Biomass-derived Conductive Biocarbon for Flexible Strain Sensors: A Review

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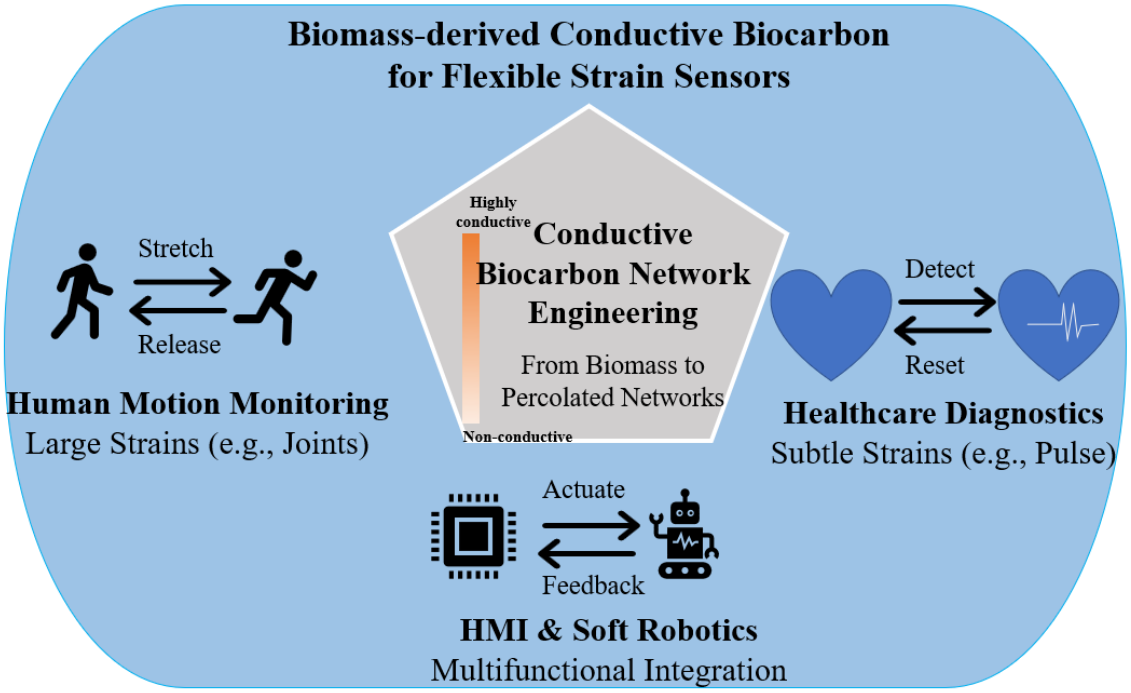
GRAPHICAL ABSTRACT



Biomass-derived Conductive Biocarbon for Flexible Strain Sensors: A Review

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Growing demand for environmentally sustainable wearable electronics is driving the development of high-performance electromechanical sensing materials from carbonized renewable resources. Despite rapid progress, key challenges remain in understanding how biomass carbonization pathways influence conductive network formation and electromechanical sensing performance. This review first analyzes the conversion of biomass feedstocks into conductive biocarbon through pyrolysis and hydrothermal carbonization, highlighting strategies for tuning hierarchical graphitic structure. Then, the review elucidates the electromechanical mechanisms governing strain sensing behavior in biocarbon composites, correlating microstructural evolution with key strain sensor metrics. By synthesizing recent advancements and identifying critical bottlenecks, this review aims to provide a roadmap for advancing next-generation, eco-friendly flexible biocarbon strain sensors from laboratory prototypes to practical applications.

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Keywords: Biomass; Carbonization; Biomass-derived biocarbon; Percolation; Flexible strain sensors

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INTRODUCTION

The rapid expansion of soft robotics, personalized healthcare monitoring, and integrated smart systems has catalyzed a transformative transition in electronics from rigid architectures to flexible, stretchable, and conformable systems (Nasseri *et al.* 2023; Won *et al.* 2023). As the interface between biological systems and digital data expands, there is a critical demand for wearable devices that possess multisensory capabilities, biocompatibility, and mechanical resilience (Hui *et al.* 2023; Wang *et al.* 2025; Zhu *et al.* 2025). Central to this transition is the development of flexible strain sensors capable of transducing mechanical deformation into detectable electrical signals (Amjadi *et al.* 2016). Flexible strain sensors commonly rely on carbon nanomaterials, metal conductors, conductive polymers, or their hybrids. While graphene and carbon nanotubes offer flexibility and stability, their high cost and scalability limitations hinder widespread use (Hosseini *et al.* 2018; Jindal *et al.* 2022). Metal nanowires and thin films provide high conductivity, but they suffer from oxidation and mechanical fatigue. Conductive polymers, though mechanically compliant, are constrained by limited long-term stability (Feng *et al.* 2023; Souri *et al.* 2020; Zou *et al.* 2025). Consequently, there is a growing demand for conductive materials that can simultaneously deliver high electromechanical performance while meeting requirements for sustainability, scalability, and economic viability.

Biocarbon refers to conductive carbon materials derived from renewable biomass precursors (*e.g.*, cellulose, lignin, or other feedstocks) through thermochemical conversion processes such as pyrolysis or carbonization. Biocarbon has emerged as an emerging and promising candidate in this domain (Jin *et al.* 2025; Liu *et al.* 2015; Xue *et al.* 2025; Yu *et al.* 2024). In contrast to traditional carbonaceous materials, biocarbon utilizes the inherent, hierarchical microstructures of natural precursors, ranging from woody biomass to herbaceous plants, to establish conductive networks (Gabhi *et al.* 2020; Wu *et al.* 2023a; Wu *et al.* 2023b; Yang *et al.* 2023). These natural architectures, evolved over generations for mechanical resilience and transport efficiency, possess astonishing structural properties and excellent mechanical strength and transport efficiency (Chen *et al.* 2020a; Schubert *et al.* 2022). For instance, the unique cell structure in wood and the fibrous networks in cotton can be preserved during carbonization, providing a tunable platform for engineering high-performance sensing composites (Barreiro *et al.* 2019; Lai *et al.* 2021; Zhang *et al.* 2017).

Recent techno-economic analyses indicate that decentralized biomass pyrolysis systems can convert forest residues into biocarbon at a minimum selling price of approximately $500 to $600 per ton (Puettmann *et al*. 2020; Sahoo *et al*. 2021). Complementary life-cycle assessments have demonstrated that pyrolysis-derived biocarbon can retain a major portion of the original biomass carbon in a stable form over centennial timescales. This enables a net-negative global warming potential by accounting for the avoided emissions otherwise generated by biomass decay or open burning (Costa *et al*. 2025; Woolf *et al*. 2010). Collectively, environmental and techno-economic assessments support biomass-derived carbon as a scalable, cost-effective, and environmentally advantageous material platform for next-generation flexible electronics.

Despite these advantages, the translation of biomass into biocarbon and functional strain sensors presents great challenges (Chheda *et al.* 2007; Liu *et al.* 2015; Yu *et al.* 2024). It requires an in-depth understanding of carbonization and sensing mechanisms (Claro *et al.* 2022; Gong *et al.* 2023). Converting complex biopolymers into graphitic structures involves highly intricate reactions (Kawamoto 2017). Moreover, piezoresistive biocarbon sensors operate as complex, dynamic networks of countless overlapping electrical pathways. The macroscopic conductivity relies on the formation of a percolated network, as well as a multiplicity of potential and complete micro-circuits. As the composite undergoes mechanical deformation, the exact state of tension dictates the localized disconnection and reconnection of these discrete circuits, driving the overall resistance change. There is a clear gap in connecting biocarbon characteristics to the final performance of biocarbon-based strain sensors. Consequently, the inherent heterogeneity of biomass precursors is often viewed as a barrier to reproducibility rather than a tunable feature (Tiwari *et al.* 2022).

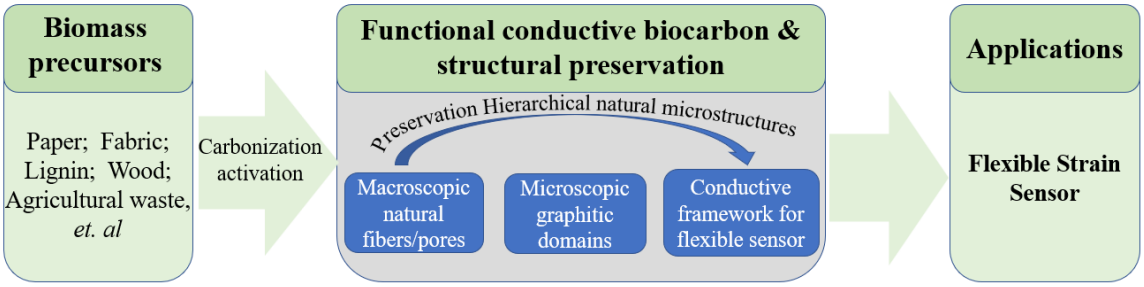

Fig. 1. Schematic roadmap illustrating the valorization of diverse biomass precursors into functional biocarbon for flexible electronics.

The focus of this review is that the inherent structural complexity of biomass, if deterministically controlled, offers a distinct advantage over other conductive fillers in strain sensing (Fig. 1). The hypothesis argues that the superior electromechanical performance of biocarbon sensors is not governed primarily by the intrinsic conductivity, but is critically dependent on the resulting hierarchical architectures and percolation networks (Lai *et al.* 2021; Wang *et al.* 2024). Therefore, the rationale for this review is to bridge biomass carbonization and sensor performance. The objective is to transform the field from phenomenological observation to predictive strain sensor engineering.

HIERARCHICAL MICROSTRUCTURES: NATURAL TEMPLATES AND SYNTHETIC AEROGELS

The sensitivity and durability of biocarbon-based strain sensors are fundamentally governed by the continuous conductive network architectures. The hierarchical microstructures of biomass precursors serve as critical templates (Fig. 2). Woody biomass provides a highly robust, anisotropic scaffolding characterized by well-aligned tracheids, vessel elements, and thick, heavily lignified secondary cell walls (Fengel and Wegener 2011; Hızal 2022; Jakes *et al*. 2019; Qiu *et al*. 2023). These rigid, evolutionary-optimized channels ensure excellent mechanical strength and facilitate highly directional, continuous transport pathways. In contrast, herbaceous plants present distinct cellulose microfibril organizations, varied hemicellulose branching, and a generally lower lignin content. This leads to less rigid primary cell wall architectures (Crang *et al*. 2018). Beyond naturally evolved templates, synthetic biomass-based aerogels offer highly engineered, customizable hierarchical structures. The strategic reassembly of biopolymers *via* sol-gel and freeze-casting protocols facilitates precise, multi-scale control over the internal pore distribution, ranging from micro- to macroscopic regimes (Chen *et al*. 2024). These synthetic frameworks frequently exhibit isotropic cellular foams or biomimetic anisotropic structures (Jiang *et al*. 2026).

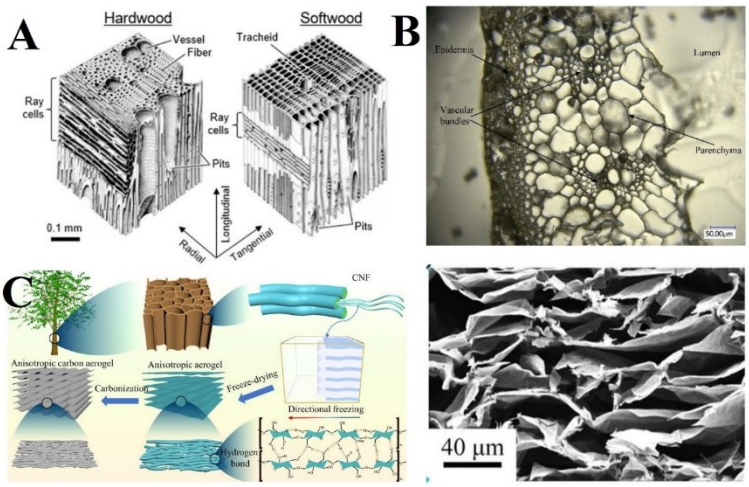

Fig. 2. Multiscale hierarchical architectures of natural and synthetic biomass templates for conductive biocarbons. (A) Schematics of highly anisotropic woody biomass, contrasting hardwoods with softwoods (Jakes *et al*. 2019). (B) Cross-sectional micrograph of wheat straw (Reprinted with permission from Wang *et al*. 2015, Springer Nature). (C) Schematic and SEM image detailing the bottom-up fabrication of synthetic cellulose aerogel (Reprinted with permission from Lai *et al*. 2021, American Chemical Society)

Preserving the hierarchical microstructures of biomass during thermochemical conversion presents a large engineering challenge. High-temperature pyrolysis frequently induces catastrophic volumetric shrinkage and pore collapse due to violent volatilization of biopolymers. Recent protocols overcome this through pre-stabilization (delignification or 180 °C hydrothermal treatment), controlled pyrolysis, and directional ice-templating (Zhang *et al*. 2017; Ji *et al*. 2022; Chen *et al*. 2020b). These protocols effectively thermoset the hierarchical framework, significantly suppressing volatile release and allowing the material to withstand subsequent high-temperature graphitization without severe structural degradation or mass loss (Ren *et al*. 2026). Such engineered architectures effectively delocalize mechanical stress through reversible deformation, granting the resulting biocarbon aerogels exceptional stretchability, ultra-high compressibility, and superior fatigue resistance compared to conventional carbon fillers.

BIOMASS CARBONIZATION AND DERIVED CONDUCTIVE BIOCARBON

Biomass Carbonization

The carbonization of lignocellulosic biomass generally yields two distinct classes of functional carbon. One of these is biochar, which can be optimized for environmental remediation (Fan *et al*. 2022; Jing *et al*. 2019; Liu *et al*. 2018; Zhang *et al*. 2019a; Zhang *et al*. 2019b), soil amendment (Ali *et al*. 2020; Zhang *et al*. 2020; Zhang *et al*. 2024a) and catalyst carrier (Shao *et al*. 2024).

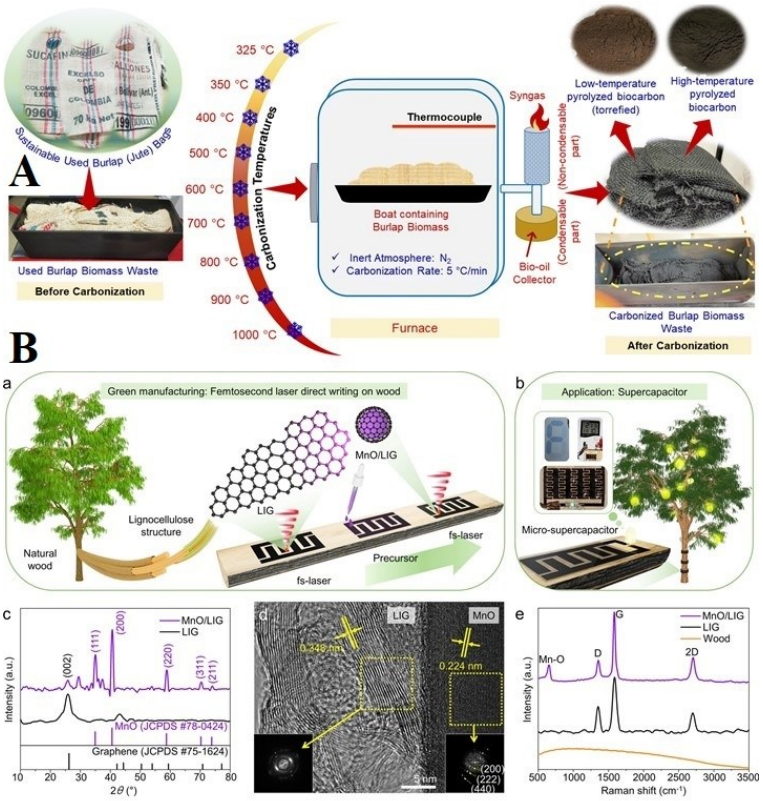

Fig. 3. Typical carbonization pathways of lignocellulosic biomass. (A) Carbonization route for the production of burlap-derived biocarbon (Tripathi *et al.* 2022). (B) Laser-induced graphitization (LIG) on wood surfaces (Kim *et al.* 2024)

The other class is conductive biocarbon, which can be tailored for electronics (Jiang *et al.* 2025; Li *et al.* 2023a; Li *et al*. 2023b; Mahmood *et al*.; 2025Tiwari *et al.* 2022). Although both originate from the same biomass precursors, their preparation and applications differ significantly. Specifically, carbonization of biomass is a complex structural evolution involving bond cleavage, rearrangement, and aromatization. At low-to-moderate temperatures (typically 300 to 600°C), carbonization proceeds under kinetically constrained conditions dominated by heterolytic reactions. These pathways favor the retention of disordered carbon domains and oxygenated functional groups, including carboxyl, hydroxyl, carbonyl, and lactone moieties. These functionalities, together with hierarchical porosity, enable biochar's utility in environmental remediation (Chen *et al.* 2023; Wang and Wang 2019; Wang *et al.* 2022). Meantime, biochar can also be converted into conductive biocarbon through high-temperature posttreatment or activation (Ouyang *et al.* 2024; Yu *et al.* 2024).

Biomass-Derived Conductive Biocarbon

The transformation of insulating lignocellulosic biomass into functional conductive biocarbon is governed by precursor chemistry and thermodynamic processing conditions (Fig. 3). Successful sensor performance relies on an in-depth understanding of the competitive kinetics between heteroatom elimination and the subsequent drive toward sp^2-hybridized hexagonal networks. In this context, the chemical identity of the precursor is the primary determinant of the final carbon yield and microstructure. Lignin's cross-linked phenolic structure and high carbon content (40 to 60%) provide structural integrity during

thermal degradation (Appiah *et al.* 2022; Jin *et al.* 2025). Its aromatic rings serve as nucleation sites for the growth of carbon domains (Jia *et al.* 2023; Kawamoto 2017; Liu *et al.* 2022; Meng *et al.* 2022). Conversely, cellulose tends to depolymerize into volatile levoglucosan. This pathway leads to large mass loss and low carbon yield (<20%). The crystalline cellulose domains remain crucial for forming ordered graphitic fibers that provide the necessary mechanical tensile strength (Chen *et al.* 2021; Lai *et al.* 2021; Long *et al.* 2023).

Traditional pyrolysis serves as the primary synthetic route, in which the mechanical and electronic properties of the resulting carbon are dictated by the competition between homolytic and heterolytic pathways. At temperatures exceeding 600 °C, the radical-mediated homolysis mechanism predominates. This facilitates the cleavage of C–C and C–O bonds and the subsequent recombination of radicals into polycyclic aromatic hydrocarbons (Kawamoto 2017). These aromatics promote the growth of extended graphene sheets, which are essential for high electronic conductivity. In contrast, lower-temperature regimes or chemically catalyzed environments favor ionic heterolysis. This mechanism generates ether bridges and extensive cross-linking that disrupts the developing graphitic lattice. The result is a disordered carbon that is mechanically robust but lacks the long-range electronic coherence required for high-performance sensing (Yang *et al.* 2023).

Alternative processing strategies such as hydrothermal carbonization (HTC) and laser-induced graphitization (LIG) offer distinct kinetic advantages and limitations (Ischia *et al.* 2025; Kim *et al.* 2024). HTC operates in subcritical water (180 to 250°C) (Gong *et al.* 2023; Jin *et al.* 2025; Yu *et al.* 2024; Zhang *et al.* 2024b). However, the resulting hydrochars are inherently limited to semiconducting behaviors (Gong *et al.* 2023; Ischia *et al.* 2025). To overcome this π-conjugation deficit, secondary high-temperature annealing is required to restore the aromatic structures necessary for conductive filler applications (Yu *et al.* 2024; Zhang *et al.* 2023). Conversely, LIG partially solves these kinetic bottlenecks by utilizing laser radiation to achieve instantaneous graphitization. The efficacy of LIG is intrinsically tied to the laser absorption coefficients of the precursor. For instance, the superior performance of lignin relative to cellulose is attributed to more efficient vibrational coupling at the CO_2 laser wavelength (Claro *et al.* 2022).

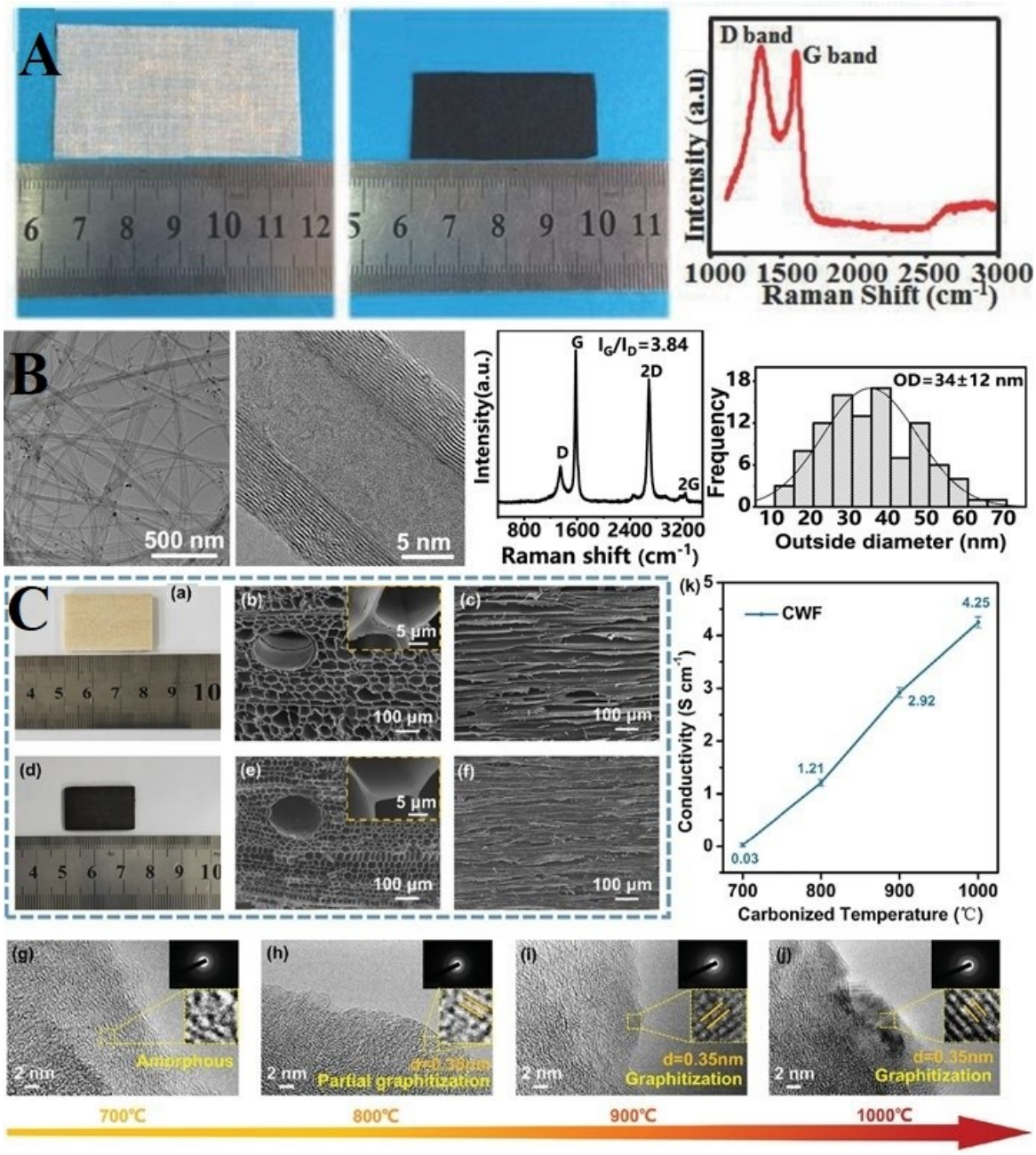

Fig. 4. Morphological diversity of biomass-derived conductive biocarbons. (A) Carbonized cotton fabrics retaining the woven textile structure (Reprinted with permission from Zhang *et al.* 2017, Wiley). (B) Structures of the lignin-derived carbon nanotube fiber (Liu *et al.* 2022). (C) Structural and conductive properties of carbonized wood frameworks (CWF) (Reprinted with permission from Ji *et al.* 2022, Wiley)

Table 1. Synthesis and Electrical Conductivity of Biocarbons from Woody Materials, Herbaceous Plants, and Synthetic Biomass-based Aerogels

Biomass type	Raw biomass	Biocarbon synthesis	Substrates	Conductivity	Application	Ref
Woody materials	Balsa wood	Delignification, freeze-drying, carbonization at 1000°C	PDMS	5.62 S cm^{-1}	Strain sensor	(Ji *et al*. 2022)
	Balsa wood	Delignification, freeze-drying, carbonization	Self-standing	High	Human-motion detection	(Chen *et al*. 2018)
Herbaceous plants	Loofah	Carbonization at 750°C	Ecoflex	High	Strain sensor + TENG	(Tang *et al*. 2023)
	Banana peel	Hydrothermal with urea, KOH activation, carbonization at 900°C	TPU	High	Tensile strain sensing	(Lu *et al*. 2024)
	Peanut waste	Stabilization at 230°C, carbonization at 900°C	SEBS	1.17×10^{-7} S cm^{-1}	Tunable piezoresistive	(Cetin *et al*. 2023)
	Wheat bran	Hydrothermal carbonization (180°C), KOH activation, carbonization (800°C)	PDMS	9.71 MΩ sq^{-1}	Strain sensor	(Ren *et al*. 2017)
Synthetic biomass-based aerogels	BC/CNF	Carbonization, directional freeze-drying	Paper/Regenerated cellulose tape	High	Pressure sensor	(Chen *et al*. 2021)
	CNF	Freezing-induced assembly, freeze-drying, carbonization at 900°C	Self-standing	0.32 S cm^{-1}	Human-motion detection	(Chen *et al*. 2020b)
	Tissue Paper	High-temperature pyrolysis at 800°C	PDMS	12.4 S m^{-1}	Strain sensor	(Li *et al*. 2016)

Ultimately, the macroscopic hierarchy of the precursor dictates the efficiency of the percolation network in the final sensor (Fig. 4). In naturally aligned precursors such as delignified wood, the pre-existing anisotropic channels template the growth of oriented graphitic domains (Chen *et al.* 2020b). This facilitates efficient electron transport along the fiber axis. Preserving the lamellar architecture of wood in biocarbon yields a conductivity of 562 S m^{-1}, which evidently outperforms isotropic structures derived from disordered biomass (Ji *et al.* 2022). In contrast, randomly oriented precursors such as tissue paper and cotton fabric lack this structural template. This results in fragmented, turbostratic carbon islands where transport relies on inefficient electron hopping across amorphous defects. A modest conductivity of 11 S m^{-1} for carbonized cotton due to the tunneling barriers was reported (Li *et al.* 2015).

Addressing the trade-off between conductivity and mechanical compliance is a critical engineering challenge. Achieving high conductivity typically requires carbonization temperatures exceeding 800 °C to maximize graphitization (Tripathi *et al.* 2022). However, this process inherently compromises mechanical compliance due to volumetric shrinkage and embrittlement. To mitigate this, recent strategies favor low-temperature reduction or hybridization. A hot-press reduction at a mild 180 °C was used to restore the conjugated network of graphene oxide on cotton (Ren *et al.* 2017b). This approach achieved a sheet resistance of 0.9 kΩ/sq without degrading the textile's flexibility. Similarly, it was demonstrated that the percolation network is enhanced when insulating gaps in low-temperature lignin carbon are bridged with multi-walled carbon nanotubes (Wang *et al.* 2023). High sensitivity is effectively balanced with the structural integrity required for robust flexible electronics by this hybrid architecture.

CONDUCTIVE BIOCARBON NANOCOMPOSITES: ENGINEERING AN ELECTRON TRANSPORT NETWORK WITH DEFORMATION

The efficacy of flexible strain sensors is fundamentally dictated by the electromechanical architecture of the conductive filler under deformation. While synthetic carbon nanotubes and graphene offer near-ideal electrical performance, biocarbon presents a unique multiscale architecture ranging from fibrous networks to porous aerogels. The primary engineering challenge in these composites lies in addressing the modulus mismatch between rigid carbonaceous fillers and viscoelastic polymer matrices. In conventional particle-dispersed systems such as biocarbon in PDMS, the electron transport network relies on quantum tunneling between proximal conductive islands. Upon tensile deformation, the Poisson effect compresses the matrix transversely while expanding inter-particle distances longitudinally. If the interface is weak, this triggers irreversible disconnection of the percolation network, which leads to signal hysteresis and limited working ranges (Ren *et al.* 2017b). However, biocarbon possesses a distinct interfacial advantage over synthetic counterparts. Residual oxygenated moieties on the pyrolyzed surface act as anchoring sites for hydrogen bonding or covalent coupling with polar matrices such as thermoplastic polyurethane. This chemical interlocking promotes effective stress transfer to force rigid carbon domains to rotate and align rather than detach. Consequently, this mechanism maintains the tunneling pathways required for conductivity under high strain (Wang *et al.* 2023).

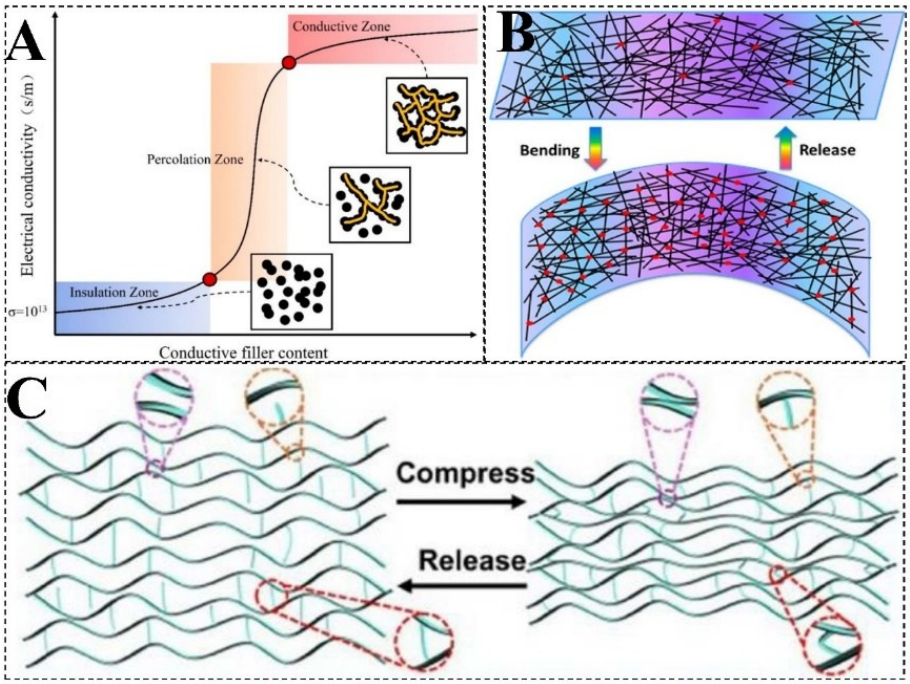

Fig. 5. Schematic illustration of representative strain sensing mechanisms in biomass-derived carbon composites. (A) Percolation model for conductivity of composites (Zhang *et al*. 2024c). (B) Schematic representation showing the internal network changes of the carbon paper/PDMS composite before and during applied strain. The carbon fibers are illustrated as black lines, and red points highlight breaks or gaps that form in the conductive pathways (Reprinted with permission from Li *et al*. 2016, American Chemical Society). (C) Compression mechanism of biocarbon aerogel (Reprinted with permission from Jiang *et al*. 2026, Wiley).

Figure 5 schematically illustrates the piezoresistive sensing mechanisms of three representative biomass-derived carbon strain sensors. Figure 5A depicts percolation behavior, in which electrical conductivity rises sharply at the percolation threshold as isolated fillers (black spheres in the insulation zone) form interconnected networks (yellow branched structures in the conductive zone) (Zhang *et al*. 2024c). Figure 5B shows the tissue-paper-derived CP/PDMS composite, where bending disrupts the carbon-fiber network (red contacts break) while release restores conductive paths (Li *et al*. 2016). Figure 5C illustrates the biocarbon aerogel, with compression closing interlayer gaps and elastic release fully recovering the original spacing and conductivity. Unlike conventional dispersed particulate fillers that suffer rapid electrical disconnection due to strain-induced inter-particle separation, continuous 3D biocarbon frameworks accommodate macroscopic strain through localized deformation (Jiang *et al*. 2026). This geometric reconfiguration effectively delocalizes stress and topologically preserves the conductive pathways, thereby preventing catastrophic network fracture. These tailored architectures enable reversible conductive-path modulation essential for high-sensitivity strain detection.

To overcome the percolation threshold limitations of particulate composites, recent architectures have shifted toward continuous 3D biocarbon frameworks encapsulated within elastomers. This encapsulation is typically achieved *via* vacuum-assisted impregnation or dip-coating methods, which drive the liquid prepolymer into the porous scaffold to eliminate trapped air before curing (Chen *et al*. 2019). Beyond traditional polyurethane (PU) and polydimethylsiloxane (PDMS), advanced elastomers such as natural rubber, Ecoflex (Tang *et al*. 2022), and styrene-ethylene-butylene-styrene (SEBS)

(Turgut *et al*. 2018) have proven highly suitable for biocarbon sensors due to their exceptional fatigue resistance and tunable viscoelasticity. In these systems, stretchability is governed by the macroscopic geometric deformation of the conductive scaffold rather than intrinsic lattice elongation. For instance, the "vein-like" cellulose nanofiber aerogel dissipates strain energy through reversible bending of hierarchical structures (Jiang *et al.* 2026). When backfilled with an elastomer, this interconnected architecture delocalizes stress to prevent catastrophic crack propagation. Specifically, the "vein-like structure" refers to a biomimetic interconnected fibrous network analogous to natural leaf veins, where branching carbon fibers form continuous pathways within the layered framework (Jiang *et al*. 2026). This architecture facilitates efficient stress distribution and helps maintain conductive pathways during deformation, thereby enhancing the mechanical stability and sensing reliability of the material. Consequently, the electron transport network survives strains exceeding 50% because conductive pathways are topologically preserved through geometric reconfiguration. This contrasts with brittle carbonized films, where conductivity relies on random contact between fractured islands. While that mechanism yields high sensitivity, it often compromises cyclic durability (Ji *et al.* 2022; Tang *et al.* 2022). Thus, the superior stretchability of biocarbon nanocomposites is achieved when the structural design converts tensile stress into bending moments within a pre-percolated and mechanically robust network.

To further overcome the intrinsic conductivity limits of biocarbon, hybrid composites offer a synergistic pathway. Decorating biocarbon scaffolds with MXenes or silver nanowires creates robust heterostructures. In these systems, the biocarbon acts as a high-surface-area skeleton to prevent MXene re-stacking while high-conductivity metallic fillers bridge the tunneling gaps between biocarbon domains (Wu *et al.* 2023a,b). This strategy effectively lowers the percolation threshold and boosts the gauge factor to address the trade-off between sensitivity and range. To address the critical challenges of filler leaching and bonding instability in heterogeneous composites, advanced interfacial engineering strategies, such as bio-inspired polydopamine (PDA) coatings, are employed to robustly anchor secondary metallic fillers *via* strong covalent and non-covalent bonds (Wang *et al*. 2026; Zhou *et al*. 2026). Concurrently, electrostatic bridging is widely utilized to firmly tether negatively charged MXene nanosheets to the biocarbon framework, effectively suppressing their intrinsic restacking and ensuring uniform, long-term spatial dispersion (Luo *et al*. 2024).

APPLICATIONS OF BIOCARBON FOR FLEXIBLE STRAIN SENSORS

The growing emphasis on sustainable precursors in flexible electronics has positioned conductive biocarbon nanocomposites as a robust alternative to conventional conductive fillers (Amoah and Skene 2025; Jin *et al.* 2025; Liu *et al.* 2024a; Siyu *et al.* 2020; Wang *et al.* 2021a; Wu *et al.* 2023a,b; Wang *et al.* 2025; Zhu *et al.* 2025). Current literature indicates an evolution from preliminary carbonization studies to the precise engineering of structure-property relationships. By exploiting the intrinsic hierarchical structures, recent biocarbon strain sensors demonstrate sensitivities and dynamic ranges comparable to, or exceeding, those of traditional strain sensors.

Recently developed biocarbon strain sensors have achieved sensitivities and dynamic stretchability that decisively outperform the rigid electromechanical limitations of traditional metallic strain gauges (Amjadi *et al*. 2016; Tang *et al*. 2022; Wang *et al*. 2016;

Zhang *et al*. 2017). Furthermore, biocarbon provides a distinct interfacial advantage over chemically inert synthetic carbon fillers, such as pristine carbon nanotubes or graphene, which frequently require complex, costly functionalization to prevent agglomeration (Giorcelli *et al*. 2019; Idrees *et al*. 2018). The native retention of functional groups on biocarbon surfaces facilitates robust interfacial interlocking with elastomeric matrices, thereby maximizing stress transfer and minimizing signal hysteresis during dynamic cyclic loading (Wang *et al*. 2021b; Wu *et al*. 2023). The utility of these materials is not defined merely by their conductivity, but also by their interaction with the elastomeric matrix under deformation. A critical analysis reveals that biocarbon strain sensor performance is dictated by the specific architecture, percolated conductive networks, and biocarbon-polymer interfacial mechanics (Jin *et al.* 2025; Wu *et al.* 2023a,b). This section evaluates biocarbon applications in piezoresistive sensing.

Fundamental Sensing Mechanisms

The electromechanical behavior of biocarbon strain sensors arises from different fundamental mechanisms, which collectively dictate sensitivity and sensing range. These include tunneling effects within percolated networks, crack propagation, and geometrical deformation. Notably, there is no strict one-to-one correlation between a specific biocarbon and a single sensing mechanism. Instead, multiple mechanisms often overlap. However, the dominant sensing mode is heavily dictated by the sensor's engineered hierarchical architecture. For natural woody and herbaceous plant-derived biocarbons, the retention of highly oriented, rigid longitudinal micro-channels frequently leads to a contact-dominated mechanism driven by micro-crack propagation (Ji *et al*. 2022). Under applied strain, the reversible separation and overlapping of these stiff, fractured graphitic edges yield high sensitivities, though this often results in narrower linear sensing ranges and a higher susceptibility to fatigue. In contrast, artificial synthetic biomass aerogels and natural 3D reticular networks predominantly rely on macroscopic geometric reconfigurations. These highly interconnected architectures, such as biomimetic networks, accommodate massive mechanical strain through the reversible bending, twisting, and stretching of continuous carbon structures. This structural response effectively delocalizes stress and topologically preserves the primary conductive pathways without relying on brittle fracture, thereby providing exceptionally wide sensing ranges and vastly superior cyclic durability (Tang *et al*. 2022; Jiang *et al*. 2026).

A critical distinction must be drawn between tunneling-dominated and contact-dominated responses. In composites utilizing dispersed biocarbon fillers such as nanospheres or nanodots, resistance changes are largely driven by the quantum tunneling of electrons between adjacent conductive islands (Yi *et al.* 2025). According to Simmons' theory, tunneling resistance depends exponentially on inter-particle distance. This relationship yields high gauge factors but often results in non-linear responses at large strains. The macroscopic sensitivity of biocarbon composites is governed by classical percolation theory. The conductive filler forms a multitude of parallel and series circuits within the insulating matrix. The electrical conductivity near the percolation threshold can be modeled mathematically by a scaling law,

$$\sigma \sim (\varphi - \varphi_c)^t \quad (1)$$

where φ is the volume fraction of the filler, φ_c is the critical percolation threshold, and t is the critical exponent reflecting the dimensionality of the network. Under applied tensile strain, the geometric expansion of the matrix forces adjacent carbon domains apart. This

mechanical deformation systematically ruptures localized contact points, thereby decreasing the total number of complete parallel circuits.

Critically, high-aspect-ratio fillers such as carbonized fibers have demonstrated superiority over spherical counterparts for broad-range sensing. This advantage arises because fibers maintain percolation networks more effectively under deformation (Liu *et al.* 2024b; Yi *et al.* 2025). Conversely, ultra-high sensitivity at low strains is achieved through controlled micro-crack propagation in 2D films. However, the unpredictable initiation of cracks often introduces evident hysteresis and signal noise, which limits reversibility (Chen *et al.* 2021). Recent strategies to bridge these cracks with flexible nanowires or viscoelastic substrates have improved durability, though this often occurs at the expense of sensitivity. Monolithic 3D aerogels rely on the macroscopic deformation of their 3D conductive framework. Because biocarbon materials, such as interconnected aerogels derived from wood or synthetic aerogel, possess pre-existing 3D continuous frameworks rather than randomly dispersed particles, they provide a highly deterministic template for how these circuits interrupt and reform. The structural integrity of these specific biocarbon networks ensures that while individual local circuits can periodically disconnect, in response to strain, to provide high sensitivity, the global network avoids catastrophic failure, allowing the circuits to reliably reconnect upon strain release (Tang *et al.* 2022).

The optimization of biocarbon strain sensors is fundamentally constrained by the inverse relationship between sensitivity and strain range. While crack-based architectures achieve high gauge factors, they typically suffer from rapid signal saturation at strains below 10%. Conversely, percolation-based composites maintain electrical continuity over large deformations (>100%) but exhibit limited sensitivity (Cetin *et al.* 2023). Addressing this trade-off requires structural engineering. For instance, anisotropic aerogels with hierarchical porosity effectively buffer stress concentrations to delay network failure and extend the linear response regime (Lai *et al.* 2021). Beyond static performance, signal reliability is often compromised by hysteresis. This phenomenon represents the discrepancy between loading and unloading pathways driven by the viscoelastic lag of the polymer matrix and interfacial slippage. In this context, biocarbon offers a distinct physicochemical advantage over synthetic counterparts. Unlike the chemically inert surfaces of carbon nanotubes or graphene, biomass-derived carbon retains residual functionalities. These moieties facilitate robust interfacial interlocking with elastomers such as TPU or PDMS. Consequently, this interaction evidently reduces slippage and minimizes signal hysteresis (Jain *et al.* 2023; Lu *et al.* 2024).

Despite the advantage achieved by biocarbon strain sensors, a persistent challenge in their long-term deployment is the gradual drift in electrical response during repeated cyclic usage. This drift is primarily driven by the viscoelastic creep of the elastomeric matrix and the incomplete reconstruction or irreversible sliding of the biocarbon conductive network over thousands of deformation cycles. Currently, the standard laboratory approach to mitigate this instability is mechanical pre-stretching, which forces the network into a temporary equilibrium state before use. However, for continuous, long-term practical applications, this static approach is insufficient. To maintain suitable accuracy over time, future research must focus on dynamic, on-the-fly recalibration methodologies. By pairing biocarbon sensors with machine learning algorithms, or by integrating continuous feedback loops from undeformed reference circuits, devices could autonomously adjust their baseline resistance and gauge factor in real-time. Transitioning from passive sensing materials to these smart, self-calibrating systems represents a critical

evolutionary step required to move biocarbon wearable electronics from laboratory prototypes to reliable, commercial applications.

Emerging Applications

Recent literature shows that the sensor's mechanical structure imposes two distinct functional modes. Large-scale motion monitoring demands high stretchability and linearity. Conversely, clinical diagnostics require low detection limits and high sensitivity at minute strains (Fig. 6). The following sections critically evaluate these domains alongside emerging implementations in human-machine interfaces (HMI).

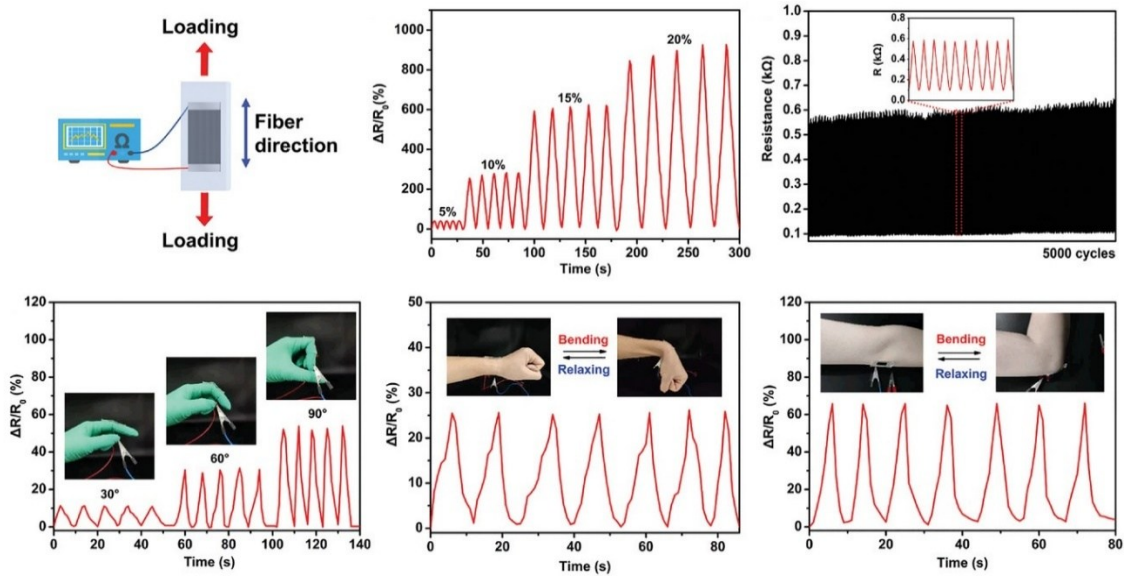

Fig. 6. Application of biocarbon flexible strain sensors in human motion monitoring. Monitoring of movements using wood-derived carbon framework strain sensors (Reprinted with permission from Ji *et al.* 2022, Wiley).

Human motion monitoring

The monitoring of vigorous human activities requires biocarbon sensors capable of withstanding strains exceeding 50% while maintaining signal fidelity. Carbonized fabrics and natural fiber networks have emerged as dominant architectures for this purpose due to their hierarchical woven structures. Sensors based on carbonized cotton fabrics utilize the reversible disconnections and reconnections among small conductive structures within carbonized yarns to monitor large-scale joint movements such as knee bending and marching (Ding *et al.* 2024; Zhang *et al.* 2017). This transient disconnection and connection-based mechanism yields high gauge factors (GF of 64 at 80 to 140% strain) but often introduces signal noise due to the brittle nature of carbonized fibers. Similar micro-crack propagation mechanisms in carbonized silk fabrics enable the detection of complex movements such as running and jumping (Wang *et al.* 2016). To mitigate structural instability, elastomeric encapsulation is frequently employed. The natural 3D reticular structure of *Juncus effusus* fibers encapsulated in Ecoflex was utilized to achieve a stretchability of 600% and a GF of 76 (Tang *et al.* 2022). The sensitivity arises from the geometric deformation and subsequent crack propagation within the 3D network during stretching. This mechanism offers superior durability compared to brittle carbonized films.

Aerogel-based composites address the trade-off between elasticity and sensitivity through pore structure engineering. The "vein-like" network using polyimide/cellulose nanofibers withstands 20,000 compression cycles at 50% strain while maintaining 96.7% stress retention (Jiang *et al.* 2026). This structural reinforcement prevents the irreversible collapse often seen in pure carbon aerogels and renders them suitable for long-term monitoring. Similarly, electrostatic interactions between lignin carbon nanospheres and softwood pulp fibers create a stable conductive network capable of enduring 5000 cycles with a response time of 0.3 s (Yi *et al.* 2025). These findings indicate that preserving the integrity of the conductive network through hierarchical reinforcements is critical for reliable large-strain monitoring. Recent work further supports this by utilizing a delignified wood-derived carbon framework where the preserved lamellar channels facilitate electron transport under tensile stress (Ji *et al.* 2022).

Particle-based composites rely on tunneling effects between dispersed biocarbon fillers. A sensor using wheat bran-derived carbonaceous materials encapsulated in PDMS showed high linearity due to the uniform dispersion of carbon particles (Ren *et al.* 2017a). Walnut shell powder was employed to achieve stable responses at strains of up to 40% (Siyu *et al.* 2020). To overcome the percolation threshold limitations of particulate fillers, multi-walled carbon nanotubes were combined with lignin-based carbon nanofibers (Wang *et al.* 2023). Gaps between nanotubes were bridged by the high aspect ratio of the nanofibers, extending the sensing range to 125% with a GF of 114.7. Furthermore, it was demonstrated that a GF of 25.3 could be achieved even with simple tissue paper-derived carbon embedded in PDMS (Li *et al.* 2016). These studies collectively suggest that controlling filler geometry and dispersion is essential for optimizing the percolation network in composite sensors.

Clinical and healthcare diagnostics

In the regime of subtle strain detection, the primary design constraint shifts from stretchability to low detection limits and rapid response times. Carbonized biomass aerogels with layered microstructures have proven particularly effective here. A high sensitivity of 10.1 kPa^{-1} was achieved by utilizing a wave-layered carbon aerogel derived from glucose and cellulose nanofibers (Long *et al.* 2021). The wave-shaped layers maximize the variation in contact area under minute pressures to allow for the clear resolution of the percussion and diastolic waves in human pulse signals. This contact-dominated mechanism was further refined in the work of (Lv *et al.* 2025), where a bamboo cellulose-based aerogel with a directional honeycomb structure detected ultra-low pressures of 10 Pa with a response time of 66 ms. Anisotropic carbon aerogels derived from cellulose nanofibers were similarly utilized (Lai *et al.* 2021; Lv *et al.* 2025) to demonstrate effective stress transfer for precise pressure sensing.

To detect high-frequency physiological signals, minimizing the viscoelastic lag of the sensor material is required. Distinct resistance patterns derived from throat vibrations were utilized to distinguish phonation words using reduced graphene oxide-dyed cotton fabrics (Ren *et al.* 2017a). Lignin-derived porous graphene was employed to achieve a high GF of 149, which allowed for the accurate identification of throat vibrations during swallowing and coughing (Yang *et al.* 2022). Furthermore, a pressure sensor was produced from carbonized cotton with a sensitivity of 6.04 kPa^{-1}, which successfully monitored respiration rates by detecting airflow pressure changes (Li *et al.* 2015). Similarly, PANI/bacterial cellulose/chitosan aerogels capable of detecting 32 Pa pressure were synthesized for respiratory monitoring (Huang *et al.* 2019).

Pressure mapping for gait analysis represents another critical diagnostic application. A fully biomass-based pressure sensor using loofah and bacterial cellulose was developed (Gu *et al.* 2025), in which the hierarchical pore structure enabled the distinction between walking, running, and jumping based on plantar pressure distribution. Adjustable sensitivity was achieved in carbonized bacterial nanocellulose/wood-derived cellulose aerogels (Chen *et al.* 2021). This tunability allows for specific customization depending on whether the target is high-pressure gait analysis or low-pressure tactile sensing. It is underscored by these studies that stiff carbonized frameworks with minimal polymeric damping offer superior performance for diagnostic applications compared to viscoelastic elastomer-heavy composites (Jiang and Guo 2025).

Human-machine interfaces (HMI) and soft robotics

Biocarbon sensors are increasingly integrated into active HMI systems and soft robotics, where they function as control inputs or feedback loops. The versatility of biocarbons allows for the integration of multiple functions into a single device. A banana peel-derived carbon sensor was integrated with a memristor to create a strain-memory device (Lu *et al.* 2024). This system retains strain information after the removal of external stimuli to mimic the sensory memory of human skin and offer a pathway for neuromorphic computing in soft robotics.

Communication applications rely on the distinct resistance changes of biocarbon sensors to encode complex information. Biomass-based *Chlorella* hydrogels were developed with ionic conductivity that exhibited excellent self-healing properties and were used to control a robotic hand via gesture recognition (Zhang *et al.* 2025). Environmental adaptability is another frontier for robotic interfaces. Li *et al.* (2026) engineered a biomass-derived carbon aerogel/PDMS composite that maintains a stable piezoresistive response across a temperature range of -30 to 100 °C. This thermal stability is crucial for outdoor robotic applications. A hydrophobic carbonized cotton/rGO foam was fabricated that functioned simultaneously as a high-performance oil-water separator and a pressure sensor (Gu *et al.* 2020). Such duality is vital for autonomous environmental monitoring robots.

Energy harvesting addresses the power constraints of wearable HMIs. Carbonized loofah was utilized not only as a piezoresistive sensor but also as the electrode for a triboelectric nanogenerator (TENG) (Tang *et al.* 2023). This device achieved an open-circuit voltage of 19.3 V to drive wearable electronics. Similarly, it was demonstrated that nitrogen-doped carbon aerogels could function simultaneously as pressure sensors and supercapacitor electrodes with a specific capacitance of 220.2 F g^{-1} (Long *et al.* 2021). These multifunctional architectures represent a critical evolution from passive sensing elements to autonomous and intelligent biocarbon systems.

CONCLUSIONS

1. The transition from conventional metal- and conductive polymer-based electronics to sustainable biocarbon systems marks a critical evolution in materials science. Biocarbon-based strain sensors have received great attention due to their exceptional balance of high sensitivity, broad sensing ranges, and mechanical robustness. This review has critically assessed recent breakthroughs in biocarbon nanocomposites, establishing them as a transformative foundation for the next generation of eco-friendly, flexible strain-sensing technologies.

2. Diverse biocarbon composite architectures were evaluated, demonstrating that biocarbon's unique physicochemical properties enhance multifunctionality even at low filler loadings. Achieving high-performance sensors relies on the synergistic optimization of carbonization-induced microstructures, percolated conductive networks, and biocarbon-polymer interfacial mechanics. This design framework is essential for balancing high electrical sensitivity with the mechanical compliance and durability required for sustainable wearable electronics.
3. Biocarbon's rich surface chemistry facilitates uniform dispersion, creating robust networks that empower applications ranging from motion tracking and electronic skins to soft robotics. However, future research must prioritize precise analytical modeling of biocarbon-polymer interactions, the development of intricate sensor geometries, and wireless system integration. Addressing the scalability of these architectures remains the final frontier. Collectively, these advancements define a clear roadmap for engineering sustainable, high-performance flexible electronics.
4. Biocarbon sensor transduction relies on quantum tunneling and micro-crack propagation for low-strain sensitivity. It also relies on dynamic percolation *via* geometric reconfiguration for large-deformation stability. To mitigate inevitable long-term baseline drift, future research must pair these robust physical architectures with data-driven predictive algorithms for dynamic recalibration, ensuring the ultimate accuracy and reliability required for continuous monitoring applications.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of Generative AI

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