PERSPECTIVE

Cellulose Beyond Substrates: Emerging Functional Roles in Sustainable Advanced Electronics

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Abstract

Cellulose, the most abundant natural polymer, is emerging as a versatile biomaterial platform for sustainable advanced electronics beyond its conventional role as a passive substrate. Its hierarchical fibrillar architecture and hydroxyl-rich chemistry enable unique combinations of mechanical compliance, interfacial reactivity, ionic transport, and optical transparency. This perspective highlights cellulose as a multifunctional system spanning structural and interfacial integration, ionic-electrochemical behavior, and optoelectronic interfaces, which together underpin its growing relevance in flexible, energy, and transparent electronic technologies. However, intrinsic coupling between hydration sensitivity, conductivity limitations, and structural stability defines key design trade-offs that must be addressed for practical implementation. Future progress will rely on transforming these inherent characteristics into tunable design parameters through hierarchical structuring and sustainable hybridization strategies, enabling cellulose-based architectures for next-generation environmentally adaptive electronics.

Keywords: cellulose, bioelectronics, energy storage, electrospinning, sustainable electronics, wearable technologies.

1 Introduction

Cellulose is the most abundant natural polymer on Earth, widely distributed in plants, wood, certain algae, and bacterial systems, where it serves as a primary structural component [1]. It is a linear polysaccharide consisting of repeating $\beta(1\rightarrow4)$-linked D-glucose monomers, forming chains that typically extend

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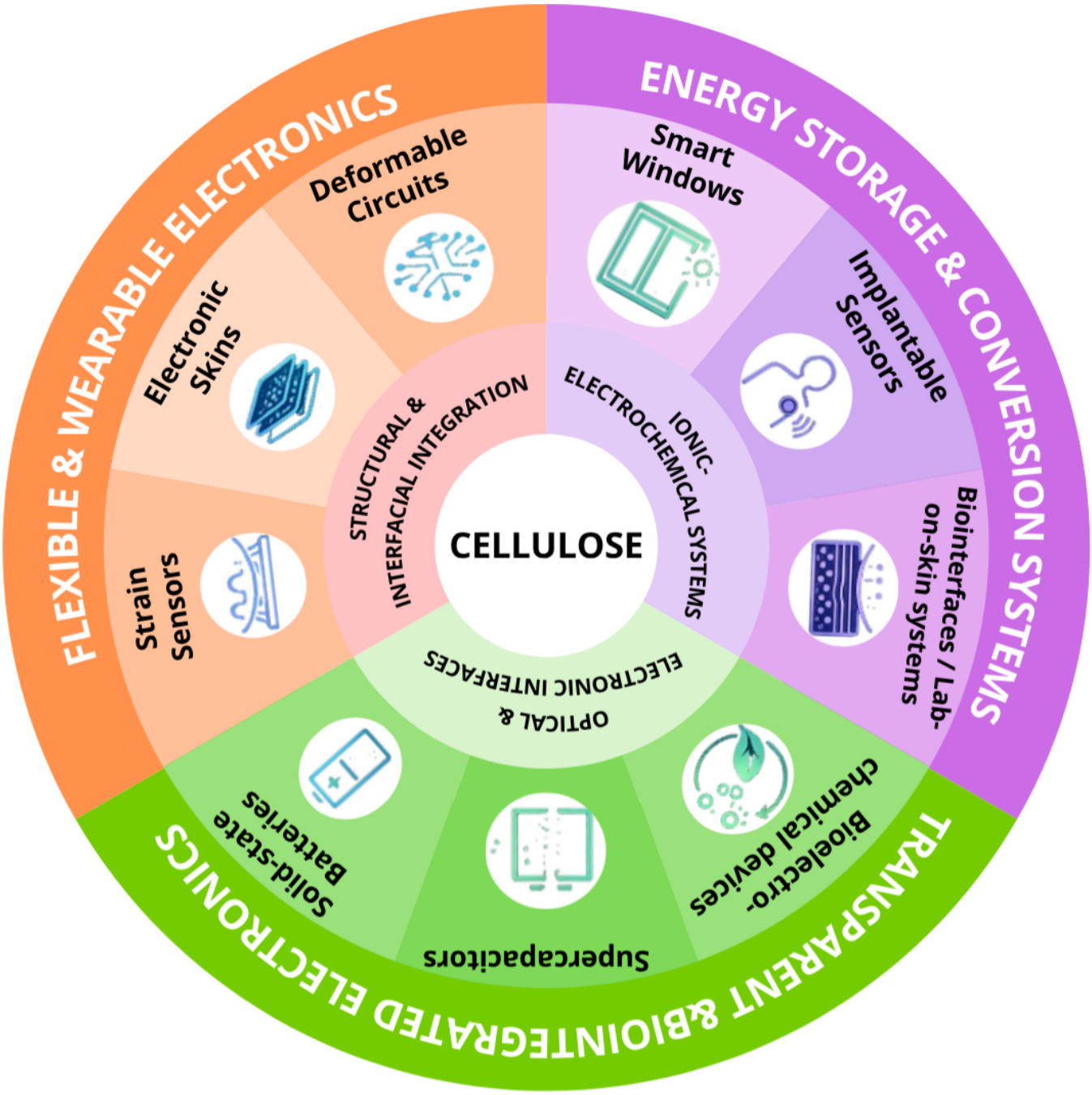

Figure 1. Cellulose as a hierarchically integrated materials platform for emerging sustainable electronics.

from hundreds to several thousand units. These molecular chains assemble through extensive intra- and intermolecular hydrogen bonding into elementary fibrils, which further organize into nanofibrils and hierarchical fibre networks [3], giving rise to a distinct nanocellulose family—comprising microfibrillated cellulose, nanocrystalline cellulose, and bacterially biosynthesized nanocellulose—each isolated through different top-down or biofabrication routes and valued for combining nanoscale dimensions with high specific surface area [2]. In natural systems, cellulose is closely associated with hemicellulose and lignin within composite cell wall architectures, contributing to its mechanical robustness and structural stability [4].

Beyond its biological role, this hierarchical and chemically functional architecture has positioned cellulose as a versatile platform material for advanced technologies. The combination of abundant hydroxyl groups, multiscale fibrillar organization, and tunable interfacial chemistry enables cellulose to interact with a wide range of functional materials while maintaining mechanical compliance and environmental

sustainability. In the context of emerging electronics, these characteristics have motivated its transition from a passive structural substrate to an active component within multifunctional systems.

This perspective article outlines cellulose as a hierarchically integrated materials platform for emerging sustainable electronics, as summarized in Figure 1. Specifically, cellulose is discussed in terms of three coupled domains: structural and interfacial integration, ionic-electrochemical systems, and optical and electronic interfaces, which together underpin its emerging role in flexible, energy, and transparent electronic technologies.

2 Functional Roles of Cellulose in Emerging Electronic Systems

2.1 Structural, Interfacial, and Mechanical Integration Platform

The multifunctionality of cellulose originates from its hierarchical molecular and fibrillar architecture, spanning molecular chains, nanofibrils, and mesoscale fibre networks. At the molecular level, cellulose consists of $\beta(1\rightarrow4)$-linked D-glucose units densely decorated with hydroxyl groups, enabling extensive hydrogen bonding that governs crystallinity, cohesion, and interfacial reactivity [5].

This chemically rich surface makes cellulose a highly adaptable interfacial scaffold for hybrid electronic systems. Hydroxyl-mediated interactions facilitate robust adhesion and assembly of conductive nanomaterials (e.g. carbon nanostructures, metallic nanowires and conducting polymers) without requiring aggressive surface activation. At the nanoscale, TEMPO-mediated surface oxidation can individualize cellulose into nanofibrils with aspect ratios exceeding 100 and selectively introduced surface carboxylate groups; the resulting electrostatic stabilization promotes uniform dispersion and large specific interfacial area, providing scaffolds capable of efficient stress transfer and stable composite formation [6].

Mechanically, this hierarchical architecture confers a combination of low density, flexibility, and toughness. Engineered formats such as nanopaper, flexible cellulose films, and fibre mats maintain structural integrity under repeated bending, folding, and cyclic deformation [7]. Importantly, the fibrous network enables strain redistribution across multiple length scales, mitigating local stress concentration and suppressing mechanical failure in functional coatings and embedded conductive networks.

These two characteristics combined establish cellulose as a structural-functional integration platform in which interfacial compatibility and mechanical compliance are inherently co-designed. This dual functionality underpins its suitability for flexible and wearable electronic systems requiring stable hybrid interfaces under mechanical deformation.

2.2 Ionic-Electrochemical Systems Capability

Although intrinsically electrically insulating, cellulose exhibits strong electrochemical relevance through its dielectric polarization behavior and ion-transport characteristics [8]. The hydroxyl-rich backbone generates strong dipolar responses under an electric field, contributing to interfacial and bulk dielectric polarization in hydrated or functionalized environments. These features promote its use in ionically dominated electronic systems, including separators, gel electrolytes, and solid-liquid hybrid electrolyte matrices in energy-storage devices. Within such systems, cellulose provides both structural confinement and ion-conduction pathways, enabling coupled mechanical-ionic responses essential for soft electrochemical devices.

Beyond energy storage, cellulose-based ionic conduction has enabled emerging ionotronic and bio-integrated devices, where ionic motion is directly coupled to mechanical deformation or interfacial potential modulation. In these systems, cellulose functions simultaneously as electrolyte host, mechanical scaffold, and ion-regulating matrix.

2.3 Optical Transparency and Printable Functional Surfaces

Nanostructured cellulose films, particularly those derived from nanofibrillated or nanocrystalline cellulose, can exhibit high optical transparency and low surface roughness due to feature sizes well below the wavelength of visible light [9]. This minimizes scattering and enables mechanically flexible, optically clear substrates suitable for transparent electronics. In addition to optical properties, cellulose provides a chemically active and mechanically conformal surface for additive and subtractive patterning of functional materials. Its hydroxyl-rich surface promotes strong adhesion and uniform spreading of conductive inks and coatings, while its porosity facilitates infiltration and anchoring of nanomaterials.

Compatibility with scalable manufacturing

approaches, e.g. inkjet printing, screen printing, spray deposition, and roll-to-roll coating, enables spatially defined integration of conductive and semiconductive components. This positions cellulose as a viable platform for large-area, low-cost transparent electronics, including optically transparent sensors, smart windows, and distributed sensing layers.

3 Design Challenges and Future Opportunities

3.1 Interfacial Responsiveness and Environmental Stability

A fundamental challenge in cellulose-based electronic systems arises from the intrinsic hydroxyl-rich chemistry of cellulose, which enables strong interfacial interactions but also presents pronounced sensitivity to water uptake and hydration. While this hydration responsiveness supports wettability, ion transport, and bio-integration through hydrogen-bond-mediated network reconfiguration, it simultaneously induces coupled structural and functional instabilities, including swelling, dimensional drift, dielectric fluctuation, and time-dependent electrical variability [10].

In flexible and wearable systems, such environmental sensitivity can destabilize conductive percolation networks and degrade sensing reliability. Rather than eliminating moisture interactions, future design strategies are likely to focus on controlling interfacial water dynamics through selective surface modification, crosslinking, multilayer encapsulation, and hybrid ionic-electronic architectures.

This shift reframes cellulose not as a moisture-stable inert substrate, but as a chemically adaptive interface whose environmental response can be engineered as a functional parameter.

3.2 Functional Hybridization and Sustainable Electronic Performance

Another limitation of cellulose-based electronics lies in the disconnect between intrinsic insulation and required electronic conductivity [11]. To address this, most systems rely on conductive fillers such as graphene, carbon nanotubes, MXenes, metallic nanowires, or conducting polymers. While effective, this hybridization introduces a key sustainability trade-off: high-performance conductivity is often achieved at the cost of increased reliance on non-biodegradable or resource-intensive additives. This partially offsets the environmental advantage of cellulose-based systems.

Future development is therefore shifting from maximizing conductivity toward optimizing structural efficiency of conductive networks. The thermal conversion method (pyrolysis) represents one route to intrinsic conductivity but introduces critical trade-offs: it destroys optical transparency, alters biodegradation pathways, and disrupts the hierarchical fibrillar architecture and mechanical flexibility that define cellulose's functional advantages. Consequently, pyrolysis is incompatible with applications that require optical clarity, rapid biodegradability, or preservation of the complete fibrillar hierarchy; in such cases, low-additive hybridization or network-engineering strategies are more appropriate. Specifically, hierarchical porosity control, anisotropic fibre alignment, and interface-dominated percolation design offer viable routes to reduce conductive filler loading while maintaining the electrical percolation threshold, thereby reconciling conductivity requirements with the sustainability and structural integrity of the cellulose platform.

A complementary strategy is cellulose-derived carbonization, where controlled pyrolysis transforms cellulose into conductive, hierarchically porous carbon frameworks. This preserves structural morphology while introducing intrinsic electronic conductivity, enabling applications in flexible supercapacitors, wearable batteries, and self-powered systems.

3.3 Architecturally Engineered Cellulose Systems for Device Integration

High-performance cellulose electronics increasingly rely on advanced structural engineering to reconcile competing requirements: flexibility, conductivity, ion accessibility, and mechanical robustness [12]. However, scalable fabrication of such architectures remains constrained by reproducibility, solvent processing, throughput, and structural durability.

Among emerging approaches, electrospun regenerated cellulose fibre systems represent a particularly promising route. Electrospinning enables the formation of interconnected fibrous networks with tunable fibre diameter, porosity, and alignment, providing a highly configurable platform for multifunctional electronic systems. These architectures support simultaneous integration of sensing, ionic conduction, thermal management, and electromagnetic shielding functionalities. Future directions are expected to focus on multi-level architectural programming, including aligned fibre

arrays, coaxial or core-shell structures, gradient porosity, and multifunctional surface coatings.

Such structurally engineered systems position cellulose not only as a material platform, but as a designable architecture for next-generation sustainable electronics.

4 Conclusion

Cellulose is emerging as a multifunctional materials platform that integrates mechanical adaptability, ionic activity, and optoelectronic compatibility within a single hierarchical framework. Its hydroxyl-rich and fibrillar architecture enables unique cross-scale coupling of structure and function, spanning interfacial assembly, ion transport, and transparent electronic integration. However, these same features introduce intrinsic trade-offs in hydration sensitivity, conductivity, and structural stability, defining a constrained but highly tunable design space for device integration. Future progress will depend on treating cellulose not as a passive substrate, but as an active, architecturally programmable material system, where performance is governed by hierarchical structure and sustainable hybridization rather than intrinsic composition alone.

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Conflicts of Interest

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AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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