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Bio-Nanocomposites for Sustainable Energy Technologies: Linking Green Synthesis, Interfacial Engineering and Device Performance

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Abstract

The transition toward sustainable energy technologies requires advanced materials that can simultaneously deliver high functional performance, resource efficiency, environmental compatibility, and scalable processing. Bio-nanocomposites, formed by integrating bio-based polymers, biomass-derived materials, or biologically sourced components with nanoscale functional materials, have emerged as promising platforms for addressing these requirements. Their tunable surface chemistry, hierarchical structures, renewable feedstock availability, and nanoscale interfaces provide opportunities for applications in electrochemical energy storage, energy conversion, and emerging flexible energy technologies. However, the use of a renewable precursor does not inherently ensure overall sustainability, while excellent material-level electrochemical performance does not necessarily translate into practical device-level performance. This review critically examines the relationships among green synthesis pathways, sophisticated interfacial engineering, and the resulting performance in diverse energy devices including solar cells, batteries, supercapacitors, and fuel cells. Key findings highlight that biopolymers such as cellulose, chitosan, and lignin, when derived from agricultural waste or biogenic sources, provide sustainable alternatives to petroleum-based polymers. Interfacial engineering strategies, such as the construction of 3D ion transport channels and the use of biomimetic membranes, significantly enhance charge and ion transport kinetics. These advancements have led to superior device metrics, including area energy densities exceeding 53.5 mWh cm^{-2} in flexible supercapacitors and over 89.21% conversion efficiency in biocatalytic energy processes. Despite these successes, challenges remain regarding the scalability of green extraction methods and the full mechanistic understanding of bio-synthetic interfaces. This report concludes that bio-nanocomposites represent a viable, eco-friendly pathway for achieving high-performance, circular energy solutions by establishing a direct relationship between green synthesis, interfacial chemistry, structure–property relationships, device performance, and sustainability.

Keywords: Bio-Nanocomposites, Sustainable Energy, Green Synthesis, Hydrogen Energy

1. Introduction

1.1 The Global Energy Transition and Material Sustainability

The global transition from fossil-fuel-dependent energy systems toward renewable and low-carbon technologies has created an increasing demand for advanced materials capable of supporting efficient energy conversion, storage, and utilization. Solar and wind energy have become important components of the emerging energy landscape, but their intermittent nature requires complementary technologies capable of storing or efficiently converting energy when and where it is needed (Zhang et al., 2017; Bairagi et al., 2025). Consequently, the development of high-performance batteries, supercapacitors, fuel cells, electrocatalytic systems, and other emerging energy technologies has become closely associated with advances in materials science and nanotechnology.

Conventional energy materials have achieved remarkable technological progress; however, their sustainability remains a significant concern. The extraction and processing of critical elements, energy-intensive material synthesis, use of hazardous chemicals, and difficulties associated with end-of-life management can contribute

substantially to the environmental footprint of advanced energy devices. These concerns have stimulated interest in renewable, waste-derived, and biologically sourced materials as alternatives or complementary components for next-generation energy technologies [1-2].

1.2 The Promise of Bio-Nanocomposites

In this context, bio-nanocomposites have emerged as a particularly interesting class of multifunctional materials. Broadly, they can be described as composites in which a bio-based matrix, biomass-derived carbonaceous phase, or biologically derived component is combined with nanoscale functional materials. Biopolymers such as cellulose, chitosan, starch, gelatin, alginate, and lignin can provide renewable carbon, mechanical flexibility, functional groups, and processability, while nanomaterials such as graphene, carbon nanotubes (CNTs), metal oxides, transition-metal compounds, and other two-dimensional materials can introduce electrical conductivity, catalytic activity, high surface area, and enhanced electrochemical functionality [3-5].

The importance of bio-nanocomposites extends beyond their renewable origin. At the nanoscale, interactions between the bio-derived component and the inorganic or carbonaceous nanophase can produce properties that are not achievable from either component independently. Nanostructuring can shorten ion-diffusion pathways, increase electrochemically accessible surface area, and create additional active sites. Meanwhile, functional groups originating from the biological component can influence surface wettability, ion adsorption, interfacial charge transfer, and chemical compatibility with electrolytes. Thus, the performance of a bio-nanocomposite is determined not simply by the identity of its constituents but by the architecture and chemistry of their interfaces [3,5]. Vivid engineering field how they are interrelated has been shown in Fig.1

1.3 Paradigm Shift in Biomass Valorization

Biomass-derived carbon represents another important development. Agricultural residues, forestry biomass, food-processing wastes, and other biological resources can be converted into porous carbonaceous materials through carbonization, pyrolysis, and activation. These materials can subsequently be combined with nanoscale metal oxides, sulfides, carbons, or other functional phases. A recent literature survey highlighted biochar nanocomposites for supercapacitors, lithium- and sodium-ion batteries, electrocatalysis, and photocatalysis, emphasizing the relationships among biomass feedstock, pyrolysis/activation conditions, and nanocomposite architecture [6-7].

However, the rapid expansion of this field has created an important conceptual problem. Renewable origin alone does not make a material sustainable. The environmental benefit of a biomass-derived or biopolymer-based material can be reduced by energy-intensive carbonization, chemical activation, toxic solvents, repeated purification, low material yield, or incorporation of difficult-to-recycle nanomaterials. Similarly, a material exhibiting a high specific capacitance or capacity under laboratory conditions may not provide comparable advantages when evaluated at practical electrode loading, in a full cell, or at commercially relevant current densities [8].

1.4 The Central Research Gap and the SSIPS Framework

The principal gap addressed in this review is the insufficient integration of four interconnected dimensions: (i) green synthesis and precursor selection, (ii) nanoscale architecture and interfacial chemistry, (iii) realistic device-level energy performance, and (iv)quantitative sustainability considerations. Existing literature frequently treats these parameters separately. Material synthesis may be discussed independently from electrochemical behavior; interfacial phenomena may be described without connecting them to practical device metrics; and sustainability may be inferred from the use of biomass without evaluating the complete synthesis and end-of-life pathway [4].

To address this gap, this review proposes a green synthesis–structure–interface–performance–sustainability (SSIPS) framework. The central premise is that sustainable energy materials should be evaluated using a

multidimensional relationship rather than a single electrochemical parameter: Sustainability + Structure + Interface + Performance + Practicality.

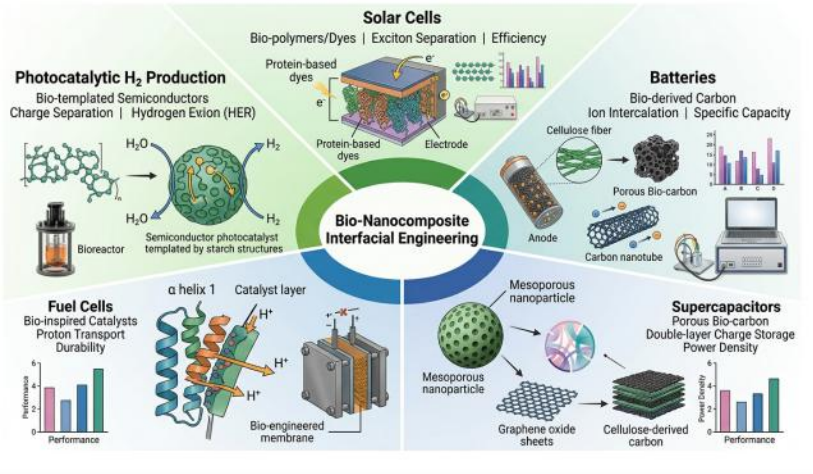


Figure 1. Representation of Bionanocomposites for interfacial Engineering

2. Classification, Components, and Design Principles

2.1 Concept and Definition of Hybrid Bio-Nanocomposites

Bio-nanocomposites represent a broad class of hybrid materials in which a biologically derived component is integrated with one or more nanoscale functional phases to obtain synergistic physicochemical properties. The bio-derived component may originate from natural polymers, agricultural residues, forestry resources, food-processing wastes, microorganisms, or other renewable biological sources. The nanoscale component can include carbon nanomaterials, metal and metal-oxide nanoparticles, transition-metal compounds, two-dimensional materials, conductive polymers, or other functional nanostructures [3].

The concept is particularly relevant to sustainable energy technologies because biological materials can provide renewable feedstocks, hierarchical structures, surface functionality, and mechanical flexibility, whereas nanomaterials can introduce electrical conductivity, catalytic activity, high surface area, defect sites, and electrochemical activity. The resulting composite can therefore exhibit properties that are difficult to achieve using either component individually [3].

2.2 Five Major Categories of Bio-Nanocomposites

I. Biopolymer–nanomaterial composites: These systems use an intact natural or bio-derived polymer as the continuous matrix. Representative matrices include cellulose, cellulose nanofibers (CNF), cellulose nanocrystals (CNC), chitosan, starch, alginate, gelatin, lignin, agarose, and natural protein-based materials [2].These matrices can be combined with graphene, graphene oxide, carbon nanotubes, metal oxides, MXenes, transition-metal sulfides, and conductive polymers. Their principal advantages include flexibility, functional surface groups, and processability.

II. Biomass-derived carbon nanocomposites: In this class, biomass is converted into carbonaceous materials through pyrolysis and carbonization, and subsequently integrated with nanoscale functional materials. Examples include biomass-derived porous carbon/MnO_2, carbon/Fe_3O_4, carbon/Co_3O_4, carbon/ZnO, carbon/Si, and carbon/MXene [3].

III. Biochar-based nanocomposites: Biochar possesses a combination of porosity, surface functionality, a carbon framework, and renewable origin. pristine biochar often suffers from relatively low conductivity and heterogeneous structure. Incorporating nanoscale functional phases (such as transition-metal oxides)

overcomes these limitations, providing a conductive carbon framework, redox-active sites, improved electrolyte accessibility, and additional pseudocapacitance.

IV. Bio-templated nanocomposites: Naturally occurring biological structures are used as templates to control the morphology of resulting nanomaterials. Biological templates provide hierarchical pores, channels, fibrous networks, and ordered architectures. The biological structure acts as a nanoscale template for controlling the architecture of the functional material.

V. Hybrid and multifunctional bio-nanocomposites: These systems incorporate more than two functional components, such as biomass-derived carbon + metal oxide + graphene, or biopolymer + MXene + metal oxide. The objective is to create complementary functions: the carbon phase provides electron transport, the porous bio-derived matrix facilitates ion accessibility, the metal oxide provides redox activity, and the biopolymer maintains mechanical integrity [9]. Representation of Biocomposites in Energy storage applications has been depicted in Fig.2

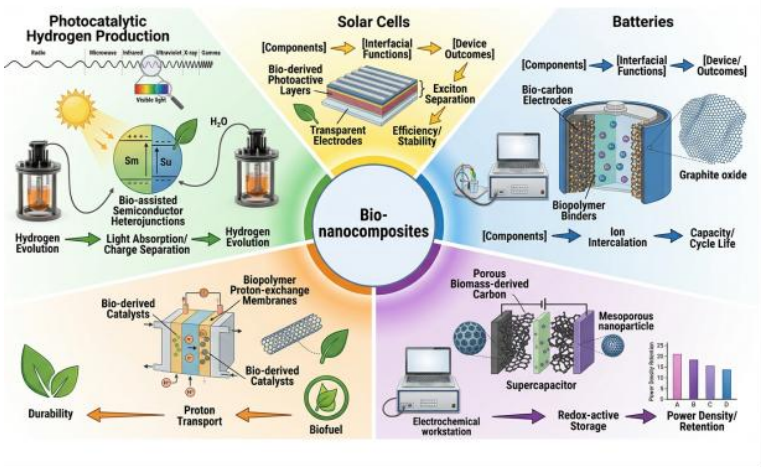


Figure.2 *Representation of Biocomposites in Energy storage applications*

2.3 Precursors and Feedstock Variability

The choice of biological precursor strongly influences the final properties of the nanocomposite. Cellulose offers high abundance, mechanical strength, a hydroxyl-rich surface, and the ability to form nanofibers/nanocrystals. Chitosan contains amino and hydroxyl groups that participate in metal-ion coordination, hydrogen bonding, and ionic interactions. Starch is inexpensive and widely available, contributing to flexible structures. Lignin is an abundant aromatic biomass component serving as a precursor for carbonaceous materials. Agricultural residues (rice husk, coconut shell, banana waste, corn residues, sugarcane bagasse, fruit peels, and sawdust) are attractive because they simultaneously provide waste valorization and low-cost feedstock.

However, feedstock variability is a major challenge. The composition of biomass varies with species, geographic origin, cultivation conditions, and processing history. This translates into variability in carbon yield, ash content, porosity, and surface chemistry. Recent literature identifies feedstock variability as one of the significant barriers to reproducible and scalable bio-nanocomposites.

2.4 Design Principles for Genuinely Sustainable Bio-Nanocomposites

A rational design strategy should simultaneously consider five parameters: P1. Resource sustainability (renewable or waste-derived feedstocks); P2. Synthesis sustainability (low solvent toxicity, low temperature, minimal washing and energy); P3. Structural optimization (accessible surface area, hierarchical pore-size distribution, and efficient electron/ion pathways); P4. Interfacial optimization (efficient charge transfer, ion adsorption/diffusion, and mechanical stability); P5. Practical performance (mass loading, full-cell

configuration, rate capability, and cycle life). This gives us a five-dimensional design framework: Resource → Synthesis → Structure → Interface → Device.

3. Green Synthesis and Fabrication Pathways

The synthesis route is a decisive factor in determining the structural, chemical, electrochemical, and environmental characteristics of bio-nanocomposites. In conventional nanomaterial synthesis, high temperatures, toxic reducing or stabilizing agents, organic solvents, and multistep purification procedures generate considerable environmental burdens. Green synthesis provides an alternative by exploiting renewable biological resources, benign reaction media, lower-energy processing, and waste-derived precursor [10]. However, the term 'green synthesis' should not be used solely because a biological precursor is involved. The complete synthesis pathway—including pretreatment, reaction, purification, drying, calcination, or carbonization—must be considered when evaluating sustainability [8].

3.1 Biogenic and Plant-Mediated Synthesis

Plant-mediated synthesis is one of the widely investigated approaches for preparing nanoparticles. Plant extracts contain naturally occurring phytochemicals such as polyphenols, flavonoids, terpenoids, sugars, and proteins that can participate in the reduction, nucleation, and stabilization of nanoparticles, replacing conventional toxic synthetic reducing and capping agents. For example, Aspergillus nidulans extract has been utilized to synthesize ZIF-8 bio-nanocomposites, which show enhanced photoelectrochemical hydrogen evolution [11]. Biomimetic approaches have also been employed to fabricate ZrO_2@PdO nanocomposites, offering an economically viable and sustainable pathway compared to conventional environmentally harmful methods [12].

3.2 Microbial Synthesis and Biomass carbonization

Microorganisms including bacteria, fungi, algae, and yeast can act as biological platforms for nanoparticle formation, utilizing extracellular enzymes, proteins, and metabolites for reduction and stabilization. These biogenic routes often involve specific synthesis steps such as carbon extraction from biomass, preparation of metallic material solutions, and post-processing steps like filtering and washing. Common green techniques include microwave-assisted methods, sonochemical synthesis, hydrothermal treatment, and mechanochemical synthesis. For biomass-derived carbon platforms, pyrolysis is commonly used. Precursor composition, carbonization temperature, heating rate, residence time, and atmosphere significantly affect the resulting carbon structure. The Table 1 depicts the comparative assessment of fabrication routes.

Table 1: Comparative Assessment of Fabrication Routes

Method	Major Advantage	Major Limitation	Sustainability Concern	Energy Relevance
Pyrolysis	Converts waste into carbon	High temperature required	Energy consumption	Battery/supercapacitor electrodes
Chemical activation	High surface area	Chemical consumption	Washing/wastewater	Supercapacitors
Physical activation	Reduced chemical waste	High temperature	Energy demand	Porous carbon electrodes
Plant-mediated	Renewable biological reagents	Batch variability	Extract purification	Nanoparticles
Microbial	Biological reduction	Complex processing	Culture and purification	Nanoparticles
Hydrothermal	Controlled morphology	Pressure and time	Energy/drying	Nanocomposites

Microwave	Rapid processing	Scale-up limitations	Energy efficiency at scale	Nanomaterials
Solvent-minimized	Reduced chemical burden	Processing flexibility	Solvent recovery	General
Bio-derived electrolyte	Renewable component	Conductivity limitations	Processing and stability	Batteries/supercapacitors

4. Interfacial Engineering and Charge/Ion Transport Kinetics

The performance of a bio-nanocomposite in an energy device is governed not only by the intrinsic properties of its individual components but also by the interactions occurring at their interfaces. In heterogeneous systems, interfaces provide the regions through which electrons, ions, and chemical species are transferred between different phases. Consequently, rational control of the bio-derived matrix–nanomaterial interface is essential for improving electrical conductivity, ionic transport, charge-storage kinetics, catalytic activity, and structural stability. This is particularly important for bio-nanocomposites because the constituent phases often have substantially different physicochemical characteristics. Biopolymers contain abundant hydroxyl, amino, or carboxyl groups but exhibit limited electronic conductivity, whereas carbon nanomaterials and transition-metal compounds provide high conductivity or redox activity.

4.1 Fundamental Transport Boundaries and coexisting Interfaces

A simplified bio-nanocomposite electrode can be represented as a multi-component system comprising the bio-derived matrix, the active nanomaterial, and the electrolyte. Within this system, several critical interfaces coexist: (1) the bio-matrix/nanomaterial interface, which determines nanoparticle dispersion and the continuity of transport pathways; (2) the nanomaterial/nanomaterial interface, where electronic coupling alters charge distribution and transport; (3) the electrode/electrolyte interface, which governs the migration, adsorption, and desolvation of ions; (4) the electrode/current-collector interface, which controls contact resistance [13-15].

4.2 Native Functional Groups and Heteroatom Doping

Bio-derived materials naturally contain functional groups such as –OH, –COOH, –NH_2, and C=O. These groups modify surface chemistry by improving wettability with aqueous electrolytes, facilitating ion adsorption, and anchoring nanoparticles to prevent aggregation. Heteroatom doping (with N, S, P, B, and O) is another effective strategy for modifying electronic structures and defect density. Nitrogen configurations—specifically pyridinic, pyrrolic, and graphitic nitrogen—alter electron density and introduce active sites, significantly enhancing charge storage and catalytic activity.

4.3 Hierarchical Porosity vs. Volumetric Energy Density

For porous carbon frameworks, matching pore architectures (micro, meso, macro) with electrolyte ion dimensions is essential for rapid transport. A hierarchical transport network utilizes macropores (>50 nm) as electrolyte reservoirs, mesopores (2–50 nm) for rapid ion diffusion, and micropores (<2 nm) for high charge accumulation. However, simply maximizing surface area is not optimal. Recent studies emphasize the importance of balancing pore architecture with electrode density and volumetric performance. A balance between micro–mesoporous channels and structural compactness is required to simultaneously obtain useful gravimetric and volumetric performance, preventing low volumetric energy density and excessive parasitic reaction.

5. Applications in Sustainable Energy Storage Systems

Energy-storage technologies represent one of the most important application areas for bio-nanocomposites because the combination of renewable feedstocks and nanoscale functional materials can address several limitations of conventional electrode and electrolyte materials. In particular, biomass-derived carbons provide

porous conductive frameworks, while biopolymers provide flexibility, surface functionality, and mechanical integrity.

5.1 Next-Generation Batteries

Lithium-ion and sodium-ion battery chemistries benefit significantly from bio-nanocomposites. In silicon-based battery anodes, which suffer from massive volume variation during lithiation/delithiation, a porous bio-derived carbon matrix acts as a conductive network and mechanical buffer, accommodating volume changes and maintaining electrical contact. In lithium-sulfur batteries, bio-derived porous carbon is attractive as a sulfur host, where a functionalized carbon/metal-compound interface provides physical confinement, chemical adsorption of polysulfides, and catalytic conversion, significantly reducing the shuttle effect.

Zinc-ion batteries (ZIBs) are also highly attractive aqueous systems. Incorporating bio-derived functional surface structures allows for controlled Zn^{2+} flux, which suppresses zinc dendrite formation and side reactions like hydrogen evolution, improving cathode stability.

5.2 High-Performance Flexible Supercapacitors

Supercapacitors combine electric double-layer capacitance (EDLC) from porous bio-carbons and pseudocapacitive charge storage from transition-metal oxides or conducting polymers. A major breakthrough has been demonstrated with 3D ion transport channels based on cellulose nanofibers (CNF) to create intercalated structures. For example, a composite film using graphene (rGO) as the plane layer and layered double metal hydroxide (LDH) as the support layer utilizes CNF as a flexible connection agent (Yan et al., 2024). This CNF-rGO-LDH composite film achieved an area energy density of 53.5 mWh cm^{-2} at a power density of 1071.2 mW cm^{-2} while retaining 89.8% of its initial capacitance after 10,000 charge-discharge cycles, showing outstanding mechanical and electrochemical integrity. Here, Table 2 gives the role of bio nanocomposites in storage technologies.

Table 2: Role of Bio-nanocomposites Across Storage Technologies

Technology	Bio-nanocomposite Role	Main Advantage	Major Challenge
Li-ion battery	Anode/support/binder	Conductivity and structural buffering	Practical loading and stability
Na-ion battery	Hard-carbon anode	Abundant Na resource + tunable structure	Initial Coulombic efficiency
Zn-ion battery	Electrode/electrolyte/interface	Aqueous compatibility and dendrite control	Zn dendrites and side reactions
Li–S battery	Sulfur host/catalyst	Polysulfide physical/chemical confinement	Polysulfide shuttle effect
Metal–air	Catalyst/support	Porous conductive gas-diffusion architecture	Catalytic activity and durability
Supercapacitor	Electrode	High power density and rapid charging	Moderate energy density
Hybrid supercapacitor	Electrode	Higher energy–power balance	Electrode kinetics matching
Solid-state device	Electrolyte/separator/electrode	Mechanical flexibility and safety potential	Ionic conductivity and stability

6. Applications in Energy Conversion and Harvesting

The application of bio-nanocomposites is not limited to electrochemical energy storage. Their renewable origin, tunable surface chemistry, hierarchical morphology, mechanical flexibility, and compatibility with nanoscale functional materials make them promising for energy conversion and energy harvesting. In contrast

to storage systems, where the primary objective is to store electrical energy efficiently, energy-conversion technologies transform one form of energy into another—for example, solar energy into electricity or chemical energy into electrical energy [16-17]. Energy-harvesting technologies additionally provide opportunities to capture small amounts of otherwise wasted mechanical, thermal, or environmental energy.

6.1 Solar Energy Conversion and Photocatalysis

In solar energy applications, bio-nanocomposites serve as sustainable alternatives for photovoltaic devices and photocatalysts. Biomimetic ZrO_2@PdO nanocomposites exhibit a low overpotential and an exceptionally low charge transfer resistance (Rct = 3.23 Ω), making them promising candidates for water splitting and solar-to-fuel conversion. Furthermore, ZIF-8 bio-nanocomposites synthesized with fungal extracts show a synergistic enhancement in photoelectrochemical hydrogen evolution, improving the efficiency of sustainable solar-to-hydrogen energy devices.

6.2 Fuel Cells and Biofuel Generation

Fuel cells convert chemical energy directly into electrical energy. Biopolymer-based proton exchange membranes (PEMs) derived via solution casting, such as pectin-based and polyvinyl alcohol (PVA)/cellulose nanocrystal-based (CNC) membranes, are developed for direct methanol fuel cells (DMFCs) and glucose biofuel cells (Subramanian and Raj, 2017; Rezzouq et al., 2026). The interface between organic and inorganic phases—specifically pectin/chitosan blends and sulphonic acid-modified TiO_2—is crucial for maximizing tensile strength and proton conductivity [15, 18-19].

In the field of biofuel production, cellulose-magnetite nanocomposites have demonstrated high catalytic activity for biodiesel synthesis, achieving an 89.21% conversion rate of oleic acid to methyl esters with a low activation energy of 16.56 kJ/mole (Helmiyati and Anggraini, 2019). For hydrogen production, hybrid systems combining biological and thermochemical routes have achieved conversion efficiencies up to 5.2 mol H_2 per mol of substrate.

6.3 Triboelectric and Piezoelectric Harvesting

Triboelectric nanogenerators (TENGs) convert mechanical motion into electrical energy. Biopolymers (cellulose, chitosan, gelatin, starch) are lightweight, flexible, and easily processed into films. Introducing functional nanoparticles modifies surface roughness and dielectric properties, dramatically increasing surface charge density and electrical output. Piezoelectric materials generate electrical potential under mechanical deformation, where bio-based flexible nanocomposites are utilized for wearable sensors and self-powered monitoring. The Table 3 illustrates the role of bio-nanocomposites in energy conversion and harvesting.

Table 3: Bio-nanocomposite Roles in Energy Conversion and Harvesting

Technology	Bio-nanocomposite Role	Key Mechanism	Major Challenge
Solar conversion	Conductive scaffold/interfacial layer	Improved charge separation & light absorption	Long-term environmental stability
Photocatalytic H_2	Semiconductor support/co-catalyst	Accelerated electron transfer, lower recombination	Optimum carbon loading balance
Fuel cells	Catalyst support/membrane	Renewable PEM membranes, reduced methanol crossover	Proton conductivity under dry conditions
ORR/OER	Heteroatom-doped catalyst	Surface redox reactions on active heteroatom/defect sites	Bifunctional activity and durability
Metal–air	Air electrode support	Porous conductive gas-diffusion, high gas accessibility	Catalyst degradation & electrolyte evaporation
Triboelectric	Flexible active layer	Contact electrification and electrostatic induction	Mechanical wear and interface fatigue

Piezoelectric	Flexible composite matrix	Stress-induced polarization in flexible architectures	Relatively low electrical output
Thermoelectric	Matrix/nanofiller	High Seebeck coefficient with suppressed thermal conductivity	Conductivity–thermal conductivity trade-off
Solid-state systems	Electrolyte/separator	Safe ion transport in flexible layouts	Interfacial resistance and compatibility

7. Life-Cycle Assessment, Techno-Economic Analysis, and Circularity

The use of biomass and biopolymers as precursors for nanostructured energy materials is frequently described as a sustainable strategy. However, the renewable origin of a precursor does not by itself establish environmental sustainability. A bio-nanocomposite may contain a renewable carbon or polymeric component while still requiring energy-intensive carbonization, chemical activation, toxic reagents, solvent-intensive purification, or difficult-to-recycle nanomaterials.

7.1 The Carbonization Temperature Dilemma and Activation Burden

Carbonization illustrates the central performance–sustainability trade-off. Increasing carbonization temperature results in greater carbon ordering, higher graphitic character, and improved electrical conductivity, but dramatically increases processing energy consumption. A similar trade-off exists in activation: chemical activation with highly corrosive activating agents generates exceptional specific surface area but requires corrosive chemicals, extensive washing, neutralization, and generates significant wastewater. Genuinely sustainable synthesis must optimize pore structure per unit of environmental input rather than simply maximizing surface area.

7.2 Nanomaterial Toxicity and supply-chain criticalities

The incorporation of inorganic nanomaterials introduces environmental risks. Materials such as metal oxides, quantum dots, and MXenes may exhibit toxicity depending on particle size, morphology, dissolution behavior, and persistence in the environment. Thus, a bio-nanocomposite is not automatically benign because its matrix is bio-base. Furthermore, relying on cobalt, nickel, and platinum-group catalysts introduces supply-chain criticalities and high carbon footprints. Sustainable designs must utilize earth-abundant active phases such as Fe, Mn, Zn, and Si [16, 20-21].

7.3 Life-Cycle Assessment (LCA) and Techno-Economic Analysis (TEA)

To systematically evaluate these materials, life-cycle assessments (LCA) must establish boundaries from 'cradle-to-grave' or 'cradle-to-cradle'. Defining the functional unit is particularly critical: rather than comparing impact per 1 kg of material, evaluations should be based on 1 kWh of delivered energy over the device lifetime. This shifts the comparison from material quantity to energy-service performance. Techno-economic analysis (TEA) must evaluate feedstock costs, transport, equipment, processing energy, yield, and recyclability. The key economic metric should be material cost per unit functional performance ($/kWh), as a low-cost but low-lifetime carbon is economically unviable [8]. Here, Table 4 summarises the quantitative reporting framework to perform.

Table 4: Suggested Quantitative Reporting Framework

Category	Suggested Metric	Scientific Rationale / Purpose
Feedstock	kg waste / kg material	Quantifies resource circularity and collection efficiency
Yield	%	Evaluates synthesis efficiency and mass recovery
Energy Input	MJ kg^{-1}	Tracks carbonization, activation, and thermal demands
Water Consumption	L kg^{-1}	Quantifies chemical washing and post-synthesis neutralization

Chemical Consumption	kg kg^{-1}	Evaluates toxic activation and synthesis agents
Carbon Footprint	kg CO_2-eq	Enables direct Global Warming Potential comparison
Electrochemical Perf.	F g^{-1} / mAh g^{-1}	Standard specific material metrics
Areal Performance	mAh cm^{-2} / F cm^{-2}	Critical for realistic thick-electrode device evaluation
Lifetime & Retention	cycles / %	Tracks durability and mechanical stability
Device Energy Density	Wh kg^{-1}	Full-cell operational metric
Cost	\$ kg^{-1} or \$ kWh^{-1}	Techno-economic commercial viability
Recyclability	% recoverable	Tracks end-of-life recovery and design-for-recycling
Toxicity	Standard endpoint	Ensures chemical safety of nanomaterial phases

8. Conclusion and Future Perspectives

Bio-nanocomposites have emerged as promising multifunctional materials for sustainable energy technologies because they combine the renewable characteristics of biological resources with the tunable physicochemical properties of nanomaterials. Their potential extends beyond conventional energy storage to include energy conversion, harvesting, electrocatalysis, and flexible energy devices.

This review has established a structure–interface–performance–sustainability framework connecting the different stages of bio-nanocomposite development: Bio-resource → Green synthesis → Nanoarchitecture → Interfacial engineering → Charge/ion transport → Device performance → Sustainability. Green synthesis and biomass valorization can reduce dependence on conventional feedstocks, while nanoscale engineering provides opportunities to control porosity, conductivity, surface chemistry, and catalytic activity. Interfacial engineering is particularly important because the interface between the bio-derived matrix and functional nanomaterial governs electron transport, ion diffusion, charge transfer, and structural stability.

Bio-nanocomposites demonstrate considerable potential in lithium-, sodium-, and zinc-ion batteries, lithium–sulfur batteries, supercapacitors, metal–air systems, photocatalytic energy conversion, fuel cells, and mechanical energy harvesting. Nevertheless, high laboratory-level electrochemical performance should not be interpreted automatically as evidence of technological or environmental superiority. Practical evaluation requires consideration of electrode loading, areal and volumetric performance, cycling stability, device configuration, and scalability.

The most important unresolved issue is the performance–sustainability trade-off. High-temperature carbonization, chemical activation, heteroatom doping, and incorporation of advanced nanomaterials can enhance performance while simultaneously increasing energy consumption, chemical demand, cost, or environmental burden. Consequently, future research should move from the concept of simply 'green synthesis' toward quantitatively sustainable materials design, integrating life-cycle assessment, techno-economic analysis, and device-level performance. Future development should therefore focus on standardized reporting, high-mass-loading and full-device studies, low-energy and low-chemical synthesis, quantitative LCA/TEA, and design-for-recycling to identify materials occupying the high-performance/high-sustainability region.

References

[1] Y. Zhang, X. Liu, S. Wang, L. Li, and S. X. Dou, "Bio-Nanotechnology in High-Performance Supercapacitors," Advanced Energy Materials, vol. 7, no. 21, p. 1700592, Nov. 2017. doi: 10.1002/AENM.201700592.

[2] S. Bairagi, S. Ahmed, and M. Jawaid, "Biopolymer-based Composites for Energy Generation and Storage," Elsevier, Oct. 2025. doi: 10.1016/c2023-0-52357-2.

[3] H. Shaghaleh, X. Xu, and S. Wang, "Current progress in production of biopolymeric materials based on cellulose, cellulose nanofibers, and cellulose derivatives," RSC Advances, vol. 8, no. 2, pp. 825–842, Jan. 2018. doi: 10.1039/C7RA11157F

[4] S. Dutta et al., "3D network of cellulose-based energy storage devices and related emerging applications," Materials Horizons, vol. 4, no. 4, pp. 522–545, July 2017. doi: 10.1039/C6MH00500D.

[5] S. Ramkumar, T. Theivasanthi, S. Venkatesh, and M. Ajitha, "A review on potential biopolymer nanocomposites in energy storage devices", Ionics, 2026. doi: 10.1007/s11581-026-07377-3.

[6] S. Peter, N. Lyczko, D. A. Gopakumar, H. J. Maria, A. Nzihou, and S. Thomas, "Nanocellulose and its derivative materials for energy and environmental applications," Journal of Materials Science, vol. 57, no. 13, pp. 6835–6880, Mar. 2022. doi: 10.1007/s10853-022-07070-6.

[7] J. O. Oyekale, "An overview of the conventional synthesis of biomass-derived nanocomposites and applications to systems for energy and the environment," Bitlis Eren University Journal of Science and Technology, vol. 13, no. 1, pp. 61–75, June 2023. doi: 10.17678/beuscitech.1233168.

[8] S. Suresh, A. Chatterjee, and S. Batabyal, "Paving the Way Towards Sustainable Next-Generation Energy Storage Through Green Biopolymer Binders", ACS Sustainable Resource Management, 2026. doi: 10.1021/acssusresmgt.6c00190/5247720.

[9] C. Yan et al., "Constructing a 3D Ion Transport Channel-Based CNF Composite Film with an Intercalated Structure for Superior Performance Flexible Supercapacitors," ACS Applied Materials & Interfaces, Apr. 2024. doi: 10.1021/acsami.3c19037

[10] M. D. Patil, S. D. Dhas, and A. V. Moholkar, "Green Synthesis of Nanocomposites," pp. 77–100, Jan. 2022. doi: 10.4018/978-1-7998-8936-6.ch004.

[11] A. Trabelsi, F. Alkallas, A. Aboraia, and M. Abouelela, "Synergistic Enhancement of Photoelectrochemical Hydrogen Evolution, Antimicrobial, and Cytotoxic Activities in a ZIF-8/Aspergillus nidulans Extract...", MDPI Catalysts, vol. 16, no. 8, pp. 712, 2026.

[12] T. Zahra et al., "Biomimmetic ZrO2@PdO nanocomposites: fabrication, characterization, and water splitting potential exploration," International Journal of Energy Research, vol. 46, no. 6, pp. 8516–8526, Feb. 2022. doi: 10.1002/er.7736.

[13] A. Rezzouq, I. Fettah, D. Belfadil, A. Taoufyk, and O. Tigri, "Sustainable PVA/Cellulose Nanocrystal-Based Proton Exchange Membranes for Potential Application in Glucose Biofuel Cells", MDPI Sustainability, vol. 18, no. 15, pp. 7953, 2026.

[14] A. Emre, E. S. T. Emre, and N. A. Kotov, "Bioinspired Multifunctional Nanocomposites for Energy Storage Applications," Meeting Abstracts, vol. MA2024-01, no. 6, pp. 3044–3044, Aug. 2024. doi: 10.1149/ma2024-0163044mtgabs

[15] L. C. Tomé et al., "Overview of Membrane Science and Technology in Portugal," Membranes, vol. 12, no. 2, pp. 197, Feb. 2022. doi: 10.3390/membranes12020197.

[16] G. Kaliyaperumal et al., "Converging pathways in biomass-to-biohydrogen conversion: A review on hybrid systems, nanotechnological interventions, and sustainable integration frameworks," Environmental Progress & Sustainable Energy, Dec. 2025. doi: 10.1002/ep.70295.

[17] F. Sher, M. Ilyas, M. Ilyas, U. Liaqat, and E. Lima, "Biorenewable nanocomposites as robust materials for energy storage applications," ACS Symposium Series, Mar. 2022. doi: 10.1021/bk-2022-1410.ch008.

[18] M. Subramanian and V. Raj, "Preparation and Characterization of Pectin Based Proton Exchange Membranes Derived by Solution Casting Method for Direct Methanol Fuel Cells," World Academy of Science, Engineering and Technology, International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering, vol. 11, no. 9, pp. 639–644, July 2017.

[19] A. Kausar, I. Ahmad, T. Zhao, M. Maaza, and P. Bocchetta, "Green Nanocomposite Electrodes/Electrolytes for Microbial Fuel Cells—Cutting-Edge Technology," Journal of Composites Science, vol. 7, no. 4, pp. 166, Apr. 2023. doi: 10.3390/jcs7040166.

[20] A. Emre, J. Fan, A. Gerber, V. Cecen, and N. Kotov, "Bioinspired Nanoporous Ion Conducting Membranes for Next Generation Batteries", Meeting Abstracts, vol. MA2020-02, pp. 2480-2480, 2020. doi: 10.1149/ma2020-024802mtgabs.

[21] H. Helmiyati and Y. Anggraini, "Nanocomposites comprising cellulose and nanomagnetite as heterogeneous catalysts for the synthesis of biodiesel from oleic acid," International Journal of Technology, vol. 10, no. 4, pp. 798–807, July 2019. doi: 10.14716/IJTECH.V10I4.2597.

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