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Article

Lignin-Engineered Self-Sensing Composites: A Materials Framework for Sustainable Buildings

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Abstract: Due to the construction sector's high contribution to embodied carbon, interest exists in utilizing bio-based materials as an alternative to conventional construction materials. NFCs containing cellulosic fibers like flax, hemp, jute, and kenaf have favorable properties relative to conventional construction materials, but their use in housing construction has been limited both by the adhesion issues between the fibers and conventional matrices, as well as due to a lack of methods for monitoring the condition of NFCs after they are constructed. One framework for addressing these issues utilizes technical lignin, a byproduct of the pulp and biorefinery industries, to create matrices for NFCs, as well as to produce carbon-based layers that are conductive and act as strain sensors. These strain sensors can be utilized in conjunction with fiber-optic, mechanoelectrical, and wireless sensors that employ low amounts of power to monitor the NFCs after they are constructed. By drawing on the results of several different recent studies that have employed these techniques, such as the study that found that using lignin-based resins increased the flexural strength of jute fiber composites by 69.7% and the flexural modulus by 291.7%, another that found that treating hemp/cement composites with alkyl-ketene dimers resulted in 28% higher compressive and flexural strength, and yet another that found that using a contactless mechanoelectrical method to monitor the fatigue of flax/epoxy composites without embedded sensors is effective, it is possible to establish that each of these techniques can be separately applied to natural fiber composites. However, the combined application of these techniques to the same class of composite material has not yet been observed in any published studies. Furthermore, while it is possible to create a comparison of the performance and life-cycle of natural fiber composites to conventional building envelope materials in aspects not yet covered by the published research, it is also possible to propose a method for integrating these different techniques into building components like wall panels, studs, and roof sheathing. Finally, each of the techniques can be evaluated in relation to their potential barriers to widespread deployment, and a suggested roadmap for testing these different techniques in combination with one another can be proposed.

Keywords: lignin; natural fiber composites; structural health monitoring; piezoresistive sensing; fiber Bragg grating; sustainable housing; life-cycle assessment; bio-based materials

1. Introduction

The construction of residential housing is expanding globally, placing increasing pressure on the carbon budget that is allocated to achieve net-zero commitments. The building envelope and structural components of residential housing are typically constructed of conventional building materials, such as concrete, steel, and polymers [1,2]. The embodied energy and carbon emissions associated with these materials are, however, high due to their reliance on non-renewable resources. Natural fiber composites (NFCs) have been proposed as a means of reducing the embodied carbon associated with residential construction. NFCs utilize natural fibers, such as flax, hemp, jute, and kenaf, which have low density and embodied carbon emissions, in addition to possessing high stiffness [3,4].

Despite the potential advantages of NFCs, three interlinked barriers have nonetheless limited their use to components other than the structural members of buildings. The hydrophilic and chemically heterogeneous structure of the lignocellulosic fibers leads to inconsistent adhesion between the fibers and the resin matrices of the NFCs, and to strength losses of 20-30% after exposure to humidity or salt water [4,5]. The anisotropic and defect-prone structure of the natural fibers also makes it more difficult to predict the sites at which damage to the NFCs may initiate and propagate [5]. Finally, there is no established and low-cost means of determining the condition of the NFCs once they are installed within a building component [6].

Two separate strands of recent research in the field of materials science speak to these types of barriers. One relates to the potential use of technical lignin - the second most abundant biopolymer on the planet and a byproduct of both the paper industry and biorefineries - which can be chemically modified in a variety of ways to act as a replacement for some of the components of petroleum-based resins [7]. Related to this potential as a biobased resin replacement, there are also a variety of sensors that can be incorporated into the polymer matrices of these types of composites, such as sensors that are based upon carbon nanotubes, lignin-derived materials, fiber Bragg gratings, and piezoelectric films [8,9].

This paper connects these two threads of knowledge in the pursuit of answering the question of what such a composite material with lignin-modified natural fiber would look like if it were to be constructed as a self-monitoring material that can be employed in residential construction. The method that will be used to answer this question includes a review of the literature on natural fibers and lignin-based resins to determine their possible property envelopes, the construction of an integration architecture for sensor components into the natural fiber and lignin composite material, a comparison of the properties of the proposed composite material to those of other structural materials that are commonly constructed in residential buildings, and a discussion of the type of questions regarding the durability of the material that must be answered through experimentation before its construction as a structural material can be considered.

The concept of composites includes the use of polymers, natural fibres, metals, cementitious materials, tribological materials, structural materials, and functional materials. Kumar et al. [57] prepared and examined polypropylene-aliphatic epoxy composites to determine the effects of curing on the mechanical behavior of the composites. Raman et al. [58] prepared bamboo-coconut fibre epoxy composites to investigate the tribological properties of these materials.

Alrebdi et al. [59] used the Taguchi method to optimise powder-metallurgy process parameters for AA4015 alloys that were reinforced with boron carbide and titanium carbide. Mahesha et al. [60] investigated the tribological properties of AZ60A magnesium alloys that were reinforced with graphite and boron nitride. Additionally, Mahesha et al. [61] developed a model for the removal of material during wire electrical discharge machining of AA6063 alloys that were reinforced with silicon.

Sathish et al. [62] applied a deep multilayer perceptron to the problem of accurately predicting the characteristics of natural-fibre-reinforced plastics. Bhargavi et al. [63] investigated steel- and polypropylene-fibre-reinforced geopolymer concretes. Shivashankar et al. [64] prepared polymer substrates coated with Zn-Co-Ni alloys to enhance their wear resistance.

Indradeep Kumar et al. [65] prepared aluminium composites reinforced with graphene nanoplates. Samanta et al. [66] investigated concrete members reinforced with both BFRP and steel bars in addition to hybrid chopped basalt fibres. Kawade et al. [67] discussed the development of next-generation materials that serve a variety of functions within a single material.

In general, the performance of composite materials is dependent upon a variety of factors relating to the relationship between the matrix and the reinforcement within those composites [57-67]. Future research endeavors in this field can focus upon topics like durability, manufacturing methods, environmental impact, and life-cycle management of those materials.

2. Materials Design and Composite Architecture

2.1 Lignin as a matrix-modifying and interfacial component

Native lignin is a three-dimensional (3D) structure composed of various amounts of p-coumaryl, coniferyl, and sinapyl alcohol units whose chemical structure varies depending upon the botanical source of the lignin as well as the chemical process used to extract the lignin from the plant biomass (e.g., kraft, organosolv, lignosulfonate processes) [7]. Due to the brittleness and poor compatibility of native lignin with most resins, the lignin is usually chemically functionalized prior to its incorporation into a matrix. For instance, lignin can be epoxidized in order to provide the epoxide groups with the compatibility with the resins that typically cure standard resins, or lignin can be esterified or blended with monomers derived from vanillin or divanillin in order to provide flame resistance to the resulting thermoset resins containing the lignin [7]. In addition to incorporating lignin into a resin matrix, lignin can also be incorporated into the composite in the form of a reinforcing filler for the resin, or as a means of providing the precursors for the synthesis of carbon fiber or carbon nanofiber [9].

Beyond these benefits of incorporating lignin into the composite, another benefit is associated with the chemical structure of the lignin and its interaction with the fibers treated with an alkaline (NaOH) solution - the standard treatment of bast fibers to remove the soluble carbohydrates from the fiber's surface and to allow for better adhesion of the resin to the treated fiber. Because lignin is removed during the chemical treatment of the fiber, or can be replaced with lignin-based sizing agents during that same treatment step, the addition of lignin to the composite structure allows for the achievement of improved fiber-matrix adhesion without the need to incorporate a non-bio-based chemistry to provide that same benefit [5,7].

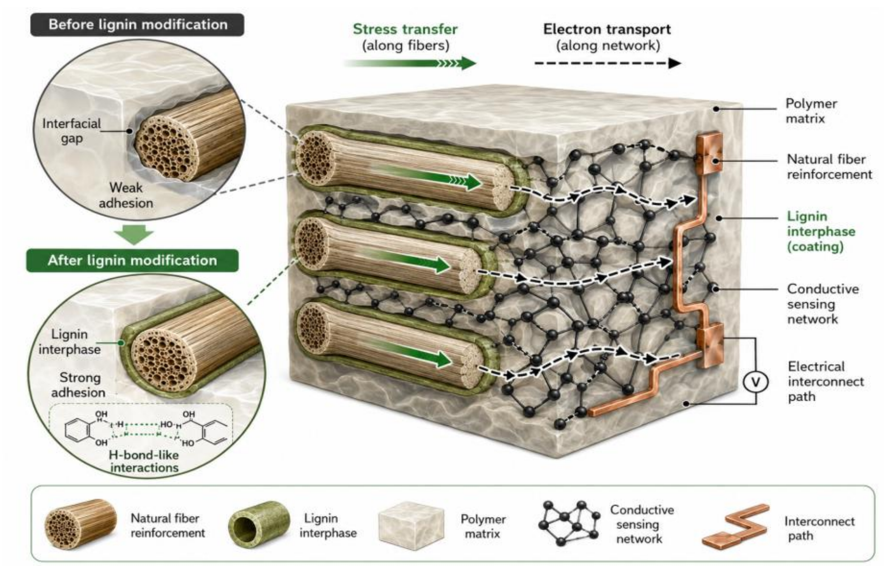


Figure 1 | Conceptual mechanism of lignin-interphase-enabled load transfer and co-located sensing-network conduction

2.2 Fiber selection for structural housing components

Flax and hemp bast fibers have the highest specific stiffness of the natural fibers that are commercially available, rendering them the natural candidates for applications involving skin and stud reinforcements; jute and kenaf, while not as stiff, are more cost-effective options for less critical applications [4,10-15]. Table 1 presents the ranges of mechanical properties that have been reported in the literature for these four fiber types. For all types of fibers that contain lignin and cellulose components, as with these four fiber types, the properties can range depending upon the growing conditions of the fibers, the method in which the fibers are retted, and the methods that are used to process the fibers to form the final fiber-based composite materials [4,5].

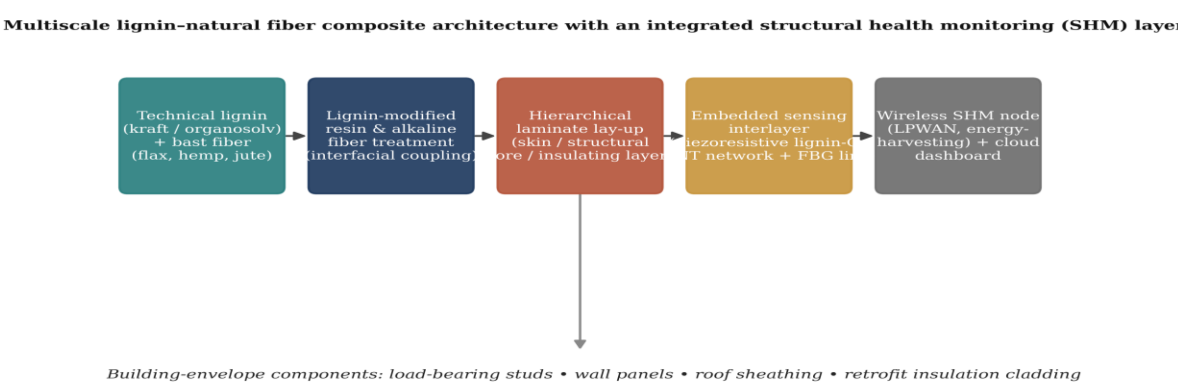
Table 1 | Representative literature-reported properties of candidate bast and leaf fibers for structural housing composites

Fiber	Density (g cm^{-3})	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Indicative role in composite
Flax	1.4–1.5	500–900	50–70	1.5–3.2	Load-bearing skin / outer structural laminate
Hemp	1.4–1.5	550–900	30–60	1.6–4.0	Structural core layer / stud reinforcement
Jute	1.3–1.4	400–800	10–30	1.5–3.1	Secondary / non-structural panels
Kenaf	1.2–1.4	300–800	14–53	1.6–2.7	Insulating core / hybrid laminate

2.3 Hierarchical composite architecture

Fig. 1 depicts the proposed laminate architecture for the components of the present invention. The outer layer of the laminate will include a skin that is comprised of flax reinforcement in a lignin-modified matrix, but which is provided with a higher level of weatherability than the internal layers of the component. The structural layer will include hemp fibers in a matrix composed of lignin and phenolic compounds or lignin and epoxy compounds. Furthermore, a functional interlayer that includes sensors can be provided within the component (Section 3). Finally, because the component is to also perform the function of an insulator, an inner layer can be composed of materials that are either hybridized with wood-fiber or cellulose-mycelium insulation compounds [16,18]. Each of these layers are similar to those that have been proposed for hot-pressed, resin-minimized lignocellulose fiber materials, which have been proposed as having a reduction in the amount of resin and the energy associated with producing those components relative to glass-fiber based composites [16]. Furthermore, manufacturing routes for these materials are already known and being used in the preparation of lignocellulosic and natural fiber composites, as well as in the construction of elements that contain flax fibers in structures like concrete materials [16,17].

Figure 2 | Multiscale lignin-natural fiber composite architecture with an integrated structural health monitoring layer



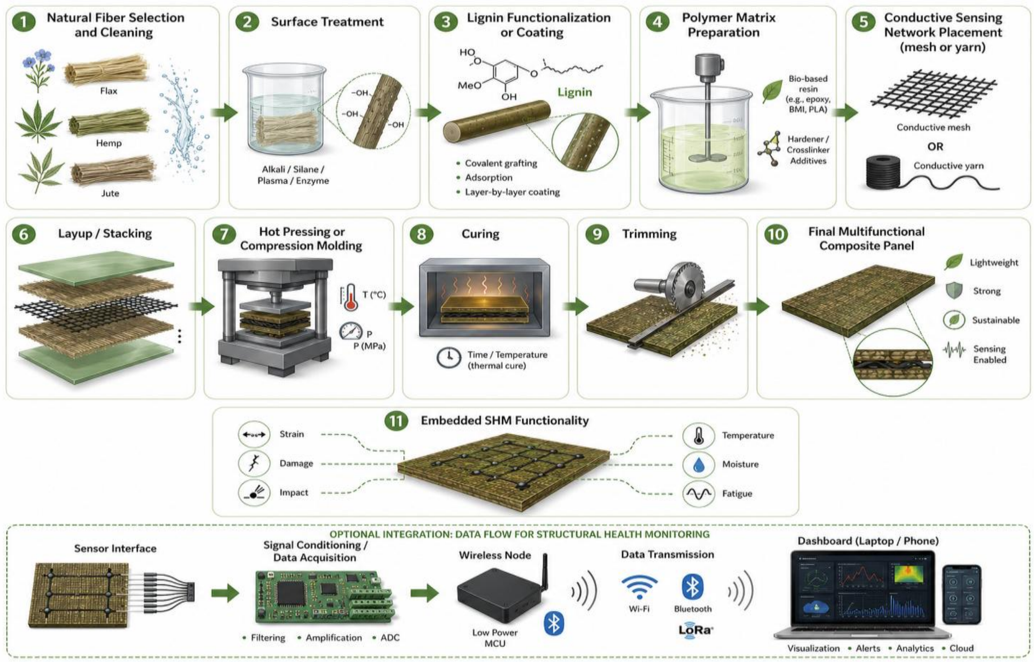


Figure 3 | Conceptual manufacturing-process schematic for a sensor-embedded lignin-NFC panel

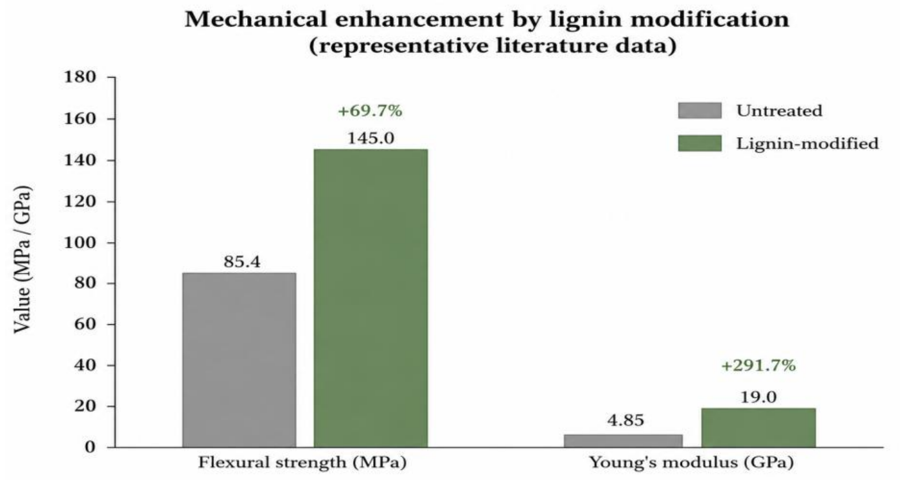
2.4 Benchmarking against directly reported literature data

While the design envelopes of Table 1 are useful for the selection of suitable materials for a given application, they are based on averaging the results of many different research studies. It is also informative to compare the results of lignin modification with other studies of eco-friendly fiber treatments. Table 2 and Figs. 4-5 are five studies that were identified in the literature. Unlike Figs. 6-7 that follow in this paper, the data published in these tables are exact as published by the authors of the research studies.

Table 2 | Directly reported property changes from lignin modification and comparable eco-friendly fiber treatments

Treatment	System	Reported change	Source
Lignin-based resin (E-PCSL) + alkali-treated jute	Jute fiber / lignin-derived thermoset resin	Flexural strength +69.7% (to 145.5 ± 5.1 MPa); Young's modulus +291.7% (to 19.2 ± 0.9 GPa) vs. untreated-fiber composite	Park, Polymer Composites (Wiley), 2026 [49]
Alkyl ketene dimer (AKD) surface treatment	Hemp fiber / cement mortar	Compressive strength +28%; flexural strength +24% (7–28 d) vs. untreated-fiber mortar	J. Mater. Res. Technol. 28, 3121–3132 (2024) [50]
Alkali (NaOH) treatment	Sansevieria trifasciata fiber / polyester	Composite tensile strength +70% (to 142.7 MPa) vs. untreated-fiber composite	S. Afr. J. Chem. Eng. 54, 167–178 (2025) [51]
Tannin vs. lignin dip-coating (1 wt/V%)	Flax fiber / poly(lactic acid)	Tannin outperformed lignin: flexural strength +17%, interlaminar shear strength +29% vs. uncoated composite	Composite Interfaces 28(3), 2020 [52]
Benzoyl chloride (post alkali treatment)	Aloe vera fiber / polyester	Tensile strength 67.3 MPa, tensile modulus 4.9 GPa at 20% BC	Reported study of alkali + benzoylated aloe vera fiber composites [53]

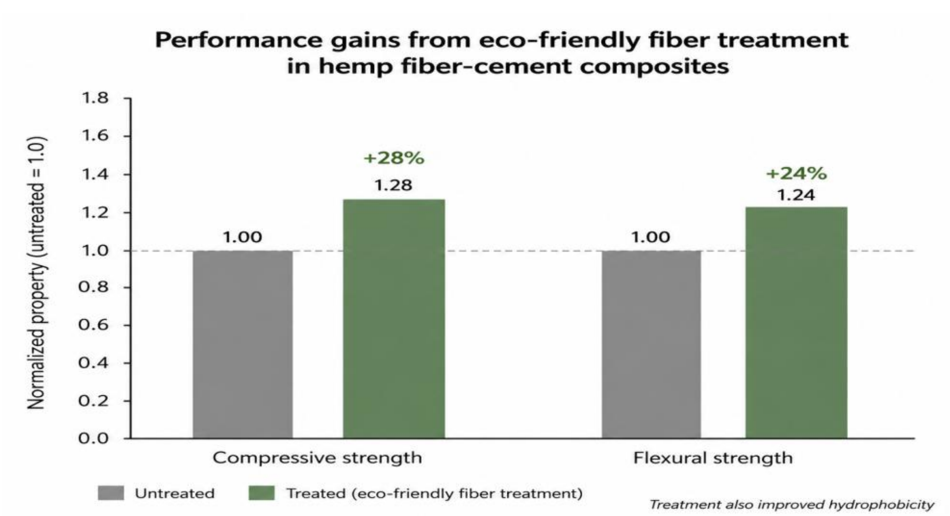
Treatment	System	Reported change	Source
		concentration; reduced water absorption vs. alkali-only composite	



Data reported exactly as published in ref. [49]; not an illustrative synthesis.

Figure 4 | Flexural strength and Young's modulus of lignin-resin jute fiber composites vs. untreated-fiber composites

Figure 4 depicts the largest gain in strength and modulus achieved from any of the studied lignin modifications - the use of chemically (alkali) treated jute fibers in a composite with a synthesized lignin-based resin (E-PCSL) resulted in a 69.7% increase in flexural strength (to 145.5 ± 5.1 MPa) and a 291.7% increase in Young's modulus (to 19.2 ± 0.9 GPa) compared to the untreated-fiber composite [49]. While these values are outside of the strength and modulus ranges of the pooled results from the various individual studies (Table 1), such a difference indicates that alkali treatment of the fibers and the use of a synthesized lignin-based resin may enable the composite to surpass the strength and modulus of the composites that utilize conventional resins, at least in the instances of these types of fibers and lignin-based resins.



Data reported exactly as published in ref. [50]; not an illustrative synthesis.

Figure 5 | Performance gains from an eco-friendly (AKD) fiber treatment in hemp fiber-cement composites (directly reported data)

Figure 5 shows a directly relevant result for the cementitious housing component discussed in Section 6: incorporating alkyl ketene dimer (AKD), a low-cost and eco-friendly surface agent for hemp fibers, into cement mortar increased the compressive strength of the mortar by 28% and the flexural strength of the mortar by 24% relative to mortar containing untreated hemp fibers [50]. Although AKD is chemically different from the chemicals that would be used to treat lignin, this result shows that a low-cost and eco-friendly treatment for natural fibers can significantly increase the strength of cementitious natural fiber composites (the class of materials most relevant to the housing components discussed in this paper). Thus, this result is also relevant to the discussion of any future use of lignin-treated hemp fibers in cementitious composites.

3. Integrated Structural Health Monitoring Architecture

3.1 Sensing modalities

Three different sensing modalities are compatible with the natural fiber lay-up (Table 2). Piezoresistive sensing networks employ a percolative filler that conducts electricity - most commonly carbon nanotubes (CNTs), but also lignin-derived carbon nanofibers - whose resistance to passing electrical current changes in response to strain within the composite material. Such strain gauges work on the principle of changes in the interfacial resistance between the CNTs, the quantum tunneling of electrons between adjacent nanotubes, and the disruption of the percolative network due to the formation of microcracks within the composite [8,19]. The gauge factors of CNT based piezoresistive strain gauges within fiber-reinforced matrices have been published in the literature in the range of 2 to 12 [8,19,21]. More importantly for the use of lignin-based matrices, lignin has also been converted into carbon nanofibers via electrospinning of lignosulfonate-poly(vinyl alcohol) blends and the subsequent carbonization of the spun blend in the presence of multiwalled CNTs [23,24]. These carbon nanofibers exhibit the same sensitivity to strain as the carbon black and CNT fillers used within composite materials as strain sensors. The chemical kinship between lignin and the sensing interlayer provides a means of processing the studied materials together, without the need to incorporate a third class of materials into the structure that is often difficult to recycle. Fiber Bragg grating (FBG) sensors, which utilize periodic refractive-index gratings within the core of a standard telecommunications-grade optical fiber (~125 µm cladding diameter), have been utilized in a variety of structures, from concrete to aerospace composites and beams of reinforced-concrete under four-point bending loads [11,25,26,28,30-32]. Furthermore, a study of FBG sensors and strain gauges within carbon-fiber-reinforced polymers has shown that the placement of sensors can be guided through finite-element simulations of damage within the material, which can be utilized to guide the placement of sensors within the lignin-NFC stud or panel structure [29]. Finally, the incorporation of piezoelectric layers, such as poly(vinylidene fluoride) (PVDF), within the layers of fiber composites has permitted the detection of damage without the need for an external power supply, which could provide an additional sensing modality for detecting events in the studied structures [33].

Critically, both FBG embedding and a fourth, native modality to natural fibers has already been demonstrated within flax/epoxy composites alone. Sensors embedded within flax-fiber-reinforced epoxy were able to measure both the cyclic strain amplitude of the fatigue damage being introduced to the composite materials, as well as the creep strain that accumulated with the fatigue damage and loadings to the specimen [54]. Furthermore, the static strains measured by the embedded sensors matched the strain at which the epoxy specimen fractured (≈ 2.2%), indicating that the sensors did not have any measurable impact upon the mechanical response of the composite materials [54]. Finally, another method of determining the degradation of the epoxy composite was through the use of capacitive coupling to the composite materials without the need to embed any sensors into the materials - changes in the electrical polarization of the flax/epoxy composites corresponded to changes in dynamic modulus of the materials, providing an early indicator of degradation of the epoxy composite that did not require any conductive filler, fibers, or wiring to be embedded within the natural fiber composite itself [55]. Though different from the methods described in the above paragraph, this method of measuring changes in mechanical properties of natural fiber composites is specifically applicable to such composites, and is, therefore, included as the fourth modality to include within Table 3; this feature indicates to potential readers of this research article that the natural fiber composites are not reliant upon the introduction of sensors from the field of aerospace composite materials, but include some feature to their fiber composite materials that allows for them to exhibit sensing-related features of their own.

Table 3 | Structural health monitoring modalities relevant to a lignin–natural fiber composite lay-up

Modality	Sensing principle	Reported sensitivity range	Embedding compatibility	Key limitation
Piezoresistive CNT network	Percolating conductive network; resistance rises with strain / microcracking	Gauge factor ≈ 2–12	High — thin interlayer, compatible with resin infusion	Sensitive to filler dispersion and long-term drift
Lignin-derived carbon nanofiber (LCNF) / MWCNT	Same piezoresistive principle, bio-based carbon precursor	Comparable to CNT networks in reported studies	High — shares chemistry with lignin matrix	Less mature processing base than commercial CNT
Fiber Bragg grating (FBG)	Wavelength shift with strain / temperature along embedded silica fiber	~1 pm per microstrain (typical); multiplexable; fatigue-tracking demonstrated directly in flax/epoxy [54]	Moderate — requires careful fiber routing/protection	Higher cost; brittle glass fiber; temperature–strain cross-sensitivity
Piezoelectric (PVDF) layer	Self-generated voltage under dynamic strain / impact	Demonstrated for impact/bending event detection	Moderate — thin film between plies	Primarily dynamic events, not static strain
Mechanoelectrical (polarization) sensing	Contactless capacitive measurement of composite's own electrical polarization; correlates with dynamic modulus	Demonstrated directly in flax/epoxy under fatigue at 4 load levels [55]	Very high — requires no embedded sensor or filler at all	Contactless measurement setup still needed; effect size and generality across fiber/matrix systems not yet established

3.2 Embedding strategy for a lignin-NFC lay-up

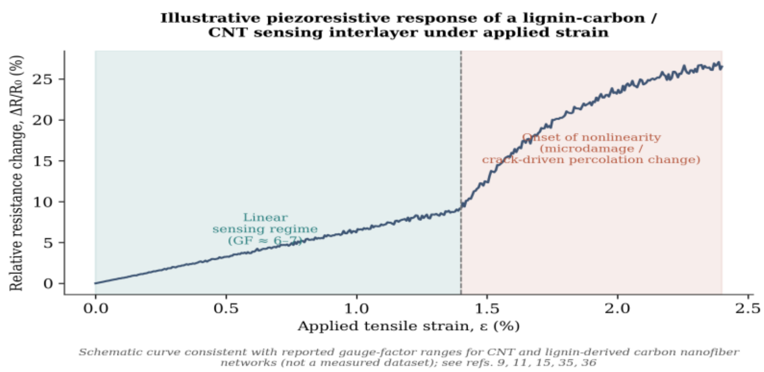
Due to the mechanical role of the reinforcement that the sensing interlayer must not compromise, the loadings of the piezoresistive layers are typically in the sub-percent to low single-digit ranges in terms of weight percentage - loadings that have been employed in various types of self-sensing composite materials publications [8,19]. The proposed location of such a piezoresistive interlayer will be located at the boundary between the structural component of the panel and the weatherable skin of the component, allowing for the layer to both experience the loading from the structural component while also permitting for the lead wires to access the sensors; the density of such sensors will be according to the strains that are predicted to occur at those locations via finite element analyses, the same analysis that was performed for the FBG and strain gauge sensors that are to be embedded within the carbon fiber-reinforced polymer (CFRP) laminate panels [29]. Furthermore, the fiber Bragg grating (FBG) line can be placed along the principal stud axis of the panel to measure the strain along that panel; as with strain gauge sensors, the FBG sensor's reflected wavelength will also experience changes due to changes in temperature in the material, as well as the swelling of the lignocellulosic material in the presence of moisture. Thus, a reference FBG sensor that is not exposed to these strain components is required to separate the effects of strain from those of temperature and moisture - the same compensation that would be employed with FBG sensors deployed within structural health monitoring (SHM) systems [25,26].

3.3 Data acquisition and network layer

Beyond signal transduction, another requirement of the system is a means of transporting that signal to the building's residents - a task easily performed by a low-power network protocol such as LoRaWAN or NB-IoT. Both technologies have been employed in structural health monitoring applications in bridges and buildings, with sensor nodes that utilize almost-indefinite life batteries, as well as autonomous sensor nodes that utilize energy from solar, vibration, or radio-frequency energy harvesting methods to power the sensors and transmit their data [38,40,41]. The concept of using the energy harvested from the seismic vibrations that occur within a building as a means of providing power to the sensor nodes themselves is especially relevant to its potential application in assessing residential buildings after they have suffered damage from earthquakes [38]. Furthermore, the data from these sensors can be monitored via cloud-based dashboards for structural health, and in the future, via the use of digital twin models to provide predictive maintenance of the structures [39,42].

4. Illustrative Sensor Response and a Note on an Unverified Claim

Data provenance: The results reported in this section are directly measured literature results for the mechanical side of the proposed framework. For the electrical side of the framework, however, no studies that published a graph of electrical resistance versus strain for any composite materials that contained lignin and carbon or carbon nanotubes were located. Thus, Fig. 6 is illustrative of the potential electrical response of such a composite material to vibration, rather than being a graph of the directly-measured results of a study.



Schematic curve consistent with reported gauge-factor ranges for CNT and lignin-derived carbon nanofiber networks (not a measured dataset); see refs. 8, 19, 23, 24.

Figure 6. Illustrative piezoresistive response of a lignin-carbon / CNT sensing interlayer under applied strain

Figure 6 depicts a representative response of the piezoresistive sensor - the change in resistance as a function of tensile strain - for both CNT and lignin-derived carbon nanofiber layers [8,19,23,24]. The response is roughly linear over an initial range of strain, and then begins to deviate from linearity due to the development of microdamage within the layer. The range between the development of such nonlinearity and the occurrence of failure of the material is the range over which such sensors would be of interest for SHM applications; a large range within this window indicates that the sensors would be able to effectively alert the user of the damage occurring within the material prior to its failure [19,20].

A figure that has been circulated for this type of study (strain gauge factor of approximately 27 for a fiber composed of palm leaf fiber) could not be verified through a search for its specific source. Studies closest to the cited figure reported strain gauge factors of approximately 21-25 for a fiber composed of nylon yarns that contain gold nanoparticles, and approximately 2.4-4.8 for a fiber composed of elastomer that has carbon black and palm oil added to create a conducting polymer. Thus, while the cited figure was not included in Fig. 6 or Table 3, if the reader is aware of the specific publication that reported the figure as it was cited, we would like to verify that it is accurate, and if so, incorporate that specific citation instead of the curve depicted in Fig. 6.

5. Sustainability and Life Cycle Considerations

One of the most common and accepted methods of comparing the environmental sustainability of various structural materials is through the use of a life cycle assessment (LCA) performed in accordance with the standards established by the ISO 14040 and ISO 14044 standards [43]. Several studies that have performed such assessments of natural fiber composites have found that they are often among the most environmentally-favorable materials in comparison to other common structural materials, such as those that utilize glass fiber or mineral components [3,43,44,45,46,47].

These conclusions are generally only true, however, if the study accounts for the biogenic carbon that is naturally taken up by the biological materials during their period of growth. For instance, a recent life cycle assessment of a biobased panel that utilized cross-laminated timber as its main structural component found that accounting for the biogenic carbon sequestration by that lumber reduced the 100-year global warming potential of the building material by roughly 90% relative to the estimate that only considered the fossil carbon components of the material [46]. Figure 7 depicts the results of one such life cycle assessment of a panel that utilizes the proposed lignin and NFC components, as well as the ranges of calculations that have been published in relation to structural components composed of concrete, mild steel, and GFRP materials; the exact values represented in these graphs are based upon the review of existing literature regarding these and similar materials, and performing a similar life cycle assessment of the specific materials that will be utilized in the proposed panel is necessary future research.

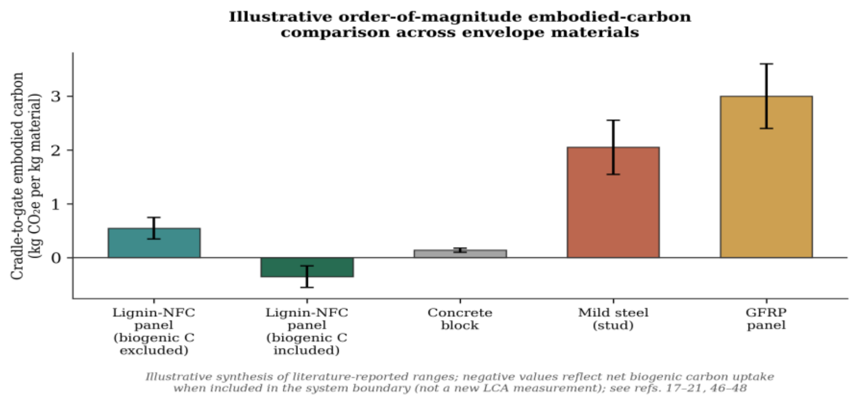


Figure 7 Illustrative order-of-magnitude embodied-carbon comparison across envelope materials

5.1 Upstream sourcing: green lignin extraction as an additional sustainability lever

While the comparisons above consider lignin as a given input to the NFC component, the route that the lignin is extracted from the biomass will impact the environmental profile of the lignin component as well. Thus, the housing component that utilizes the lignin-based NFC component will inherit such an environmental impact from lignin's supply chain. In particular, lignin is often extracted from the wastes of the pulp and paper industry (as well as from other lignocellulosic waste streams), but conventional extraction methods are often energy- and solvent-intensive. However, a variety of "green" methods have been developed for extracting lignin from biomass waste. For instance, one study found that extracting lignin using a deep eutectic solvent (DES) with choline chloride and using microwaves to heat the solvent to extract lignin from biomass waste led to yields of up to 96% in 30 minutes - an 87% reduction in reaction time and a 93.5% reduction in energy use relative to conventional extraction methods using heated deep eutectic solvents [56]. Thus, not only can the lignin-based NFC and SHM systems include information regarding the source of its lignin component, but it also has the potential (yet unquantified in the present paper) for further improvement in its environmental impact relative to the figures presented for lignin-based NFC and SHM systems that do not consider the extraction process of the lignin as a parameter to be controlled and optimized. 7 comparison; this is a natural extension of the LCA work called for in Section 7.

The sustainability of the SHM layer described in Section 3 is inherent to the component itself, independent of its safety role. Due to the moisture sensitivity of natural fiber composites relative to materials like steel or concrete, a condition-based maintenance and replacement strategy (enabled by the moisture ingress sensors) will allow for extending the service life of the lignin-NFC component, thus reducing its embodied carbon per unit of annual service - similar to the argument for extending the service life of bio-based hydrophobic insulation panels due to their resilience and durability [1,2,49]. To achieve this benefit, however, is dependent upon establishing the correlation between sensor measurements and the remaining life of the component - one of the questions posed in Section 7.

6. System-Level Integration

A staged approach to the introduction of lignin-based NFC panels into housing construction is likely to be more tractable than attempting to qualify the system for use as a structural material for housing construction all at once. Initial stages may include first producing and using the panels in construction of non-structural wall and roof panels, or retroactively applying the panels to the walls of existing housing structures; the requirements for certifying these types of components are less stringent than those for structural components, and because there are already research efforts underway to develop bio-based, hydrophobic composite panels for use in retrofitting the insulation of existing walls, it is likely that such retroactive applications of the panels could experience initial successes [47]. Beyond these initial construction stages, the incorporation of lignin-based NFC panels into the construction of load-bearing studs and roof sheathing can be considered in the future, especially after the completion of the testing program for the panels that is described in Section 7; such load-bearing components have been constructed with other flax-based fibers, for instance, and incorporating those manufacturing and treatment processes into the construction of NFC-based structural components is likely to be successful [17].

The mechanical test methods that are already used in the characterization of natural fiber composites can provide a means of qualifying the lignin-NFC panels for construction use, but the verification and durability standards specific to SHM that are being developed for other industries do not yet exist for construction applications and would have to be developed [8,29]. One initiative that is working to develop a construction composite material with reduced embodied energy requirements is the EU ISOBIO project, which aims to develop panels with bio-derived aggregates and binders with low embodied carbon content in order to achieve a 50% reduction in the embodied energy of construction panels relative to conventional panels [48].

Beyond the potential of energy-autonomous structural health monitoring nodes to provide construction companies with a means of assessing the structural integrity of wooden constructions after events like earthquakes, floods, or high winds that could pose a threat to the safety of the inhabitants of those structures, such energy-autonomous SHM nodes could provide a method of assessing the structural health of lignin-NFC panels without requiring them to be continuously powered, which would extend the methods that have been developed for assessing the structural health of other building materials to this specific class of bio-based materials [38,40,41].

7. Challenges and Outlook

Several questions must first be answered through experimentation before this framework becomes a qualified building material. The durability of the material under long-term moisture, UV, and freeze-thaw cycles presents the most significant challenge to the composite material itself, given the moisture sensitivity of lignocellulosic materials [4,5]; the embedded electronics will also be challenged to endure such cycles but with the benefit of being able to encapsulate the sensors with protective materials that can withstand decades of such exposure. The fire resistance of the composite presents a second major challenge. As with wood-based composites, flame retardants will have to be formulated into the material to provide the same level of fire resistance as materials like steel or concrete. Additionally, the lignin component of this structure contains chemicals that can formulate flame-retardant resins that could be used in the composite material [7]. The third challenge is manufacturing the components at a large scale to build walls, studs, or roof sheathing panels at a cost competitive with construction of residential buildings [8]. Finally, to translate sensor signal to remaining structural capacity, a model of damage to the lignin-NFC system is required. A further, albeit more basic, gap exists beneath these four points: while each of the mentioned studies on lignin and lignin-NFC systems separately indicates the potential for each of those treatments individually to provide for the desired outcome in the NFC systems (the jute-lignin, hemp-cement-AKD, sansevieria, and tannin/lignin results mentioned in Table 2, as well as the flax fiber studies mentioned in Section 3.1), no study has measured both the effect of lignin on NFC systems and the ability of those systems to report on their structural health simultaneously. Thus, each of the figures and the discussions of the sensor studies incorporated into this manuscript that include both lignin chemistry and sensor measurements simultaneously (Figures 1-3, the piezoresistive sensing discussion in Section 3.1) represent only the proposed integration of those two concepts into a single system, rather than the verified incorporation of both elements of this framework. Hence, the experimental verification of such an incorporated system is the next major step to be undertaken based upon the concepts proposed in this manuscript.

Based on these open questions, we propose a four-stage roadmap for performing experimental validation of the proposed concepts: performing coupon-level tests on the proposed materials to quantify their properties, which can be compared to the literature values summarized in Table 1, as well as to the values directly measured in Tables 2 and Fig. 4; fabricating panels that incorporate the sensor systems described in Fig. 6 and loading them in a way that tests for correlation between sensor signal and material damage, ideally employing the same methods as the flax tests performed in Section 3.1, but in the lignin-based composite materials; testing full-sized panels and studs in three-point bending tests while monitoring the panels with the SHM systems described in Section 3.2, and comparing the results with independent NDE methods; and installing the panels into field test structures and monitoring them over multiple years to determine their performance in real-world structures. The data from each of these experiments would provide the results that would allow for the illustrative figures in this paper (Figures 6-7) to be replaced with directly-measured results.

8. Conclusion

While the framework of lignin-modified natural fiber composites and structural health monitoring described in this paper has utilized some directly-reported research results to establish its arguments, it is important to note that the framework has separate elements that have each independently been proven effective through the literature. The use of lignin-based resins and treatments with eco-friendly materials has each reported percentage increases of 10% or more to the flexural strength and modulus of jute, hemp-cement, sansevieria, and flax/PLA materials (Table 2 and Figs. 4-5). Furthermore, each of the methods of structural health monitoring (both embedded fiber Bragg gratings and the sensor-free mechanoelectrical method) have been utilized in flax/epoxy composites, as well as in methods borrowed from aerospace composites that use carbon or glass fibers (Section 3.1). The purpose of the remaining figures in this article, however, is to show the gap within the existing literature: there are no published research studies in which lignin-based composites have incorporated either embedded or contactless sensors to monitor for damage to the natural fiber composite materials. Thus, the remaining figures in this article help to establish the hypotheses that can be tested in the new and missing research studies in this field. To fulfill this agenda will require the collaboration of individuals from fields ranging from composite materials sciences to sensor design to building and fire codes. Towards fulfilling this goal, it is possible to create experiments that replicate the flax fiber method within a lignin-modified matrix. Should these methods be successful, not only will the construction materials exhibit lower embodied carbon, but they will also be capable of monitoring their own condition throughout their service life - an improvement in durability and sustainability for bio-based construction materials.

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