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Bio-Derived Nanocarbon for Multifunctional Structural Energy Storage Systems: Materials, Trade-Off Engineering, and Analytical Design Frameworks

Uchenna Ekene Okaforobah, *Obiora Nnaemeka Ezenwa*, *Calistus Princewill Odeh*, *Chigozie Samuel Okaforobah*

[a]Nnamdi Azikiwe University, Faculty of Mechanical Engineering, Anambra State, Nigeria.
***Corresponding author:** ue.okaforobah@stu.unizik.edu.ng

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ABSTRACT

Structural energy storage composites have emerged as promising multifunctional materials capable of simultaneously providing mechanical load bearing and electrochemical energy storage functions for applications in aerospace, transportation, and portable electronics. This review examines the potential of bio derived nanocarbon as a sustainable functional phase in such systems, with emphasis on the trade offs between stiffness, interlaminar integrity, ionic transport, and energy storage performance. An analytical design envelope framework is proposed to support comparative architectural selection by highlighting feasible regions within the modulus–capacitance design space that balance structural and electrochemical requirements. A comparative assessment of matrix dispersion, interleaf reinforcement, and fibre surface functionalisation strategies indicates that localised incorporation of bio derived nanocarbon can improve the balance between electrochemical performance and structural integrity. The review further discusses the influence of biomass conversion and activation processes on pore development, surface area, resin infiltration behaviour, and mechanical stability. Current approaches for improving electrolyte stiffness and interface durability, including phase separated polymer systems, inorganic reinforcement strategies, and multifunctional electrolyte architectures, are also evaluated. Sustainability considerations involving renewable feedstocks, lightweighting potential, and lifecycle extension are examined alongside challenges related to scalability, standardisation, and mechanochemical reliability. The study provides a structured analytical perspective for the development of sustainable multifunctional structural energy storage materials and identifies key priorities for future experimental, modelling, and computational validation.

Keywords: *Bio-derived carbon, Composite materials, Mechanical–Electrochemical Coupling, Structural energy storage, Supercapacitors.*

I. INTRODUCTION

The increasing demand for electrification of transportation, renewable energy systems, and lightweight multifunctional structures has intensified research on advanced energy storage technologies that can reduce overall mass and improve performance. Electric vehicles, aircraft, and portable electronics often face persistent challenges because conventional energy storage devices, such as batteries and supercapacitors, are treated as distinct components, leading to penalties such as redundant

weight and increased volume in system design. These penalties directly impact range, efficiency, and mechanical performance in weight-critical applications.

One way to overcome these constraints is to create structural energy storage systems in which structural components also fulfil energy storage tasks. Structural energy storage has the ability to lower the total mass of a device by combining mechanical load bearing capacity with electrochemical activity in the same material. In this manner, composite materials can be designed to function as both a mechanical structure and an energy storage medium, lowering mass while preserving or improving system performance. This multipurpose system design is particularly important for applications that require both mechanical integrity and energy storage, such as aerospace, automotive, and portable electronics (Zschiebsch et al., 2024).

Within structural energy storage, two major device types have been investigated: structural batteries and structural supercapacitors. Structural batteries aim to integrate battery materials and components into load bearing composite materials, whereas structural supercapacitors combine the mechanical performance of fibre reinforced composites with a supercapacitor's ability to charge and discharge quickly (Zhou et al., 2022). Supercapacitors store energy largely through electrostatic charge accumulation at the electrode–electrolyte interface, resulting in high power density and a longer life cycle than batteries, but relatively lower energy density (Simon and Gogotsi, 2008). Structural supercapacitors, in particular, have demonstrated the ability to retain mechanical rigidity and load-bearing capability while exhibiting measurable capacitance, making them promising candidates for multifunctional energy storage systems (Wu et al., 2023).

Despite the progress in designing structural composite energy storage devices, there remain significant challenges in simultaneously achieving high mechanical performance and competitive electrochemical behavior. For example, a structural electrolytes must balance ionic conductivity with mechanical stiffness, and an electrode designs must optimize both surface area for charge storage and fiber reinforcement for load transfer, this often requires trade-offs between mechanical and electrochemical parameters. Moreover, most current research has focused on synthetic carbon precursors and polymer-derived fibers as active materials, with comparatively less exploration of sustainable alternatives that could reduce environmental impacts and improve scalability.

Bio-derived carbon materials, notably those derived from biomass feedstocks such as agricultural residues, forestry waste, and other organic by-products, present an opportunity for sustainable electrode design. Biomass can be thermochemically converted into carbonaceous materials, such as biochar and activated carbon, which possess high specific surface area, tunable porosity, and electrical conductivity (Rawat et al., 2022). These properties have been demonstrated to enhance electrode performance in supercapacitors and other electrochemical devices, while leveraging renewable resources and potentially lowering material costs (Hazarika et al., 2026).

However, integration of bio-derived nanocarbon materials into structural energy storage devices has not been comprehensively reviewed within a unified mechanical-electrochemical evaluation framework. Most studies report mechanical or electrochemical performance independently, making direct comparison and optimization difficult. A structured analytical approach that normalizes performance metrics such as elastic modulus, specific capacitance, and energy density across multifunctional systems to identify feasible design trade-offs for sustainable structural energy storage is needed.

In this perspective, the current paper aims to:

I. Review the principles of structural batteries and supercapacitors, focusing on the mechanisms that connect mechanical and electrochemical behaviors.
II. Investigate the possible use of bio-derived nanocarbon materials as multifunctional electrodes in energy storage systems.
III. Develop an analytical methodology to assess multifunctionality by comparing normalized mechanical and electrochemical performance parameters from literature.
IV. This study examines the design opportunities and constraints of sustainable structural energy storage systems by integrating bio-derived carbon materials into load-bearing composite

structures and using quantitative performance evaluation. The emphasis on engineering trade-offs, rather than individual performance increases, is intended to emphasize viable paths for future research and applications.

II. FUNDAMENTALS OF STRUCTURAL ENERGY STORAGE SYSTEMS

Structural energy storage refers to a class of materials and composite systems designed to simultaneously bear mechanical load and store electrical energy. This approach diverges from conventional energy systems where the structure and energy storage elements are separate, introducing opportunities to reduce mass and volume in applications that are weight sensitive such as aerospace, automotive, and portable electronics (Zhou et al., 2022).

Structural energy storage systems broadly fall into two categories: structural batteries and structural supercapacitors.

A. Structural Batteries

Structural batteries are engineered materials in which the load bearing composite architecture also provides electrochemical energy storage, typically through intercalation chemistry. In structural energy storage composites, carbon fibers provide mechanical reinforcement and serve as electrochemically active electrodes, whereas the polymer matrix performs dual roles as a load-transfer binder and ionic transport phase (Danzi et al., 2021).

Research in this area has investigated composite materials where carbon fibers act as electrodes and the polymer matrix serves as an electrolyte or supports solid electrolyte phases. The challenge in structural batteries lies in reconciling the often-contradictory requirements of mechanical stiffness and high ionic conductivity, as polymer electrolytes that provide ion transport tend to be mechanically compliant compared to structural resins, and electrochemically active electrode materials may not possess high stiffness (Nie et al., 2023). Due to these conflicting demands, structural batteries generally exhibit lower specific energy and mechanical properties than dedicated commercial batteries or structural composites, and ongoing research focuses on novel solid electrolyte formulations, tailored fiber modification, interface optimization, and multifunctional composite architectures to improve electrochemical and mechanical performance simultaneously (Javaid and Ali, 2018; Lutkenhaus and Flouda, 2020).

B. Structural Supercapacitors

In contrast, structural supercapacitors use electric double layer capacitance mechanisms to store charge at the electrode–electrolyte interface rather than relying primarily on Faradaic reactions. This frequently results in higher power density, rapid charge–discharge capability, and longer cycle life compared to batteries, making them attractive for applications requiring repeated cycling and fast energy delivery (Dubal et al., 2015; Zschiebsch et al., 2024).

Structural supercapacitors are usually composed of:

- Carbon fibre electrodes which serve as both reinforcement and charge collectors.
- Solid or multifunctional polymer electrolytes that promote ionic transport while maintaining structural integrity.
- Separators or interlayers that electrically isolate electrodes while allowing ion migration.

Carbon fibers are favored because of their high strength-to-weight ratio, fatigue resistance, and electrical conductivity, which allow them to contribute simultaneously to the composite's mechanical and electrochemical functions (Wu et al., 2023).

Structural supercapacitors have been demonstrated in various configurations, including laminated composites where carbon fiber electrodes are separated by glass or polymer layers infused with multifunctional electrolytes. Such systems can achieve moderate capacitance and mechanical stiffness; however, balancing electrochemical performance with structural reliability remains a persistent design challenge due to issues such as electrolyte softening, interfacial degradation, and crack propagation within interleaf regions during electrochemical cycling (Nie et al., 2023).

C. Mechanical–Electrochemical Coupling

The central technical challenge across structural energy storage systems is mechanical and electrochemical coupling, that is, the ability of a material to retain its mechanical properties such as stiffness and strength while simultaneously sustaining electrochemical performance under mechanical loading and charge-discharge cycling conditions (Adam et al., 2018).

Three major factors to be considered in achieving Mechanical–Electrochemical coupling are:

- Ionic conductivity vs. stiffness: Solid polymer electrolytes should enable ion transport but are mechanically softer than structural resins, creating an intrinsic conflict between electrochemical facilitation and load transfer capacity (Danzi et al., 2021).
- Electrode architecture: Carbon fiber electrodes must provide high accessible surface area for charge storage while also retaining fiber alignment and continuity for mechanical reinforcement (Li et al., 2020).
- Interfacial integrity: The interfaces between fiber, electrolyte, and matrix significantly influence the effective transfer of both mechanical stress and ionic charge, making interface design critical for multifunctional performance (Shirshova et al., 2013).

This is because multifunctional performance metrics (e.g., specific capacitance, energy density, modulus, strength) are often reported separately in the literature, direct comparisons across systems are difficult. An analytical approach that correlates these metrics is essential to identify practical performance windows and optimization strategies (Zhou et al., 2022).

To contextualize these architectures, Figure 1 illustrates representative structural energy storage configurations and their constituent components.

Figure 1(a) presents a structural battery architecture consisting of a carbon fiber reinforced positive electrode and a carbon fiber negative electrode, separated by a glass fiber separator. A structural electrolyte enables ionic transport while simultaneously contributing to mechanical integrity. Current collectors are integrated to facilitate electron transport across the electrodes. This multilayer architecture allows simultaneous energy storage and mechanical load bearing, although mechanical and electrochemical functions remain partially distributed across distinct phases (Asp et al., 2019).

Figure 1(b) shows a structural supercapacitor architecture based on carbon fiber or carbon aerogel electrodes embedded within a structural electrolyte matrix. The electrolyte serves both as ionic medium and mechanical binder, while a separator prevents electrical short circuiting. Current collectors ensure efficient charge transport. Compared to structural batteries, this configuration typically exhibits higher power density but lower energy density due to electrostatic charge storage mechanisms (Asp and Greenhalgh, 2014).

Overall, both architectures illustrate different strategies for achieving multifunctionality, where structural elements are engineered to provide both mechanical reinforcement and electrochemical functionality. The design differences reflect the inherent trade-off between energy density, power density, and mechanical stiffness in multifunctional structural energy storage systems (Adam et al., 2018).

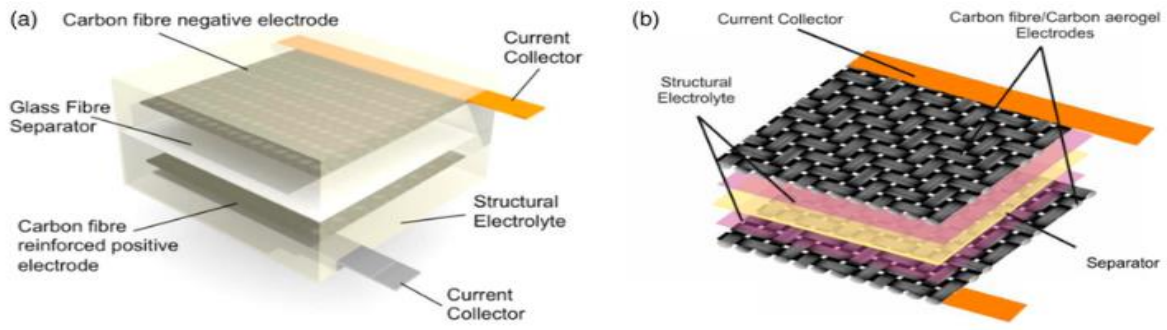

Figure 1. Schematic illustration of (a) structural battery and (b) structural supercapacitor composite architectures (Ishfaq et al., 2023; Asp et al., 2019; Asp and Greenhalgh, 2014)

Table 1. Comparative overview of structural energy storage system types.

Feature	Structural Batteries	Structural Supercapacitors
Charge Storage Mechanism	Faradaic (intercalation)	Double-layer capacitance
Energy Density	Relatively higher	Moderate but faster charge/discharge
Power Density	Lower	High
Cycle Life	Limited	Very high
Mechanical–Electrochemical Trade-off	Pronounced	Manageable with composite design

Structural supercapacitors, due to their mechanically compatible architecture and simpler charge storage mechanism, present a compelling pathway for sustainable load bearing energy storage systems, especially when paired with carbon based electrodes and multifunctional electrolytes (Senokos et al., 2018; Zhou et al., 2020).

III. BİO-DERIVED NANOCARBON AS A SUSTAINABLE STRUCTURAL ELECTRODE PLATFORM

Research on structural supercapacitors is dominated by carbon materials because of their mechanical compatibility with fiber-reinforced composites, chemical stability, and electrical conductivity (Wu et al., 2023; Zschiebsch et al., 2024). For the manufacturing of carbon fibre and activated carbons, conventional systems mostly rely on synthetic precursors like polyacrylonitrile (PAN) and feedstocks generated from petroleum. Despite the great performance of these materials, their manufacture requires a lot of energy and is highly dependent on fossil fuels (Glogic et al., 2022; Li et al., 2024).

Carbon materials made from biomass provide a sustainable substitute. Carbon compounds with controllable porosity and surface chemistry can be produced thermochemically from agricultural wastes, lignocellulosic waste, and other organic by-products (Iwuozor et al., 2023; Chen et al., 2025). These carbons are further modified for electrochemical applications through the procedures of activation and graphitisation (Rawat et al., 2022; Hazarika et al., 2026).

Bio-derived carbons have demonstrated high specific surface area, tunable pore structures, and competitive capacitance values in supercapacitor systems, and these developments makes them suitable candidates for integration into structural energy storage architectures (Sun et al., 2022).

A. Thermochemical Conversion Pathways

Thermochemical conversion refers to a group of heat-based processes used to transform biomass into carbon-rich solids, liquids, and gases under controlled conditions. The most common routes include pyrolysis, gasification, and hydrothermal carbonization (HTC), with each process producing different carbon structures and material properties depending on the operating conditions used (Begum et al., 2024).

Pyrolysis is one of the most widely used methods for producing biochar and carbon precursors for energy storage applications. In this process, biomass is heated in an oxygen-limited environment, causing the thermal breakdown of lignocellulosic components into solid biochar, bio-oil, and non-condensable gases. Parameters such as temperature, heating rate, and residence time significantly influence the resulting carbon structure. Generally, increasing the pyrolysis temperature improves aromaticity and electrical conductivity due to greater carbon ordering within the char matrix (Begum et al., 2024).

Gasification, on the other hand, uses controlled amounts of oxidizing agents at high temperatures to generate syngas, mainly composed of CO, H_2, and CO_2, together with a carbonaceous residue. Although the process is primarily aimed at fuel gas production, the remaining carbon residue can develop useful porous characteristics suitable for electrochemical applications. Partial gasification has been reported to enhance pore formation and surface accessibility, both of which are important for charge storage behavior in supercapacitor systems (Iwuozor et al., 2023).

Another important route is hydrothermal carbonization (HTC), which is particularly suitable for wet biomass feedstocks because it eliminates the need for extensive drying before processing. HTC occurs in a water-based environment under moderate temperatures (typically 180–250 °C) and elevated pressure. During the process, dehydration, decarboxylation, and aromatization reactions gradually increase carbon

content while forming porous hydrochar structures that can later be activated or functionalized for energy storage applications (Odeh et al., 2025). For example, Odeh et al. (2025) reported that hydrothermal conversion of African Elemi shell produced hydrochar with high carbon content and favorable surface characteristics under optimized conditions, highlighting the potential of underutilized biomass resources for sustainable carbon production.

Overall, these thermochemical pathways show that processing conditions, especially temperature, residence time, and the reaction environment (dry thermal versus hydrothermal conditions), strongly influence carbon yield, pore development, surface chemistry, and microstructure (Iwuozor et al., 2023; Begum et al., 2024; Chen et al., 2025). This level of control is particularly important when designing bio-derived carbons for multifunctional structural energy storage systems, where both electrochemical performance and mechanical compatibility must be balanced (Wu et al., 2023).

For structural supercapacitor applications, the electrochemical behavior of bio-derived nanocarbons is closely linked to pore structure and accessible surface area (Luo et al., 2021). To improve these properties, activation treatments are commonly applied after carbonization. Chemical activation using agents such as KOH, $ZnCl_2$, H_3PO_4, and NaOH is widely used to create microporous structures and increase specific surface area, which enhances ion adsorption and double-layer capacitance (Mahmood et al., 2025). Physical activation methods involving steam or CO_2 treatment can also generate hierarchical pore networks while reducing reliance on chemical reagents (Wang et al., 2017).

However, increasing porosity through aggressive activation can also introduce structural limitations. Highly activated carbons often become powder-like, with reduced particle cohesion and weaker structural continuity. During composite fabrication, such materials may absorb excessive resin, leading to resin-rich regions, void formation, and weaker interfacial stress transfer within the laminate structure (Das et al., 2021; Tamayo Vegas et al., 2022). As a result, there is an inherent trade-off between maximizing electrochemical surface accessibility and maintaining the mechanical integrity required for structural applications (Zhou et al., 2020).

To manage this balance, recent studies have explored approaches such as controlled activation severity, hierarchical pore engineering, and surface functionalization to improve electrolyte accessibility without excessively compromising structural integration within polymer matrices (Hazarika et al., 2026). These considerations are especially important for bio-derived nanocarbons intended for matrix dispersion, interleaf reinforcement, and fiber surface functionalization in multifunctional structural energy storage composites (Huang et al., 2023).

B. Comparative Mechanical and Electrochemical Properties

Table 2. Electrochemical and mechanical performance metrics of carbon materials relevant to structural supercapacitor systems.

Material	Surface Area (m^2/g)	Specific Capacitance (F/g)	Elastic Modulus	References
PAN-based Carbon Fiber	<10	~5–20 (when untreated)	200–600 GPa	(Fei et al., 2017)
Graphene (reduced GO)	500–2600	150–350	~1 TPa (intrinsic sheet)	(Tian et al., 2018)
Carbon Nanotubes	200–400	100–250	~1 TPa	(Mukai and Inoue, 2017)
Commercial Activated Carbon	1000–2000	100–300	Low structural stiffness (powder form)	(Hu et al., 2024)
Bio-derived Activated Carbon	1200–2500	150–350	Powder form; depends on composite integration	(Ziemińska and Doczekalska, 2024)
Bio-derived Hierarchical Nanocarbon	1500–3000	200–400	Enhanced when embedded in polymer matrix	(Chen et al., 2025)

Table 2 above is a comparative table of the mechanical and electrochemical properties compiled from peer-reviewed studies. According to this table, the following interpretations can be made;

- Synthetic carbon fibers provide superior mechanical stiffness but limited intrinsic capacitance.
- Graphene and CNTs exhibit exceptional intrinsic mechanical properties but are costly and difficult to scale sustainably.

- Bio-derived activated carbons demonstrate competitive capacitance values with significantly lower precursor cost and renewable sourcing.

The main limitation of bio-derived carbon is mechanical form factor, which can be mitigated through composite embedding or fiber-based fabrication.

C. Mechanical Reinforcement Potential in Structural Systems

The incorporation of nanocarbon fillers into polymer matrices has been shown to enhance interlaminar shear strength, electrical conductivity, and resistance to crack propagation in composite systems. These improvements arise primarily from improved load transfer, crack bridging, and formation of conductive percolation networks.

Nanocarbon interleaves and dispersed carbon nanotubes have demonstrated significant improvements in interlaminar fracture toughness and delamination resistance by altering crack paths and increasing energy absorption during crack growth (Huang et al., 2023).

Electrical conductivity improvements are typically achieved at low filler loadings once a percolation threshold is reached. Carbon nanotubes and graphene nanoplatelets form conductive networks within epoxy matrices which enables simultaneous mechanical reinforcement and electrical functionality (Laad et al., 2025).

Bio-derived carbon fillers have also shown potential as reinforcing agents. Biochar incorporated into polymer matrices has been reported to increase tensile modulus and flexural stiffness when dispersion and interfacial adhesion are optimized (Das et al., 2021).

For structural energy storage applications, the key design transition is to move bio-derived carbon from powder electrode form into integrated architectures such as fiber surface coatings, interleaf reinforcement layers, hybrid carbon fiber and biocarbon composite systems. Such integration enables concurrent mechanical load bearing and electrical functionality, which is fundamental to structural supercapacitor development.

D. Sustainability Considerations

Bio-derived nanocarbon materials offer sustainability advantages over traditional carbon electrodes due to their renewable origin, lower embodied environmental impact, and potential for circular lifecycle pathways. Biomass feedstocks are abundant, low-cost, and often constitute agricultural or forestry residues that might otherwise contribute to waste streams, making them attractive precursors for sustainable carbon materials (Mahmood et al., 2025).

Life cycle assessment studies of biochar production highlight its environmental potential. Biochar production via thermochemical processing can result in lower greenhouse gas emissions and reduced life-cycle global warming potential compared with conventional carbon materials, particularly when carbon sequestration during production and stable carbon retention are considered (Li et al., 2024). Moreover, biochar systems have been shown to achieve competitive environmental impact profiles in electrode production when compared with activated carbon from coconut shells, exhibiting lower overall material and energy use in several impact categories (Glogic et al., 2022).

Bio-derived carbon materials also align with circular economy principles. Stable carbon built into functional electrodes can sequester carbon over extended periods, and spent bio-derived materials retain potential for reuse or repurposing in environmental and agricultural applications, such as soil amendment or pollutant adsorbents (Li et al., 2024). Although feedstock variability and processing energy requirements remain challenges, the renewable nature of biomass and the potential for reduced chemical usage support wider deployment of bio-derived nanocarbons in sustainable structural energy storage systems.

IV. MULTIFUNCTIONAL DESIGN FRAMEWORK FOR BIO-DERIVED STRUCTURAL ENERGY COMPOSITES

A. The Mechanical–Electrochemical Coupling Problem

In structural energy storage composites, stiffness and strength must coexist with electrochemical functionality. However, the mechanisms that enhance capacitance or charge storage often modify the same microstructural features that govern load transfer. Increased porosity, higher surface area, and ion-accessible pathways improve electrochemical performance, yet these features can reduce matrix continuity, interfacial bonding, and overall stiffness.

For a composite laminate, the effective elastic modulus E_c can be approximated using rule-of-mixtures formulations:

$$E_c = V_f E_f + V_m E_m \tag{1}$$

Where:

V_f and V_m are volume fractions of reinforcement and matrix, respectively, and

E_f, E_m are their moduli.

This approximation follows classical composite mechanics formulations (Gibson, 2016).

When bio-derived nanocarbon is introduced into the matrix phase, the effective matrix modulus E_m and interfacial shear transfer characteristics are modified. At low loading levels, stiffness may increase due to nanoparticle reinforcement and improved stress transfer. Thus, electrochemical optimization cannot be decoupled from mechanical design.

B. Capacitance–Stiffness Interaction and Multifunctional Efficiency Descriptor

Electrochemical double-layer capacitance in porous carbon materials is governed primarily by accessible surface area and effective charge separation distance. For an ideal electrochemical double-layer capacitor, capacitance may be approximated as:

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} \tag{2}$$

Where:

A is electrode surface area,

d is effective charge separation distance, and

ε_r is dielectric constant of the electrolyte

ε_0 is permittivity of free space (vacuum permittivity).

This relationship is adapted from classical electrochemical double layer capacitor theory (Conway, 1999; Simon and Gogotsi, 2020).

In multifunctional structural energy storage composites, increased porosity enhances electrochemical accessibility but may reduce bulk density and disrupt load-transfer pathways, thereby lowering effective stiffness. This coupling creates a trade-off between electrochemical and mechanical performance that cannot be captured using single-property optimization.

To enable first-order comparative assessment of electrochemical–mechanical trade-offs, a normalized multifunctional efficiency descriptor is introduced as:

$$\eta_{MF} = \frac{Cs/Cs,ref}{Ec/Ec,ref} \tag{3}$$

where:

C_s is specific capacitance

Cs_{ref} is reference specific capacitance,

E_c is effective composite modulus

Ec_{ref} is reference composite modulus.

A higher η_{MF} value indicates improved electrochemical functionality relative to mechanical stiffness retention, while lower values correspond to mechanically efficient but electrochemically limited architectures.

The proposed descriptor is intended as a comparative analytical indicator for assessing electrochemical–mechanical trade-offs in multifunctional structural energy storage systems rather than as a predictive constitutive model. The framework is conceptually inspired by multifunctional efficiency assessment methodologies reported for structural supercapacitors (Zhou et al., 2020).

The normalized multifunctional efficiency descriptor provides a comparative basis for evaluating the relative balance between electrochemical performance and mechanical stiffness across different nanocarbon integration strategies. In this study, the framework is qualitatively applied to the architectures summarized in Table 3, including matrix dispersion, interleaf reinforcement, and fibre surface functionalization approaches. Strategies exhibiting high normalized capacitance retention with minimal stiffness reduction correspond to higher η_{MF} values and are therefore considered more favorable for multifunctional structural energy storage applications..

C. Bio-Derived Nanocarbon in Structural Architectures

The integration of bio-derived nanocarbon into fiber-reinforced composites fundamentally dictates the mechanical–electrochemical trade-off. Three principal structural strategies typically considered in this work are

C.1. Matrix dispersion

Nanocarbon particles or nanoplatelets are uniformly dispersed throughout the polymer matrix. This approach increases electrical conductivity by forming percolating networks and can improve local stiffness due to nanoparticle reinforcement. However, overloading or agglomeration leads to filler clusters and microvoid formation that degrade mechanical properties such as stiffness and interlaminar integrity (Tamayo-Vegas et al., 2022).

C.2. Interleaf architecture

Nanocarbon-enriched interleaves placed between fiber plies serve as localized reinforcement layers. These interleaves enhance interlaminar toughness and resistance to delamination without significantly compromising the overall laminate stiffness. The strategic placement of such layers allows electrochemical functionality to be concentrated where it minimally affects load paths (Shin and Kim, 2021).

C.3. Fiber surface functionalization

Bio-derived nanocarbon coatings or grafted films on fiber surfaces help preserve the main load-bearing fiber network while still creating a conductive pathway for ionic transport. In this way, the electrochemical function is shifted away from the bulk matrix, which helps limit the reduction in stiffness and interlaminar load transfer.

Among the available strategies, interleaf and fiber coating approaches tend to offer the most practical balance because they confine electrochemical activity to specific regions instead of distributing it throughout the structural matrix. This reduces the extent to which the reinforcement phase is diluted. The most suitable architecture still depends on the target multifunctional efficiency, the composite configuration (unidirectional, woven, or hybrid), and how compatible the bio-derived carbon is with the processing route.

As noted by Senokos et al. (2018), interleaf placement and fiber surface coating approaches can effectively localize electrochemical functionality while maintaining much of the mechanical performance of the composite, as shown in structural systems using CNT-based interleaves and polymer-coated electrodes that retain both stiffness and energy storage capability.

C.4. Design Envelope Concept

Structural energy storage composites must satisfy both mechanical integrity and electrochemical functionality within defined performance limits rather than optimizing either property independently. From a mechanical standpoint, interlaminar shear strength and resistance to delamination are critical for laminated systems, particularly where interleaf or nanocarbon-modified regions are introduced. Controlled incorporation of carbon nanotube toughening layers has been shown to significantly enhance interlaminar fracture toughness without catastrophic reduction in laminate stiffness, demonstrating that reinforcement architecture directly influences admissible mechanical performance boundaries (Zhao et al., 2024). Such findings establish the lower mechanical limits that multifunctional laminates must maintain.

Electrochemically, the performance of carbon-based materials in supercapacitor systems is governed primarily by accessible surface area and pore architecture, which directly influence electrolyte ion adsorption and transport at the electrode–electrolyte interface, thereby controlling specific capacitance and energy storage capability (Luo et al., 2021).

C.5. Implications for Sustainable Structural Systems

The design envelope concept introduced above has direct implications for developing sustainable structural energy storage systems, particularly when bio-derived nanocarbon is used as the functional carbon phase. By constraining materials and architectures to operate within admissible regions of mechanical stiffness and electrochemical performance, designers inherently promote material efficiency and resource optimization which are key metrics in sustainable engineering (Rduch et al., 2025).

Bio-derived nanocarbon offers a renewable alternative to fossil-derived carbon materials, as it can be produced from agricultural residues and other biomass feedstocks. Porous carbon materials synthesized from biomass have been shown to achieve surface areas and pore architectures comparable to or exceeding commercial activated carbons, with significant potential for use in high-capacitance electrodes (Luo et al., 2021). The use of such renewable precursors can reduce reliance on non-renewable feedstocks and lower the environmental burden associated with electrode production, supporting broader sustainability goals in multifunctional composites.

From a structural standpoint, strategies that localize electrochemical activity such as interleaf placement or surface functionalization can preserve primary load-bearing fiber networks while extending composite utility into energy storage domains. Improvements in interlaminar fracture toughness via nanocarbon reinforcement have been demonstrated without significant degradation of laminate stiffness (Zhao et al., 2024), implying that multifunctional performance can be achieved without sacrificing structural reliability. This balance reduces the need for redundant material mass, contributing to lightweighting, which is critical in sectors such as aerospace and electric vehicles where energy efficiency is paramount.

Furthermore, the adoption of bio-derived carbon materials aligns with circular economy principles: biomass residues are converted into value-added functional materials, and end-of-life composite waste may be repurposed or recycled into secondary applications (Begum et al., 2024). Such pathways enhance the lifecycle efficiency of structural composites beyond mere service performance, extending sustainability considerations into post-use stages.

Overall, engineering structural energy storage composites within a defined design envelope and using bio-derived nanocarbon not only addresses electrochemical and mechanical functionality but also advances sustainability through material selection, reduced environmental impact, and lifecycle extension (Rduch et al., 2025).

V. COMPARATIVE EVALUATION AND DESIGN IMPLICATIONS

Building on the structural architectures described in Section 4.3, this section evaluates the performance, trade-offs, and design implications of integrating bio-derived nanocarbon into multifunctional composites. Matrix dispersion, interleaf reinforcement layers, and fiber surface

functionalizationwhich are the three principal approaches are compared in terms of mechanical integrity, electrochemical functionality, and sustainability considerations.

A. Structural Batteries vs Supercapacitors

Structural batteries store higher energy densities but typically impose greater constraints on composite stiffness and interlaminar performance due to the active electrode material volume. In contrast, structural supercapacitors emphasize high power density and rapid charge/discharge, which can often be achieved with localized electrochemical layers such as interleaves or fiber coatings, imposing less compromise on mechanical performance (Simon and Gogotsi, 2008). Selecting the appropriate energy storage mechanism depends on application-specific trade-offs between energy, power, and structural reliability.

B. Synthetic vs Bio-Derived Carbon Systems

Synthetic carbons such as graphite, graphene, or carbon nanotubes offer high conductivity and controlled morphologies but rely on fossil-derived feedstocks with higher environmental impacts. In contrast, bio-derived nanocarbon, obtained from agricultural residues and biomass can develop high surface areas and tailored pore structures suitable for energy storage applications while offering the additional benefits of waste valorization, reduced environmental impact and support for circular economy principles (Li et al., 2020; Sun et al., 2022). Advances in biomass-derived carbon engineering have further demonstrated that feedstock selection, activation conditions, and pore structure control can significantly influence electrochemical performance, enabling bio-derived materials to compete with many conventional carbon materials in energy storage applications (Wang et al., 2017). The choice between synthetic and bio-derived carbon thus involves balancing electrochemical performance with sustainability objectives.

C. Performance Windows for Sustainable Structural Systems

Matrix dispersion distributes bio-derived carbon particles throughout the polymer matrix, forming percolating networks that enhance conductivity and provide localized reinforcement. Excessive filler content or poor dispersion, however, can lead to agglomeration and resin-rich microvoids, reducing interlaminar shear strength and stiffness (Tamayo-Vegas et al., 2022). Interleaf reinforcement layers localize electrochemical functionality between fiber plies, improving interlaminar toughness without significantly compromising laminate stiffness (Zhao et al., 2024). Fiber surface functionalization decouples electrochemical activity from the bulk matrix, preserving primary load paths while enabling electron transport at the fiber interface (Tian et al., 2018). Collectively, these strategies define a performance window within the design envelope, balancing mechanical reliability, capacitance, and density for sustainable multifunctional systems.

D. Design Recommendations

The comparative trends summarized in Table 3 and interpreted through the normalized multifunctional efficiency descriptor (η_{MF}) suggest that interleaf reinforcement and fibre surface functionalization strategies generally provide a more favorable electrochemical–mechanical balance in structural energy storage composites. These approaches localize electrochemical activity while minimizing disruption of primary structural load paths, thereby preserving mechanical integrity more effectively than bulk matrix modification approaches (Huang et al., 2023; Zschiebsch et al., 2024).

Matrix dispersion strategies remain advantageous for applications requiring distributed electrical conductivity and scalable processing. However, several studies have shown that excessive nanocarbon loading can lead to agglomeration, resin rich regions, and reduced load transfer efficiency if dispersion is not well controlled (Fei et al., 2017). These effects can ultimately reduce both mechanical performance and structural reliability at the laminate scale (Gibson, 2016).

Overall, the selection of nanocarbon integration architecture should be guided by the targeted balance between stiffness retention, interlaminar performance, electrochemical functionality, manufacturing

complexity, and sustainability considerations. In this context, bio-derived nanocarbons offer additional advantages through renewable feedstock and lightweight potential, while also supporting improved lifecycle sustainability in multifunctional structural energy storage systems (Li et al., 2024).

Table 3. Comparative performance metrics for bio-derived nanocarbon ıntegration strategies.

Integration Strategy	Effective Localized Modulus (GPa)	Interlaminar Shear Strength (MPa)	Specific Capacitance (F/g)	Density Impact	Notes / Trade-offs
Matrix Dispersion	2–10 (local reinforcement region)	10–25	50–200	Slight increase	Distributed conductivity; risk of agglomeration and resin-rich voids (Tamayo-Vegas et al., 2022)
Interleaf Reinforcement Layer	10–25 (maintained bulk laminate integrity)	25–50	100–350	Moderate	Localized electrochemical activity; preserves primary fiber network; excellent interlaminar toughness (Zhao et al., 2024)
Fiber Surface Functionalization	20–40 (fiber-dominated interphase region)	30–55	80–300	Minimal	Conductive coating on fibers; decouples electrochemical function from matrix; maintains load paths (Li et al., 2024)

The modulus values presented in Table 3 are representative of localized reinforcement or interphase-dominated regions associated with each integration strategy and should not be interpreted as the bulk laminate modulus of conventional structural carbon fibre composites.

VI. KEY TECHNICAL CHALLENGES AND RESEARCH OPPORTUNITIES

Despite significant progress in bio-derived structural energy composites, several technical hurdles still limit the full realization of multifunctional performance.

- Electrolyte stiffness limitation remains a primary concern because most ionically conductive polymer electrolytes are generally softer than structural resins and may reduce laminate stiffness, particularly in interleaf or coating regions. Recent studies have explored phase-separated electrolytes, block copolymer architectures, and inorganic nanofillers such as silica, nanoclay, and ceramic nanoparticles to create distinct ion-conducting and load-bearing domains within the electrolyte. These approaches can improve mechanical rigidity while maintaining ionic conductivity, although achieving an optimal balance between ion transport and structural load transfer remains a central challenge in multifunctional composite design (Nie et al., 2023).
- Interface degradation poses another major challenge. Long-term electrochemical cycling, environmental exposure, and thermal fluctuations can weaken fiber–matrix and electrode–electrolyte interfaces, leading to gradual reductions in both mechanical strength and electrochemical performance. Current mitigation strategies include surface functionalization, chemical grafting, interfacial toughening layers, and hybrid nanocarbon interphases designed to improve stress transfer, crack resistance, and interfacial stability during cycling (Huang et al., 2023).
- Scalability of integration strategies presents practical barriers. While matrix dispersion, interleaf reinforcement, and fiber coating approaches show promise at laboratory scale, translating these methods into large-area laminates with reproducible multifunctional performance requires optimized processing protocols, precise material handling, and controlled curing procedures (Javaid and Ali, 2018).
- Standardization gaps further limit progress. At present, there is no universally accepted methodology for simultaneous evaluation of mechanical and electrochemical properties, making direct comparison across studies difficult. Developing standardized multifunctional testing

frameworks will improve benchmarking and accelerate technological adoption (Rduch et al., 2025).

- Industrial integration barriers also remain significant. Incorporating bio-derived nanocarbon into conventional composite manufacturing introduces challenges related to feedstock preparation, layer placement, curing-cycle optimization, and quality control. Research into scalable manufacturing routes and in-line monitoring techniques may significantly improve industrial feasibility.

Addressing these challenges presents important opportunities for future research, particularly in electrolyte engineering, interface stabilization, scalable nanocarbon processing, multifunctional testing standards, and manufacturing integration strategies. Collectively, these developments can support the advancement of sustainable, high-performance structural energy storage composites.

VII. CONCLUSION

Structural energy storage composites incorporating bio-derived nanocarbon provide a path to multifunctional systems that combine mechanical strength and energy storage capability. The design envelope approach presented in this paper provides a practical framework for balancing stiffness, interlaminar strength, specific capacitance, and density while guiding architecture choices and material optimization. Comparative evaluation demonstrates that interleaf reinforcement and fiber surface functionalization strategies often provide superior multifunctional efficiency, while matrix dispersion may be more suitable when distributed electrochemical activity is desired. Bio-derived nanocarbon positions itself as a renewable, high-surface-area alternative to synthetic carbons, supporting sustainable material use and circular economy principles. Overall, this framework informs future engineering efforts in trade-off management, architectural design, and lifecycle-conscious development, paving the way for scalable, high-performance structural energy storage composites that meet mechanical, electrochemical, and environmental objectives simultaneously.

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