-normalized basis (Liu et al. 2022). Consequently, while absolute stiffness and strength are lower, natural-fiber composites can achieve comparable performance on a mass-normalized basis. This makes them well suited for high-rise applications, such as prefabricated façade panels, modular envelope components, and interior partitions, where weight reduction, constructability, and sustainability are prioritized over very high absolute strength. The Figure 3 presents specific modulus of natural vs synthetic fiber composites.

Serviceability limit states

Codes and standards enforce strict deflection limits for high-rise floors and cladding to avoid damage or discomfort. For example, Eurocodes (draft NA) cap the total floor deflection (dead + live) at about span/500 for rigid finishes (e.g., tile) and span/250 for flexible coverings (Standard 2002). ASCE guidance similarly recommends limiting the live-load deflection to ~L/360 for occupied floors (American Society of Civil Engineers 2017). Suspended plaster ceilings are limited to ≈L/300. Lateral story drift (wind) in tall buildings is likewise controlled to ~1/600–1/400 of story height to protect nonstructural cladding (A. S. of C. Engineers 2017). Glazed façade panels often have even tighter limits: EN 16,612 (glass) suggests deflections ≲L/60 (four-edge support) or ≲L/100 (two/three edges) of the pane (HRN EN 16612:2019 2019). NFRP composites are much less stiff than steel or concrete so an NFRP floor or panel of equal span will deflect more under load. In practice, NFRP floor systems must be designed (often with deeper sections or hybrid reinforcement) to meet the same span/deflection ratios (American Society of Civil Engineers 2017; Standard 2002). Similarly, any NFRP façade panels must be sized to satisfy standard cladding deflection limits to avoid sealant or glazing failure.

Floor vibration criteria focus on human comfort. Standards like ISO 10137 provide frequency-dependent acceleration limits for buildings (covering up to ~5 Hz) (Kurent and Brank 2025). Design guides (e.g., SCI P354, AISC DG) typically require minimum natural frequencies of ~8–10 Hz for open-plan floors and limit dynamic response under a concentrated load (often a 1 kN point load) to a few millimeters (Cheraghi-Shirazi, Crews, and Malek 2022). For example, Toratti and Talja suggest peak floor velocities of ≤8 mm/s (office) and ≤12 mm/s (residential) for acceptable comfort, with corresponding 1 kN deflection limits ≲0.5–1 mm. In general, NFRP floors will have low mass (raising natural frequency) but also low stiffness (lowering it), and they often exhibit higher damping. Design of NFRP floors must ensure these vibration limits are met – typically by achieving adequate thickness or continuity so that $fn \approx 8–10$ Hz and any induced accelerations remain within comfort thresholds (Cheraghi-Shirazi, Crews, and Malek 2022).

Durability assessment and degradation mechanisms

Tables 4–6 highlight that durability remains one of the primary technical challenges for natural-fiber-reinforced polymer composites when compared with conventional glass-fiber systems. Moisture uptake in NFRPCs is substantially higher, leading to matrix plasticization, interfacial degradation, and measurable losses in mechanical performance, particularly under prolonged humid or wet exposure. Alkaline environments associated with cementitious materials are especially aggressive, causing rapid chemical degradation and embrittlement of untreated fibers, which severely limits direct use in cement-based composites. However, the tables also demonstrate that appropriate fiber surface treatments can significantly mitigate these effects. Chemical modifications such as mercerization, silane coupling, and acetylation markedly improve fiber – matrix adhesion, reduce moisture absorption, and enhance strength retention. The key takeaway is that while untreated NFRPCs exhibit inferior durability relative to conventional composites, targeted material design and surface treatment strategies can substantially improve long-term performance, enabling their use in protected or hybrid construction applications where exposure conditions are controlled.

Table 4. Moisture absorption and water-induced property degradation.

Aspect	NFRPCs	GFRPCs	Implications
Typical moisture uptake	~5–>10 wt% (flax/epoxy ~7.5%, hemp/epoxy ~9.8%) (Haramina, Hadžić, and Keran 2023)	~1–2 wt% (Haramina, Hadžić, and Keran 2023; Huner 2015)	Higher hygroscopicity in NFRPCs
Uptake mechanism	Two-stage (surface sorption + Fickian diffusion)	Limited matrix-controlled diffusion	Faster and deeper water ingress in NFRPCs
Primary degradation effects	Matrix plasticization, fiber swelling, interfacial debonding, microcracking	Minor matrix plasticization	Larger stiffness and strength loss in NFRPCs
Mechanical property loss	Tensile/impact strength reductions ~18–30% after moisture exposure; retained strength ~40–60% after severe aging (Sathishkumar et al. 2024)	Typically <10–15%	Moisture is a critical durability driver

Table 5. Alkaline degradation in cementitious environments.

Parameter	NFRPC Behavior	Quantitative Evidence	Degradation Mechanism
Pore solution pH	Highly alkaline (pH ≈ 12.5–13.5) (Mejia-Ballesteros et al. 2025)	–	Aggressive chemical environment
Fiber strength retention	Sisal ≈34%, coir ≈59% after 210 days in $Ca(OH)_2$ (Lv and Liu 2023)	Near-zero strength after ~300 days at pH ≈ 12 (Lv and Liu 2023)	Hemicellulose hydrolysis, mineralization
Interfacial performance	Severe bond degradation	Pull-out strength reductions of tens of percent	Fiber embrittlement, interface cracking
Overall durability	Poor without protection	–	Limits direct use in cement matrices

Table 6. Fiber treatment technologies for durability enhancement.

Treatment Method	Primary Effect	Quantitative Improvement	Durability Benefit
Mercerization (NaOH 4–10%)	Removes hemicellulose/lignin; increases roughness	Fiber strength +20–45% (Adekunle 2015)	Improved bonding, reduced moisture sensitivity
Silane coupling (e.g., APTES)	Chemical fiber–matrix bonding	Composite strength +15–35%; water uptake −20–40% (Adekunle 2015)	Stronger interface, improved wet aging
Combined NaOH + silane	Synergistic surface modification	Overall strength +35–70% vs untreated (Adekunle 2015)	Best overall durability performance
Acetylation	Reduces –OH groups	Lower equilibrium moisture content	Improved humid-aging resistance
Oxidative treatments (e.g., $KMnO_4$)	Introduces reactive surface sites	Application-dependent	Enhanced interfacial stability

Comparative performance analysis: natural versus synthetic fiber systems

Mechanical properties hierarchy and performance trade-offs

Table 7 presents that continuous E-glass fiber has a longitudinal Young's modulus of about 70 GPa (Kramár and Král 2019). Natural fiber modulus span a wide range: very soft fibers like coir are only ~4–7 GPa (Mohammed et al. 2023; Nissar et al. 2025), whereas stiff bast fibers (flax, ramie, etc.) can be tens of GPa (flax ≈ 62.5 GPa (Guna et al. 2025)). Thus, at the fiber level, glass is roughly 10–20 times stiffer than the weakest natural fibers and still several times stiffer than the strongest ones. Crucially, however, the low density of plant fibers offset much of this difference. When the stiffness is expressed per unit mass (specific modulus, E/ρ), natural fibers often match or exceed that of glass (Table 7). For example, a typical flax fiber (density ~1.5 g/cm^3) has a specific modulus comparable to or higher than E-glass (density ~2.5 g/cm^3) (Ajayi et al. 2025). Indeed, recent reviews note that bast fibers (flax, hemp, etc.) can have a specific Young's modulus on the order of 30–50 GPa·cm^3/g (Ajayi et al. 2025) well above the ~28–29 GPa cm^3/g typical of E-glass (Ajayi et al. 2025; Kramár and Král 2019). In practical design, this means that lightweight natural-fiber composites can achieve high stiffness per weight. This is especially relevant for tall-building modular floors, where long spans (span/depth ratio of 20–25) drive deflection limits. As a general rule, simply supported floor spans typically employ a span-to-depth ratio of approximately 20 for serviceability (1:250 deflection) (Camilleri and Camilleri Cassar 2014). Using low-density, high-specific-modulus fibers, such as flax or ramie, thus helps control deflections in long precast panels while saving weight. In short, although natural fibers have lower absolute strength and stiffness than glass, their high specific stiffness makes them quite competitive in bending-critical, weight-sensitive structural applications (Ajayi et al. 2025; Camilleri and Camilleri Cassar 2014).

Environmental impact and life-cycle carbon assessment

Recent life-cycle studies show that flax (and other natural) fibers dramatically reduce carbon emissions compared to E-glass. For example, Cano et al. (2025) report roughly 1.15 kg CO_2e per kg of flax fiber versus ~2.14 kg CO_2e per kg of glass fiber (Lopez-Arraiza et al. 2025). Flax fiber processing requires on the order of 8–10 MJ/kg, whereas glass fiber production consumes roughly 25–55 MJ/kg (Joshi et al. 2004; Lopez-Arraiza et al. 2025).

Complete composite Lifecycle Carbon Assessment (LCA) results vary with part design; however, flax/epoxy systems consistently emit far less CO_2 than their glass/epoxy equivalents. For instance, Cano et al. found that the total lifecycle GWP of a flax-reinforced bio-epoxy boat hull was approximately 14% lower than that of an equivalent glass-reinforced polyester hull (Lopez-Arraiza et al. 2025). In general, published studies report that natural-fiber composites yield a global warming potential that is on the order of 20–50% lower than that of comparable glass-fiber composites (Lopez-Arraiza et al. 2025). Substituting conventional petroleum-based resins with bio-based epoxies (derived from plant oils or fermentation) can further reduce carbon emissions, often by tens of percent in some cases (actual savings depend on the specific resin formulation).

Table 7. Comparative properties of natural and synthetic reinforcement fibers (Carbon Fiber: A Comprehensive Overview – ERIC KIM 2025; Guna et al. 2025; Owen et al. 2025; Bewuket Teshome et al. 2024).

Fiber Type	Density (g/cm^3)	Specific Modulus (GPa cm^3/g)
E-Glass	~2.55	28–29
Flax	1.4–1.5	30–50
Hemp	1.48	20–40
Jute	1.3–1.46	7–20
Coir	1.2	3–6
Manau Rattan	~0.6	~4

A key advantage of lignocellulosic fibers is their ability to sequester biogenic carbon. Flax cultivation fixes roughly 1.2–1.3 kg CO_2/kg of fiber (via photosynthesis) (Seile, Spurina, and Sinka 2022), a credit absent in synthetic fibers. This photosynthetic sequestration offsets a portion of the production emissions (Lopez-Arraiza et al. 2025). Over long service lives (decades), the combination of lower embodied emissions and stored biocarbon results in flax/epoxy systems having markedly lower net CO_2 footprints than their glass/epoxy counterparts (Lopez-Arraiza et al. 2025; Seile, Spurina, and Sinka 2022).

Thermal insulation

Peer-reviewed studies indicate that natural-fiber-reinforced composite panels exhibit significantly lower thermal conductivity than conventional structural materials, making them attractive for high-rise building envelopes. For reference, concrete typically has a thermal conductivity (k) of ~1.0–1.8 W/m K (Ashworth and Ashworth 1991), and structural steel on the order of 50 W/m K (De Angelis and Serra 2014). In contrast, polymer composites loaded with lignocellulosic fibers typically exhibit $k \approx 0.05–0.15$ W/m K (Pawłosik, Cebrat, and Brzezicki 2025; Ramful 2026). This intrinsic low conductivity means that natural-fiber panels can act as both structural components and insulation. The exact value depends on fiber type and density: loose coir fiber boards have achieved k ≈ 0.04–0.05 W/m K (Le and Pásztory 2023), whereas denser hemp or jute-epoxy laminates are in the ~0.05–0.10 W/m K range (Pawłosik, Cebrat, and Brzezicki 2025; Ramful 2026). (For reference, common insulation materials have even lower k, e.g., expanded polystyrene ≈0.03–0.04 W/m K and mineral wool ≈0.035–0.045 W/m K (Pawłosik, Cebrat, and Brzezicki 2025).)

Translating these conductivities into panel resistance shows that a 50 mm-thick natural-fiber board can reach thermal resistance (R-values) on the order of 0.5–1.0 m^2 K/W. In one study, 50 mm binderless coir panels measured $R \approx 0.88–0.91$ m^2 K/W (Le and Pásztory 2023). By comparison, 50 mm of mineral wool (k ≈0.04 W/m K (Pawłosik, Cebrat, and Brzezicki 2025)) would yield $R \approx 1.1–1.4$ m^2 K/W, so the bio-composite approaches those levels. In high-rise applications, integrating natural-fiber composite layers into precast façade panels, sandwich walls, or floor systems can significantly reduce thermal bridging. As an illustration, one analysis showed that the heat transfrer coffiecient (U-value) of a steel-bamboo composite wall decreased from 0.65 to 0.22 W/m^2 K (≈66% reduction) when a fibrous insulation core was used (Al-Rukaibawi, Szalay, and Károlyi 2021). By analogy, precast concrete floors with embedded natural-fiber insulation would see overall U-values tens of percent lower than solid reinforced-concrete slabs, yielding substantially improved building heat loss performance.

Acoustic performance and sound absorption

In addition to thermal benefits, natural-fiber composites exhibit favorable acoustic performance, which is particularly relevant for high-rise residential and office buildings. Compared to dense, reflective materials, such as concrete (typical absorption coefficient $\alpha \approx 0.01–0.08$), fiber-based composites provide substantially higher sound absorption. Hemp- and flax-based laminates with high fiber content have reported average mid-frequency absorption coefficients of approximately $\alpha \approx 0.6$ in the 250–2000 Hz range (Yang et al. 2020). Coir-fiber panels show similar behavior, with absorption coefficients increasing from about 0.1 at low frequencies (125 Hz) to approximately 0.8 around 1000 Hz for panel thicknesses of 20–40 mm (Bravo-Moncayo et al. 2025). These effects arise from viscous and interfacial damping within the porous fiber network. In practical terms, relatively thin natural-fiber composite panels or mats can achieve sound absorption comparable to conventional glass-fiber blankets, making them well suited for high-rise applications, such as interior partitions, façade linings, and floor – ceiling assemblies where both thermal efficiency and acoustic comfort are critical (Yang et al. 2020). The Figure 4 shown sound absorption comaparision of different NFRPCs against concrete.

Structural applications in modular precast construction

Modern high-rise construction can leverage prefabricated biocomposite panels (natural-fiber/polymer or natural-fiber-foam sandwich) primarily for envelope and non-structural applications. These panels are valued for low weight, high insulation, and eco-credentials (European Commission 2011; Przybek 2025). Importantly, they are

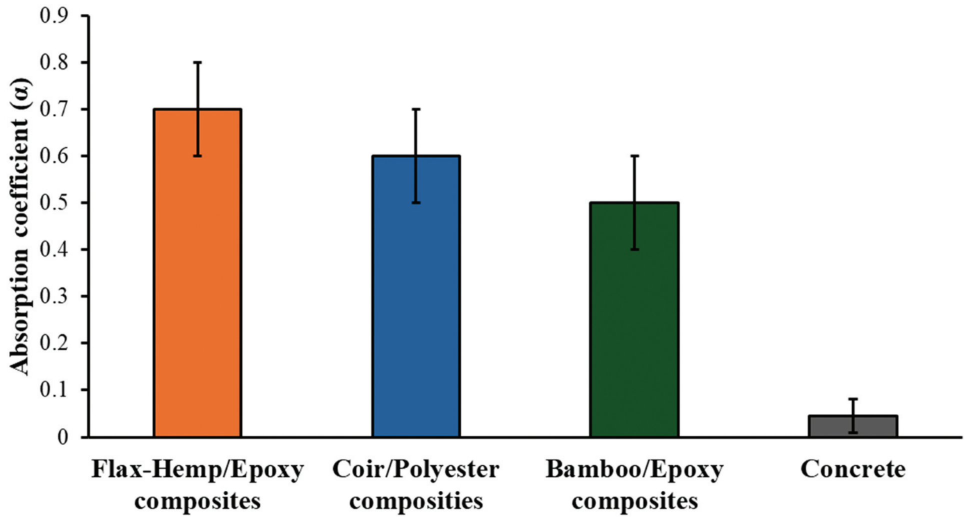

Figure 4. Sound absorption comparison of different NFRPCs against concrete.

not intended as primary load-bearing members (unlike steel or concrete); instead, they serve as lightweight cladding, partitions, and floor/roof cassettes where thermal/acoustic performance and ease of installation are priorities. Their design follows normal building standards: for example, Eurocode or IBC deflection limits (≈L/250–L/360 under service loads) still govern floor panel design (Standard 2002). Below we summarize key high-rise applications, with representative performance data and design considerations.

Facade (cladding) panel systems

Non-structural exterior cladding or curtain walls that protect and insulate the building envelope (European Commission 2011). Panels typically consist of thin fiber-reinforced skins (woven flax, hemp, jute, etc.) bonded to an insulating core (foam, wool, coir mat). Studies report epoxy–matrix panels with bast fibers achieve $\lambda \approx 0.03$–0.07 W/m K, comparable to commercial insulators (Przybek 2025). A 5–10 mm fiber-composite skin over a foam core yields panel U-values ~0.15–0.25 W/m^2 K at 60–80 mm thickness (ElHassan, Abu-Jdayil, and Ahmed 2025; Przybek 2025). For example, an 80–100-mm thick sandwich panel with coir or biofoam core has demonstrated $U \approx 0.16$–0.25 W/m^2 K. Prototype flax-fiber composite panels (≈70 mm thick) weigh on the order of 10–20 kg/m^2, far below typical precast concrete (100–200 kg/m^2). Even including fastening frames, these panels dramatically reduce facade load. Natural fibers are combustible and hygroscopic, but tests show treated biopanels can meet fire-safety standards. For example, BioBuild demonstrated epoxy/flax cladding panels achieving Euroclass B by using flame-retardant resins or coatings (European Commission 2011). Weatherproof coatings and sealed edges address moisture ingress. In practice, surface treatments or protective topcoats (often UV-stable) are applied to ensure exterior durability. They are manufactured in factory by molding or pultrusion, allowing complex shapes and embeds. Window-frame rails, stiffeners, clips or thermal-break slots can be molded in place. This yields fully finished facade panels that snap into modules on site. Because they are lightweight and dimensionally stable, these panels suit tall building installation (hoisting onto high floors) and meet high-rise code requirements for cladding (e.g., supporting their own dead load, resisting wind loads as infill).

Interior partition panels

Panels can be molded as single composite units with built-in features (electrical ducts, junction box cavities, etc.). These replace gypsum or metal studs with natural-fiber-reinforced plastics or sandwich boards. NFRPCs offer superior thermal and acoustic insulation versus gypsum. For example, panels made with jute or hemp in a polymer matrix have λ in the range ~0.05–0.07 W/m K and high sound absorption. Studies have shown jute/polypropylene partition panels outperform standard drywall on both heat transfer and stiffness (ElHassan, Abu-Jdayil, and Ahmed 2025). Wood-fiber sandwich boards (wood wool or palm fibers in cement or resin) are likewise used for acoustically damped partitions (Nair and Dasari 2022). Although not carrying structural loads, these panels can match drywall in stiffness. Fiber-composite panels with moderate fiber volume (≈20–30 wt%) achieve flexural strength on the order of tens of MPa (Przybek 2025). (By comparison, a lightweight gypsum board may have bending strength ~5–10 MPa.) Because typical interior spans are small, designers optimize for cost and weight rather than ultimate strength. A known drawback is fiber swelling if exposed. However, interior spaces have controlled humidity, so untreated fiber panels remain durable in service. Research notes that moisture-induced degradation occurs mainly under outdoor or wet conditions (Nair and Dasari 2022). For interior applications, this is negligible. Panels are often sealed or painted on all sides for additional protection. Panels must meet indoor air-quality (low VOC) and fire (e.g., ASTM E84 Class A/B or EN 13501 Euroclass) norms. Many natural-fiber composites easily comply when formulated with non-toxic binders and retardants. Their low weight also satisfies material handling rules (typically ≤50 kg per panel, easily achieved at ~10–20 kg per typical drywall sheet area).

Floor and roof panels

Floors and roofs carry significant loads and deflection limits. Natural-fiber composites can meet residential floor loads (~2 kN/m^2 live load) by using laminated constructions with oriented fibers. For example, flax or bamboo fibers aligned in the span direction (0° layers) carry bending, while cross-ply (±45° or 90°) layers resist shear and torsion. With ~30–40 wt% aligned fiber content, biocomposite slabs have demonstrated span-to-depth ratios on the order of 20–25:1, comparable to concrete (L/20–25) (Przybek 2025). In practice, a 100 mm thick bio-composite floor panel can match the strength of an ordinary concrete slab but weigh 30–40% less. (For reference, FRP sandwich floor cassettes weighing ~15–30 kg/m^2 have been built; natural-fiber versions are in the same ballpark.) Such panels inherently insulate better than concrete. A sandwich panel with natural-fiber face sheets and an insulating core can achieve high R-values. For example, a recent FRP sandwich panel (foam core 80 mm) had an overall U ≈ 0.48 W/m^2 K (R ≈ 2.1 m^2 K/W) (Berardi and Dembsey 2015). A natural-fiber roof panel of similar thickness (or slightly thicker) can easily meet modern insulation codes ($R \geq 2$–4, or U ≤ 0.25–0.5). Yet despite the insulation, the total weight remains low (often ≤15 kg/m^2 for 100–120 mm panels). Natural fibers have elastic moduli (~20–40 GPa) much lower than steel (200 GPa) (Przybek 2025). Thus, deflection, not strength, usually governs design. Codes (Eurocode, IBC, etc.) typically limit floor deflection to ~$L/250$–$L/360$ (span/deflection) under service loads. For example, a beam with $L/300$ deflection yields a floor frequency ~4 Hz, a common target for comfort. To satisfy these limits, designers employ strategies: panels are made deeper (e.g., 120–150 mm thick instead of 100 mm) to boost stiffness, or include sandwich construction (placing stiff faces far apart). Hybrid reinforcement is also used: embedding a few carbon/glass fibers or thin prestressed steel/FRP tendons in the tensile zone significantly increases stiffness locally. These measures allow bio-composite floor/roof panels to meet high-rise span requirements while saving weight and adding insulation (Przybek 2025; Spyridonos and Dahy 2024; Standard 2002). Oak Ridge National Lab recently 3D-printed a full-scale PLA/wood-fiber floor cassette for modular housing, claimed stiff enough to replace steel-concrete floors in a multi-story building. Similarly, FRP sandwich panels have been used in solar homes. These successes underline that, with proper design, natural-fiber floor and roof panels can satisfy structural and code demands in tall buildings. Ongoing research projects (e.g., EU's ATRIUM) continue to refine these systems for scalability.

Load-bearing capacity and limit state approaches

NFRPCs exhibit very large material scatter due to the inherent heterogeneity of botanical fibers (defects, variable lumen content, fibril angles, etc.). Studies of flax, hemp, and jute fibers report tensile strength coefficients of variation (CoV = σ/μ) in the 20–60% range (Aslan et al. 2011), significantly higher than those of glass or carbon fibers. This high variability is inherited by composite laminates: published databases from extensive coupon tests show natural-fiber composites' tensile strength and stiffness can also fluctuate widely (for instance, CV often >20%). In design practice, one therefore uses a conservative "characteristic" strength (typically the 5th-percentile value) rather than the mean. For a roughly normal distribution, this characteristic strength is about $\mu - 1.645\sigma$; e.g., at CV ≈ 0.30 the 5% fractile is only ≈0.5μ. In other words, design strengths for natural-fiber composites may be only half the mean strength due to scattering. (As a result, some authors have suggested that natural-fiber composites require explicit reliability analysis or markedly higher strength-reduction factors than conventional FRPs.)

Moisture and aging further reduce natural-fiber properties. Many studies report that water uptake dramatically degrades performance. For example, Bambach (2020) showed that moisture immersion can cut the compression stiffness of flax/jute FRP columns by ~44% and their ultimate strength by up to ~45% (Bambach 2020). Similarly, long-term or cyclic hygrothermal exposure can markedly reduce tensile capacity, stiffness, and interfacial bond of flax-FRP laminates (Bambach 2020; Bigaud et al. 2022). In practice, this means that "environmental reduction factors" (strength retention ratios) must be applied. In contrast to glass/aramid FRPs, for which many codes adopt moderate reduction factors, natural fibers' sensitivity to temperature and humidity implies larger uncertainty over decades of service. Accounting for this, reliability-based studies of flax-FRP strengthening have calibrated aging factors as a function of climate and target life (e.g., for 20–50-year design lives) (Bambach 2020; Bigaud et al. 2022).

Accordingly, partial safety factors in design must be large enough to cover both the intrinsic scatter and aging losses. For comparison, one recent study cites partial factors of about 1.15 (steel), 1.5 (concrete), and 1.25 (GFRP) for the ultimate limit-state design (Shahrbijari, Barros, and Valente 2023). Since natural fiber composites combine high variability with uncertain long-term strength, designers have proposed using similar or larger factors. For instance, probabilistic calibration of flax-FRP strengthening suggests that standard FRP safety coefficients often need upward adjustment for NFRP use (Bambach 2020; Shahrbijari, Barros, and Valente 2023). In practice, this means that the design (factored) strength of the fiber is taken significantly below the mean: one might take the 5%-fractile (≈mean−1.645σ) and then divide by a material safety factor (e.g., ≥1.25). Without official code guidance, such factors are justified by reliability targets: larger partial factors (beyond traditional FRP codes) effectively compensate for high CoV and environmental degradation. The net effect is that a natural fiber laminate with mean tensile strength S might have a design strength on the order of (0.5 S)/1.25 = 0.4 S (i.e., ~40% of mean) or less.

Figure 5 illustrates how increasing material variability leads to a progressive reduction in the design strength factor. This factor is defined as the ratio of the design strength (typically the 5th-percentile value adjusted by partial safety factors) to the mean material strength. It is a dimensionless quantity that quantifies how much of the nominal (mean) strength can be reliably utilized in structural design. The graph compares two typical partial safety factors: $\gamma_m = 1.4$, commonly used for well-characterized synthetic fiber composites, such as GFRPC and CFRPC, and $\gamma_m = 2.0$, often required for NFRPCs due to their higher variability and degradation risks. As CoV increases from 0.01 to 0.45, the design strength factor drops significantly, especially under the more conservative $\gamma_m = 2.0$ scenarios highlighting the impact of variability on structural reliability and allowable design limits. The Figure 6 presents difference in usable design strength.

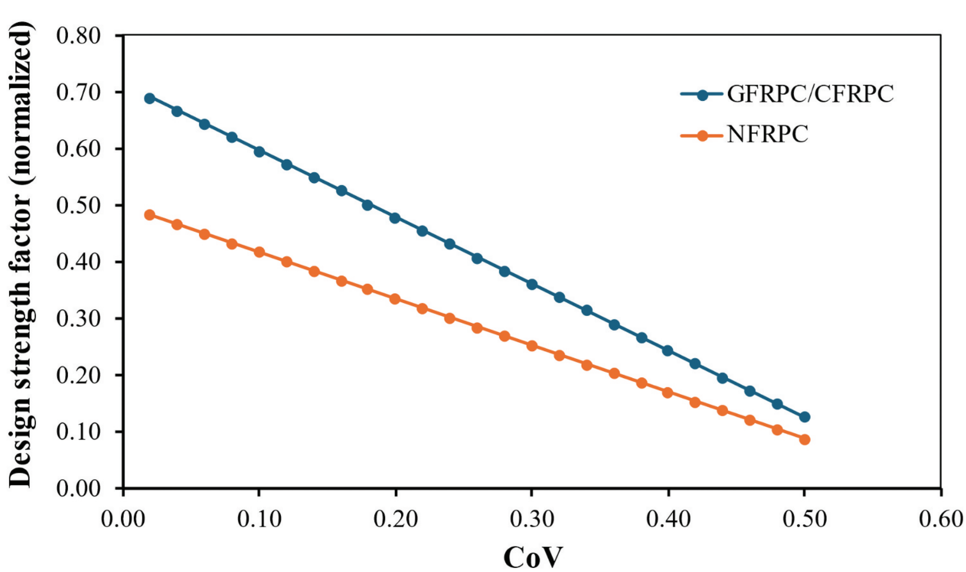

Figure 5. Design strength versus fiber coefficient of variation (CoV).

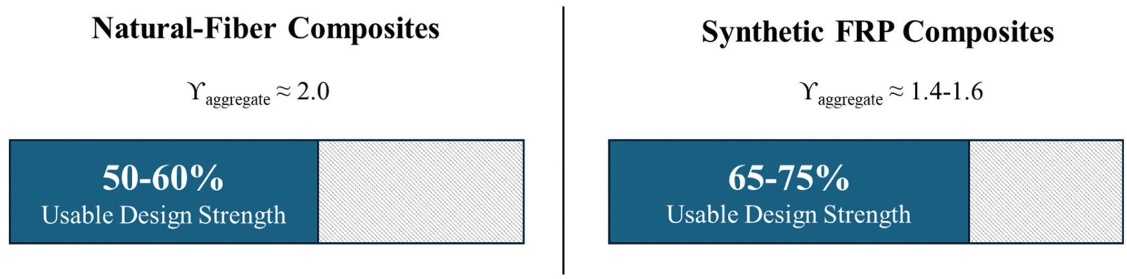

Figure 6. Difference in usable design strength (Alkhrdaji et al. 2006; Ascione et al. 2005; Correia et al. 2025; Madueke 2021; Ntsie et al. 2025).

These considerations have major implications for structural use. First, qualification testing of natural-fiber composites must be much more extensive than for synthetic FRP to establish reliable design data. Second, designers should incorporate not only short-term test data but also modeled or empirical degradation over the expected service life (possibly via durability factors or reduced design lives). Third, limit-state models may need to include creep or fatigue effects if relevant (though high-cycle fatigue effects appear minor, moisture-driven creep could be significant). Finally, given the uncertainties, natural-fiber composites are generally limited to lower stress or noncritical applications unless accompanied by conservative detailing. In all cases, codes or guidelines should treat NFRPs with caution – for example, using partial factors ≥1.25 or environmental reduction factors >1, possibly calibrated by reliability analysis.

Carbon footprint and global warming potential

Comparative life-cycle assessments (LCAs) confirm that composites reinforced with natural fibers (e.g., flax) can substantially reduce greenhouse-gas emissions relative to traditional glass-fiber composites. For instance, a recent LCA comparing a hull made with flax-reinforced bio-resin versus a conventional glass-fiber-resin composite found that the flax composite led to significantly lower global warming potential (GWP) per functional unit, primarily because of the lower embodied energy and renewable origin of flax fiber (de Cáceres et al. 2024; Lopez-Arraiza et al. 2025).

More narrowly, a cradle-to-gate LCA of flax/PLA (polylactic acid) composites reported a GWP of ~1.19 kg CO_2-eq per kg of composite substantially lower than that of a glass-fiber polyamide composite, which in the same study emitted ~9.14 kg CO_2-eq/kg composite (Seile, Spurina, and Sinka 2022). Because of this, substituting glass-fiber composites with flax-based biocomposites could reduce composite-level carbon emissions by ~60–80% (Figure 7) (Seile, Spurina, and Sinka 2022; Tchana Toffe 2021).

In practical construction use – for example, a modular facade or panel weighing 500 kg – replacing a glass-fiber composite with a flax-based composite could eliminate roughly 600–800 kg CO_2-eq (assuming flax/PLA rather than glass-polyamide). If bio-resins are used (rather than petroleum-based), further GWP reductions have been documented because of decreased reliance on fossil feedstocks and lower energy demand in resin production (Boland 2014; Tchana Toffe 2021).

Standardization and design codes

Current structural design codes address FRPs almost exclusively in terms of synthetic fibers, with no tailored provisions for natural-fiber composites. For example, American Concrete Institute guidelines (ACI 440) cover FRP bars (carbon, glass, aramid) in concrete, and the new ACI 440.1122 code provides comprehensive rules for concrete with GFRP reinforcement (Myers et al. 2023). Similarly, ISO standards (e.g., ISO 10406) and Chinese standards (GB/T 26743 for FRP bars (Rossini 2019)) specify test methods and design values for generic FRP materials. However, none of these explicitly consider plant-based fibers. Existing building codes and standards are mainly focused on traditional materials, such as steel and concrete, leaving the specific properties of natural fiber composites insufficiently addressed (Ntsie et al. 2025). In practice, NFRPCs must often be treated as an especially variable subclass of FRP but without

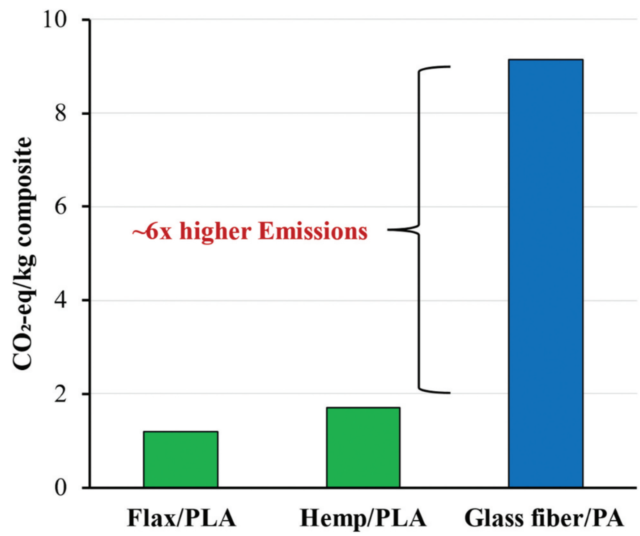

Figure 7. Difference in carbon emission in natural vs synthetic fiber composites.

dedicated code guidance. In effect, available FRP codes may be used with extra conservatism, or treated analogously to wood or textile reinforcement approaches that are not codified.

For cementitious NFRPCs (e.g., natural fibers in concrete or fiber-cement products), the situation is similar. Material standards exist to ensure fiber quality, for example, ASTM D7357 provides specifications for cellulose fibers in fiber-reinforced concrete, and ASTM/EN standards cover fiber-cement panels (often containing cellulose or mineralized fibers). However, mainstream design codes (ACI 318 for concrete, Eurocode 2, ACI 544 on fiber-reinforced concrete, etc.) do not explicitly include natural fibers. Fiber-reinforced concrete guidelines usually assume steel or synthetic fibers; natural fibers are at best treated as a type of nonstructural "microfiber" for crack control. In practice, engineers rely on general FRC provisions or *ad hoc* factors when using plant fibers in concrete. This fragmented guidance means that structural design with cementitious NFRPCs depends on trial data and conservative assumptions rather than unified code rules.

The lack of dedicated standards for NFRPCs is widely recognized as a major barrier. Surveyed experts cite lack of standard design codes as a key challenge for FRP technologies (Peças et al. 2018), a difficulty that is even more acute for natural-fiber systems. The use of natural fiber composites is constrained by the absence of standardized testing procedures and regulatory frameworks specifically developed for these materials (Ntsie et al. 2025). In other words, without approved design procedures and safety factors specific to natural fibers, engineers must over-design or avoid NFRPC solutions to ensure reliability. Closing this gap for both polymer-matrix and cementitious NFRPCs is therefore crucial, as the current absence of standardized codes is cited as a key obstacle to their practical implementation (Ntsie et al. 2025; Peças et al. 2018).

End-of-life material management

NFRPCs are often promoted as biodegradable, but in practice, their end-of-life (EOL) behavior is complex. In typical disposal scenarios, the plastic or resin matrix isolates the fibers from microbes and moisture, so degradation proceeds very slowly essentially on par with conventional plastics in a landfill (X. Zhao et al. 2022). Consequently, protected disposal (e.g., sanitary landfill) can delay fiber decomposition for decades or longer. Instead of relying on biodegradation, NFRPCs are usually managed by recycling or energy recovery. Three principal pathways have been evaluated for NFRPC waste: mechanical recycling, energy recovery, and thermal/chemical recycling.

Mechanical recycling

Mechanical recycling typically involves grinding the composite waste into small particles (often a few millimeters in size) and remelting or pressing them into new parts. In thermoplastic NFRPCs this can extend the material's service life by producing secondary feedstock for injection or compression molding. Studies show that natural-fiber thermoplastics can be reprocessed multiple times: on the order of 4–6 recycle cycles with only modest property loss (X. Zhao et al. 2022). (For example, Zhao et al. report that after about seven cycles the tensile strength falls ~17% and modulus ~28% (X. Zhao et al. 2022).) Recycled NFRPC materials typically retain moderate mechanical properties (tensile strength often only a few tens of MPa, stiffness on the order of 1–3 GPa) but these are sufficient for non-structural uses, such as non-loadbearing panels, window frames, cable trays, or acoustic boards. In practice, mechanical recycling of NFRPCs can recover roughly half of the material value and yield multiple "lifetimes" of use for the polymer and fiber (X. Zhao et al. 2022).

Energy recovery (incineration)

In regions with waste-to-energy infrastructure, fiber composites can be incinerated to recover their heat value. Under high-temperature combustion, natural-fiber plastics release energy comparable to that of conventional polymers (on the order of 15–20 MJ/kg). This process requires specialized incinerators (temperatures often >1200°C and adequate residence time) to fully oxidize the material. Lifecycle analyses indicate that recovering energy from end-of-life composites can partially offset the energy otherwise used in the production of virgin resin. In practice today, large NFRPC products (e.g., decking, panels) often end up being either landfilled or sent to waste-to-energy facilities (X. Zhao et al. 2022). Energy recovery reduces landfill volume and produces useful electricity/heat, but it destroys the fiber and polymer, returning only the embodied energy to the system.

Thermal/chemical recycling (pyrolysis)

Chemical recycling of composites typically via pyrolysis or similar high-temperature, low-oxygen processes has been investigated as a way to recover fibers or monomeric products. In pyrolysis (500–600°C) the polymer matrix is broken down and gases/oils can be collected, leaving a fiber char. In theory, this process recovers carbon energy and leaves some carbonaceous residue, but it consumes substantial energy and can degrade natural fibers. To date, pyrolytic recycling of NFRPCs has remained largely at the pilot scale. It generally requires more energy input than direct incineration, and the recovered fibers are often brittle or partially charred, which limits their reuse. Due to these challenges, pyrolysis is not yet widely commercial; its viability may depend on future policies or carbon pricing that strongly incentivize material recovery. While mechanical grinding and incineration are currently used, true chemical recycling of NFRPCs remains experimental (Rezvani Ghomi et al. 2021).

Agricultural resource requirements and sustainability

Growing natural fiber crops (e.g., flax, hemp) at scale requires significant agricultural inputs. Flax and hemp are annuals, so each year they must be sown on arable land. Nutrient demands are moderate to high: flax is known to have a shallow root system and generally requires substantial fertilization and agrochemical input for good yields (Jacobsson 2018). For instance, agronomy studies indicate that maximizing flax yield can involve on the order of 100–150 kg N per hectare (often more under high-yield targets) (Jacobsson 2018; Schoenau et al. 2018), plus phosphorus and potassium as needed. Irrigation water needs are also nontrivial. Field measurements indicate that flax can consume approximately 2000 m^3/ha on rainfed land and over 4000 m^3/ha when irrigated during dry seasons (Zinkovskaya, Kovalev, and Zinkovskiy 2016). Thus, fiber farming can be water-intensive, especially in arid regions, and fertilizer production is a significant contributor to its environmental footprint (Jacobsson 2018).

Polyculture and crop rotation

Using fiber crops in diverse rotations can mitigate some sustainability concerns. Flax and hemp readily follow cereals or legumes in rotation schemes, helping to break disease and pest cycles. In particular, hemp has a dense canopy and allelopathic compounds that suppress weeds and nematodes, meaning it often requires little herbicide or nematicide (Adesina et al. 2020). Integrating hemp (or flax) with other crops can improve soil structure and organic matter and can reduce pest pressure on subsequent crops. In well-managed rotations, fiber crops have been found to maintain or even enhance biodiversity and soil health relative to monoculture systems (Adesina et al. 2020).

By-product valorization

Another sustainability advantage comes from using processing residues. Many natural-fiber feedstocks are themselves byproducts: for example, wood flour made from sawdust or planer shavings, flax shives from flax processing, and cotton linters from ginning. These waste streams can be upcycled as composite fillers or fibers, turning what would otherwise be an agricultural or industrial waste into a valuable resource (X. Zhao et al. 2022). In effect, textile and farming residues (such as cotton linters, hemp hurds, and wood flour) can be diverted into composite production, thereby reducing the demand for additional virgin biomass. This approach improves resource efficiency by leveraging existing waste.

Carbon sequestration benefits

Finally, fiber crops fix CO_2 during growth, providing a "built-in" carbon sink. Flax and hemp capture carbon via photosynthesis and store it in their stems and fibers. Quantitatively, about 1.39 tonnes of CO_2 are embedded in each tonne of harvested fiber (for both hemp and flax) (de Beus, Carus, and Barth 2019). Industrial hemp fields are particularly effective, with estimates ranging from 8 to 22 t of CO_2 sequestered per hectare per year of hemp cultivation (de Beus, Carus, and Barth 2019), potentially rivaling or exceeding the annual sequestration of a young forest. When these fibers are locked into durable composites with long service lives that carbon remains out of the atmosphere for the life of the product. Thus, long-lived natural-fiber products can yield a net greenhouse-gas offset by delaying the return of sequestered carbon, provided the material is not burned or decomposed.

Comparing resources, natural fiber crops tend to require more land (each year's planting is fully renewed) but can also regrow annually without replanting perennials, offering high land-use efficiency in rotation. However, they are generally more water-demanding than many industrial crops when grown in dry climates (Zinkovskaya, Kovalev, and Zinkovskiy 2016). In temperate regions with adequate rainfall, water inputs are more modest and the sustainability profile improves. Overall, the environmental impact of fiber composites depends strongly on agricultural practices and location, for example, hemp grown with low inputs can have a very low net impact, whereas irrigated flax in arid areas can be resource-intensive. Careful rotation design, organic amendments, and use of byproducts can all help tilt the balance toward a more sustainable outcome (Adesina et al. 2020; Jacobsson 2018; X. Zhao et al. 2022).

Current limitations

Technical barriers to structural application

Limited strength and stiffness

NFRPCs typically exhibit tensile strengths and elastic modulus far lower than synthetic-fiber composites. For example, even hybrid panels (e.g., carbon/flax or basalt/flax layups) show tensile strengths on the order of 100–150 MPa and Young's modulus of only a few GPa (Ardanuy, Claramunt, and Toledo Filho 2015) an order of magnitude below glass or carbon composites. Consequently, structural design is often governed by deflection limits rather than ultimate load, restricting practical spans of NFRPC elements to only a few meters under typical live loads. In practice, pure natural-fiber members are generally relegated to non-primary structural roles (e.g., panel infill or secondary framing) because their stiffness is insufficient for large spans (Capretti et al. 2023; Das, Srivastava, and Grammatikos 2025).

Moisture sensitivity

Natural fibers are hydrophilic and absorb water, which dramatically degrades composite performance. Extensive studies report moisture uptake can reduce NFRPC tensile strength by up to ~40% and elastic modulus by ~20–30% (Pavlovic, Valzania, and Minak 2025). In humid or cyclic environments this leads to swelling, microcracking, and permanent loss of mechanical capacity. Thus, untreated NFRPCs are generally suitable only for protected, indoor applications or must be encapsulated in effective barriers (e.g., sealants, coatings, drainage) to prevent water ingress (Das, Srivastava, and Grammatikos 2025; Pavlovic, Valzania, and Minak 2025).

Thermal limitations

The organic constituents of natural fibers (cellulose, hemicellulose, lignin) begin to thermally degrade around 200–250°C. In practice, processing and service temperatures are kept well below ~200°C to avoid fiber charring or embrittlement (Gong et al. 2012). Even in the 100–150°C range, prolonged heating can cause appreciable loss of strength and stiffness. Without special fire retardants or insulation, NFRPC elements cannot be used on critical fire paths (e.g., exposed beams or load-bearing walls) without additional protection.

High material variability

Natural fibers exhibit large variations in diameter, defect content, and orientation, leading to wide scatter in composite properties. Coefficients of variation of strength and stiffness in NFRPCs often reach 30–50% (Das, Srivastava, and Grammatikos 2025), far above the 5–10% typical of glass- or carbon-fiber composites. This poor uniformity necessitates large safety factors and conservative design allowables. In short, the inherent scatter in natural materials fundamentally limits NFRPC reliability in demanding structural applications (Das, Srivastava, and Grammatikos 2025).

Emerging durability enhancement technologies

Research on NFRPC durability is rapidly advancing, with new treatments and formulations significantly improving long-term performance.

Advanced fiber surface treatments (alkaline, silane coupling agents, permanganate, etc.) can dramatically enhance fiber–matrix bonding and inhibit moisture uptake. Studies show sequential alkali + silane treatments greatly reduce moisture-induced damage: after accelerated hygrothermal aging, treated composites retain the majority of their initial strength (Pavlovic, Valzania, and Minak 2025). These processes must be rigorously controlled (pH, concentration, time) and scaled up via automated chemical-processing lines integrated into composite manufacturing to be industrially viable.

Nanomaterial reinforcements are also under active development. Incorporating small amounts (~1–5 wt %) of graphene, carbon nanotubes (CNTs), or silica nanoparticles into the matrix can toughen the resin and create a nanoscale "tortuous path" that slows water diffusion. For example, graphite-silane nano-coatings on fiber surfaces have produced composites that retain >90% of their strength after hot-water aging (Li et al. 2024). (In this study, a nanostructured siloxane barrier on fibers yielded a 28% higher initial shear strength and excellent retention after 30 days at 70°C (Li et al. 2024).) Similar concepts are being applied with graphene or CNT, which also improve impact toughness. Although these nanotechnologies show promise, challenges remain in uniformly dispersing them in large-scale production and controlling cost.

Bio-based epoxy matrices are a third area of innovation. Epoxy resins derived from renewable feedstocks (plant oils, lignin/fermentation byproducts, furans, etc.) can match the thermomechanical properties of petrochemical epoxies while improving sustainability. Recent reviews report many bio-epoxy formulations achieving tensile and flexural strengths comparable to DGEBA epoxies, often with higher glass transition temperatures (Capretti et al. 2023). For instance, epoxidized vegetable-oil systems have produced cured resins with modulus and thermal stability similar to bisphenol-A epoxies (Capretti et al. 2023). When combined with natural fibers, these bio-epoxy systems can yield all-green composites: one study found that carbon/flax laminates using a 30% bio-content resin had only ~5–10% lower strength than carbon/epoxy controls, suggesting feasibility for many applications (Capretti et al. 2023). Importantly, the chemical compatibility between bio-epoxy and cellulosic fibers often improves interfacial bonding, further enhancing performance. Overall, bio-epoxy development is on track to deliver structural NFRPC resins that meet mechanical targets at similar cost to conventional systems (Capretti et al. 2023).

Hybrid reinforcement architectures represent a practical compromise. By combining natural fibers in the core with outer skins of high-performance fiber (e.g., glass or aramid), engineered laminates exploit the best of both worlds. The natural core provides bulk and low density (and intrinsic thermal/insulation benefits), while the synthetic skins carry most of the load and protect the core from moisture and UV. Such hybrids have been demonstrated in prototype beams and panels: for example, a basalt/flax hybrid panel had a tensile strength (89 MPa) far above a pure flax composite while still offering weight savings (Capretti et al. 2023). Though beyond the "pure natural" scope, these hybrid designs enable span lengths and durability closer to conventional composites, making NFRPCs viable in moderately structural roles. (A recent review highlights hybridization as a key strategy for high-performance NFRPCs (Ahmed et al. 2025).)

Manufacturing technology advancement requirements

Current fabrication methods for natural-fiber composites remain largely manual or low-speed, constraining part complexity and throughput. Conventional techniques (hand lay-up, compression molding, wet/dry layup with vacuum resin infusion) are inexpensive and versatile, but they are labor-intensive and yield only moderate fiber volume fractions (Das, Srivastava, and Grammatikos 2025). Hand lay-up in particular produces significant resin-rich areas and voids, resulting in lower mechanical properties. To reach structural-grade consistency, NFRPC production must transition toward more automated, precise processes.

Automated fiber placement (AFP)

Adaptation of AFP (currently used for carbon/glass prepregs) to NFRPC would allow preforms with tailor-made fiber orientation and stacking. AFP robots can place narrow tapes or towpregs along curved or 3D surfaces, enabling optimized architecture for specific load paths. This could improve strength-to-weight ratio beyond hand lay-up by aligning natural fibers along principal stresses. Research is needed to develop natural-fiber towpregs and compatible AFP machinery, but the reward would be production of large, complex components with minimal waste and high repeatability.

Three-dimensional printing (additive manufacturing)

Emerging 3D-printing (or additive) processes can form composite parts layer-by-layer, incorporating fibers into the printed matrix or using build-on-demand tapes. Unlike casting or molding, AM can directly create intricate geometries (curved beams, lattices, integrated joints) in a single build (Das, Srivastava, and Grammatikos 2025). Early work has shown printed NFRPC parts with designed porosity and fiber paths; as print resolution and multi-material capabilities improve, complex structural elements (with integrated hardware or channels) become feasible. Additive processes also dramatically reduce waste and tooling costs. However, current limitations include achieving high fiber volume and interlayer bonding; research into new printable resin systems and printheads for continuous fiber layup is active.

Pultrusion and continuous processes

Pultrusion is a well-established method for producing continuous fiber composite profiles (beams, rods, tubes) at very high output rates. For example, glass-fiber pultrusion lines routinely produce tens of meters per minute of profile. Adapting pultrusion to natural fibers (with gentle handling and tailored cure cycles) could yield cost-effective NFRPC beams, purlins, or rebar. Key R&D tasks include engineering feeds to avoid fiber breakage, controlling moisture in continuous fiber assemblies, and formulating resins that cure at practical rates. With optimized pultrusion, NFRPC structural members (e.g., glazing mullions, decking joists) can be manufactured at speeds of 10–100 m/min or higher, enabling economical scaling.

Case studies and implementation documentation

Recent pilot projects demonstrate that factory-fabricated facade panels using natural-fiber composites can meet or exceed conventional performance while offering substantial weight savings. For example, advanced sandwich panels with fiber-reinforced polymer skins have achieved U-values on the order of 0.18–0.22 W/(m^2 K) (Shahrbijari, Barros, and Valente 2023), thereby surpassing stringent thermal insulation standards. At the same time, the low density of composite materials means that a panel of equivalent strength may weigh only roughly two-thirds that of a comparable concrete element (in one bridge-deck case, a polymer panel weighed 132,000 lb versus 206,000 lb for a concrete counterpart). This 25–35% weight reduction translates into faster handling and lower dead loads in modular assemblies. Moreover, factory production enables precise control of panel geometry and material placement, allowing for thickness tolerances on the order of millimeters and uniform fiber/resin distribution, which yields highly consistent thermal and mechanical properties. Such quality control contrasts with greater variability in on-site assembly. In practice, however, designers must account for known drawbacks of natural fibers: notably, their hydrophilicity can introduce moisture-related durability concerns (for example, some flax-fiber panels are reported to be "highly hydrophilic" and thus sensitive to water exposure) (Sah et al. 2024). Nonetheless, properly engineered composite facades have demonstrated the required service performance (Sousa et al. 2025) in real buildings.

Long-term durability of NFRPCs in construction

Recent studies show that bio-fiber composites wood-plastic can retain much of their performance over the years but are sensitive to moisture and UV. Laboratory accelerated aging tests typically simulate decades of weathering and reveal substantial strength losses under aggressive conditions. For example, hygrothermal aging (e.g., cycles at 50–60°C/90%RH) can cut flexural strength by ~62–67% in a few weeks (Das, Srivastava, and Grammatikos 2025). UV and wet/dry cycling causes ~22–50% flexural loss in similar tests (Das, Srivastava, and Grammatikos 2025). By contrast, many wood-polymer panels show moderate lab degradation: one study found MOR (flexural strength) retention above ~86% even after combined natural and accelerated aging (L. Zhao et al. 2021). Laboratory freeze-thaw and thermal-cycling tests also highlight interface damage: differential expansion stresses the fiber–matrix bond, lowering MOR, and repeated freeze–thaw uptake induces moisture that further degrades interfacial adhesion.

In practice, real-world exposure tends to produce slower degradation than extreme lab tests. Field trials of natural-fiber facades and elements (typically 1–10 years) generally report modest performance losses. For example, three WPC cladding panels exposed outdoors in Europe for 1 year suffered significant UV-induced flexural loss, but much smaller reduction in fastener pull-through strength (Friedrich 2019) – suggesting that even as the board surface weathers, structural fixings remain sound. In a Chilean 10-year soil-contact study of PP/wood-flour stakes, all formulations showed no decay or termite damage (decay/termite ratings stayed at 10) (Gardner and Bozo 2018). These stakes did swell (mostly in the first year) but above-ground portions only showed moderate weathering and fungal growth. After 10 years, flexural strength was either unchanged or only slightly reduced, depending on formulation (Gardner and Bozo 2018). Similarly, a 12-month outdoor test in Brazil on recycled PP/EVA with 30% wood flour found the composite retained most of its mechanical strength; only surface discoloration and microcracking appeared (da Silva et al. 2017).

Nonetheless, natural-fiber composites still face challenges compared to conventional materials. By their nature, plant fibers are hygroscopic and biologically vulnerable. They exhibit increased susceptibility to moisture, mold, fungi, and pests, and may decompose faster or lose insulating value over time (Przybek 2025). Laboratory studies highlight this sensitivity, but there is no widely accepted standard for predicting service life. A recent review emphasizes that no specific protocols exist to assess NFRPC durability or translate lab aging into real lifetime. In practice, research is still skewed toward short-term or accelerated tests. Long-term (>5–10 years) field data are scarce for most new composites. Hence, more long-term monitoring of real buildings (multi-year hygrothermal and UV exposure) is needed to fully quantify performance retention and refine design limits for these sustainable materials (Das, Srivastava, and Grammatikos 2025; Przybek 2025).

Conclusions

The review confirms that NFRPCs are essential for achieving sustainable modular construction goals, fundamentally altering project logistics and environmental profiles. Their low density allows for an approximate 40% reduction in structural dead load compared to synthetic equivalents, which translates into lower foundation and framing costs and accelerated site assembly critical for high-rise buildings. Environmentally, NFRPCs offer profound advantages, including significantly lower production energy requirements (e.g., flax vs. E-glass) and the unique benefit of biogenic carbon sequestration, positioning them as a critical material class for meeting aggressive global decarbonization targets.

While NFRPCs demonstrate potential for moderate structural roles with specialized designs, such as deep sandwich panels, enabling them to meet serviceability requirements for residential floor spans (L/D = 20–25) their widespread structural viability is heavily compromised by reliability challenges. The high statistical variability of natural fibers forces the adoption of punitive material partial safety factors (~2.0) to maintain structural integrity, which ultimately restricts the usable design strength to only 50–60% of the mean tested strength. This reliability deficit prevents NFRPCs from competing economically with the higher usable design strengths afforded by highly uniform synthetic composites.

To transition NFRPCs from specialized materials to mainstream structural components in high-rise construction, a focused, multidisciplinary research roadmap must be executed. This effort requires three core pillars. First, enhancing durability by industrializing cost-effective, sequential fiber treatments and integrating nanomaterial-based barriers to block moisture and chemical ingress. Second, improving reliability through the development and rigorous validation of advanced probabilistic design frameworks and service-life models that accurately account for the long-term environmental degradation factor. Third, achieving economic competitiveness by adopting high-throughput automation, such as pultrusion and Automated Fiber Placement, to minimize variability and translate raw material cost savings into scalable, finished structural components.

Abbreviations

FRP	fiber-reinforced polymers
NFRPC	Natural Fiber-Reinforced Polymer Composite
GFRPC	Glass Fiber-Reinforced Polymer Composite
MFA	Microfibril angle
LCA	Lifecycle Carbon Assessment

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Data availability statement

All data generated or analyzed during this study are included in this article.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

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