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Review

Green Batteries: A Sustainable Approach Towards Next-Generation Batteries

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Abstract

The rising demand for sustainable energy storage has fueled the development of green batteries as alternatives to conventional systems. However, a major research gap lies in the unified integration of environmentally friendly materials and processes across all battery components—electrodes, electrolytes, and separators—without compromising performance or scalability. This review addresses this gap by highlighting recent advances in eco-conscious battery technologies, focusing on green electrode fabrication using water-based methods, electrophoretic deposition, solvent-free dry-press coating, 3D printing, and biomass-derived materials. It also examines the shift toward safer electrolytes, including ionic liquids, deep eutectic solvents, water-based systems, and solid biopolymer matrices, which improve both environmental compatibility and safety. Additionally, biodegradable separators made from natural polymers such as cellulose and chitosan offer enhanced thermal stability and ecological benefits. The review emphasizes the importance of lifecycle considerations like recyclability and biodegradability, aligning battery design with circular economy principles. While significant progress has been made, challenges such as standardization, long-term stability, and industrial scalability remain. By identifying key strategies and future directions, this article contributes to the foundation for next-generation green batteries, promoting their adoption in environmentally sensitive applications ranging from wearable electronics to grid storage.

Keywords: eco-friendly electrode fabrication; green electrolytes; biodegradable separators; chitosan binder; biopolymer electrolyte; nanostructures; recyclability; biodegradability; circular economy; ionic liquids; deep eutectic solvents

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1. Introduction

1.1. Why Green Batteries

The global transition to renewable energy systems has intensified the demand for efficient, sustainable, and environmentally benign energy storage technologies for which countries are enacting comprehensive regulations and policies to promote recycling, reduce carbon footprints, and foster the adoption of electric vehicles (EVs) through robust legislative frameworks [1,2]. Conventional energy sources are not only finite but also significantly contribute to greenhouse gas emissions and environmental degradation. As renewable sources like solar and wind are inherently intermittent, the role of energy storage—particularly batteries—becomes critical in balancing energy supply and demand. Conventional batteries, such as lithium-ion (Li-ion), nickel–cadmium (Ni-Cd), and lead–acid systems, although widely used, face several ecological and technological challenges that hinder their long-term sustainability [3,4]. These batteries often contain heavy metals (e.g., cobalt, lead, nickel) and organic solvents, posing serious risks of soil and water contamination during extraction, use, and disposal [5]. The increasing reliance on critical raw materials such as lithium, cobalt, and graphite places stress on finite geological resources and raises ethical concerns related to mining practices, especially in developing nations. Traditional battery manufacturing is associated with high carbon emissions, water usage, and energy consumption, contributing to the life-cycle environmental burden of these technologies [6]. Conventional batteries can suffer from thermal runaway, leakage, or explosion under certain conditions, posing safety risks during operation and transportation. Most batteries are not adequately recycled due to technical, economic, and logistical barriers, leading to the accumulation of e-waste and loss of valuable materials [7]. These limitations necessitate the development of alternative battery systems that are not only technically viable but also environmentally and socially responsible—paving the way for the emergence of green battery technologies (Figure 1).

Figure 1. Major challenges in conventional battery systems.

Green batteries, designed through eco-conscious strategies, aim to address these concerns by incorporating renewable materials, non-toxic components, and energy-efficient synthesis methods. The concept extends beyond the reduction of environmental impact to embrace circular economy principles, including recyclability, biodegradability, and sustainable sourcing of materials [6]. Green energy storage is thus not only a technological innovation but also a pivotal component of sustainable development goals (SDGs), particularly in achieving climate neutrality and responsible consumption.

The overarching goal of this review is to systematically analyze and highlight the recent developments in green battery technologies, focusing on the design, materials, and strategies that align with the principles of environmental sustainability and resource efficiency. As global energy storage demands surge alongside concerns regarding climate change, the need for batteries that are not only high-performing but also safe end-of-life, renewable, and environmentally benign has become paramount. Figure 2 depicts the increase in number of publications in the last 10 years (2015–2025).

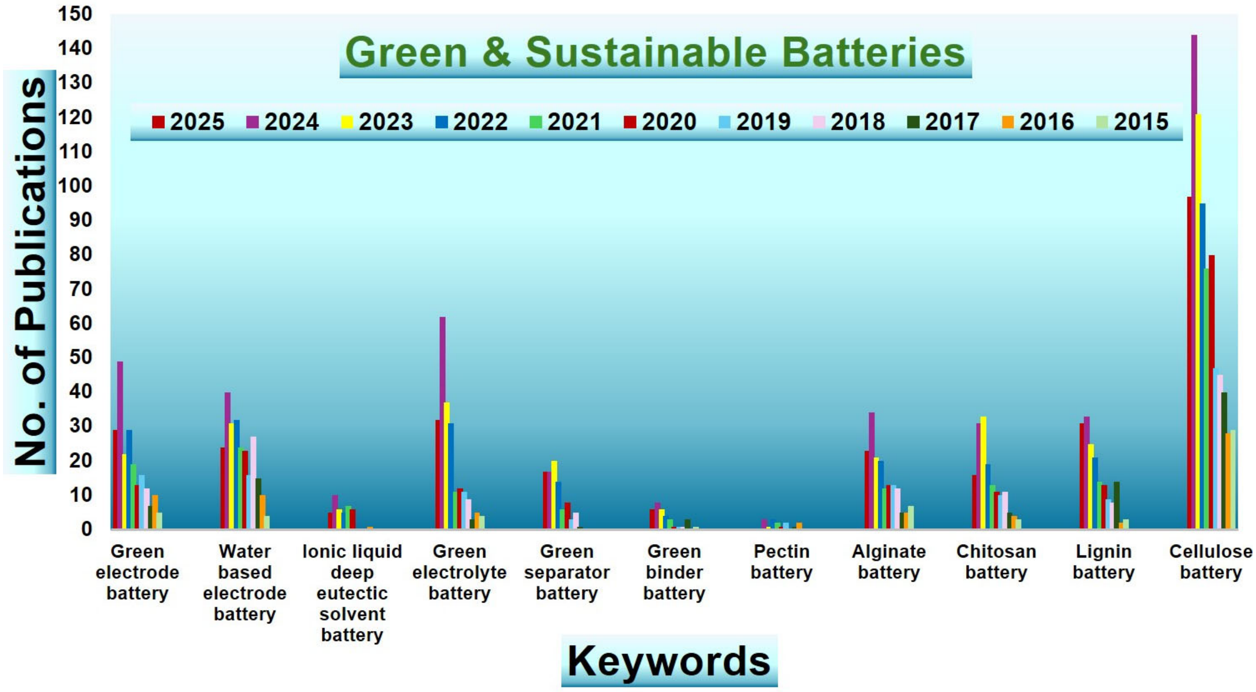

Figure 2. Decade-long publication trend (2015–2025) highlighting the growth in research on green and sustainable batteries, based on keyword-specific searches from the PubMed database (accessed on 29 May 2025).

A key emphasis is placed on sustainable and efficient electrolytes, including ionic liquids and deep eutectic solvents known for their low volatility and recyclability, as well as water-based and gel electrolytes that enhance safety and environmental compatibility [8]. Biopolymer-based solid electrolytes derived from natural sources and additive-free, renewable electrolyte systems are also critically discussed for their potential to minimize synthetic chemical use and reduce toxicity. Equally important is the development of green separators, which play a pivotal role in battery efficiency and stability. This includes cellulose- and chitosan-derived membranes that are both biodegradable and abundant, as well as bio-derived and natural polymer separators that offer mechanical integrity and ionic transport capabilities. Advanced nanostructured membranes are also explored for their enhanced electrochemical properties and structural versatility. The scope of this article spans various next-generation battery chemistries such as lithium-ion, sodium-ion, zinc–air, and other metal–air or aqueous systems, with a focus on integrating green principles into their component design. The key focus areas include green electrode fabrication, electrolytes such as ionic liquids, deep eutectic solvents, water-based and gel formulations, and biopolymer-derived solid-state systems; natural and bio-derived separators, including membranes based on cellulose, chitosan, and other biodegradable polymers, as well as advanced functional membranes engineered for high performance; green synthesis methods utilizing plant extracts, microorganisms, and waste-derived precursors for active material fabrication; environmental assessment metrics, including recyclability, biodegradability, and toxicity profiles of green battery components (Figure 3). By reviewing recent progress in materials innovation, eco-friendly processing techniques, and functional performance, this article aims to provide an in-depth understanding of how green approaches can be implemented across the full battery lifecycle. Additionally, challenges and the environmental assessment accompanied by recyclability and current market potential as per the new global government policies implemented are discussed. Ultimately, the review aspires to serve as a foundational resource for researchers and industry stakeholders pursuing the sustainable evolution of battery technology in support of global clean energy goals.

Figure 3. Current research gap and scope in developing next-generation green batteries.

1.2. Green Batteries: Concept and Principles

Green battery technologies represent a holistic and sustainable evolution of conventional electrochemical energy storage systems. The central concept is to minimize environmental impact across the entire battery lifecycle—from raw material extraction and synthesis to operation, disposal, and recyclability—while maintaining or enhancing performance. At the core of green battery design are the following principles (Figure 4):

(i). Eco-friendly material selection: Green batteries prioritize the use of abundant, renewable, and non-toxic materials. This includes replacing scarce or hazardous elements like cobalt and nickel with more sustainable alternatives such as iron, manganese, sodium, zinc, or organic redox-active materials. Natural polymers (e.g., cellulose, chitosan, alginate) are increasingly used in electrolytes and separators due to their biodegradability and functional properties.

(ii). Sustainable synthesis processes: Green synthesis techniques emphasize low-energy, solvent-free, or water-based fabrication methods. Bioinspired or bio-assisted approaches, such as using plant extracts or microorganisms for electrode material synthesis, not only reduce the use of harmful chemicals but also introduce functional groups that enhance electrochemical performance. These methods contribute to a smaller carbon footprint and reduced environmental toxicity.

(iii). Design for end-of-life and recyclability: A fundamental tenet of green battery development is circularity—designing batteries that can be easily disassembled and recycled at the end of their service life. This involves selecting materials and chemistries that allow for efficient recovery and reuse without generating hazardous waste, aligning with principles of the circular economy.

(iv). Safety and environmental compatibility: Green batteries incorporate inherently safe materials that are thermally and chemically stable. Non-flammable solid-state or aqueous electrolytes reduce risks of leakage, combustion, and thermal runaway. This improves operational safety and ensures compliance with environmental and transportation regulations.

(v). Efficient energy and resource: Minimizing the use of critical raw materials and energy during manufacturing enhances sustainability. Green batteries also strive for high energy density and long cycle life to reduce overall resource consumption over time.

Figure 4. Basic principles of green batteries.

In essence, green battery technologies aim to strike a balance between performance, cost, and sustainability. They offer a promising pathway toward next-generation energy storage solutions that are compatible with a low-carbon, resource-resilient future.

2. Green Electrode Fabrication Techniques

Sustainable battery technology increasingly relies on green synthesis methods and eco-friendly electrode fabrication techniques to reduce environmental impact. The recent research highlights several promising approaches for both battery component synthesis and electrode manufacturing that avoid toxic chemicals, minimize waste, and use renewable or benign materials (Table 1). The electrode fabrication by sustainable environment benign methods include (Figure 5) the water-based method, electrophoretic deposition, aqueous polymer binders, atomic layer deposition, dry press-coating, 3D-printing, and utilizing waste-derived precursors and plant-mediated active materials.

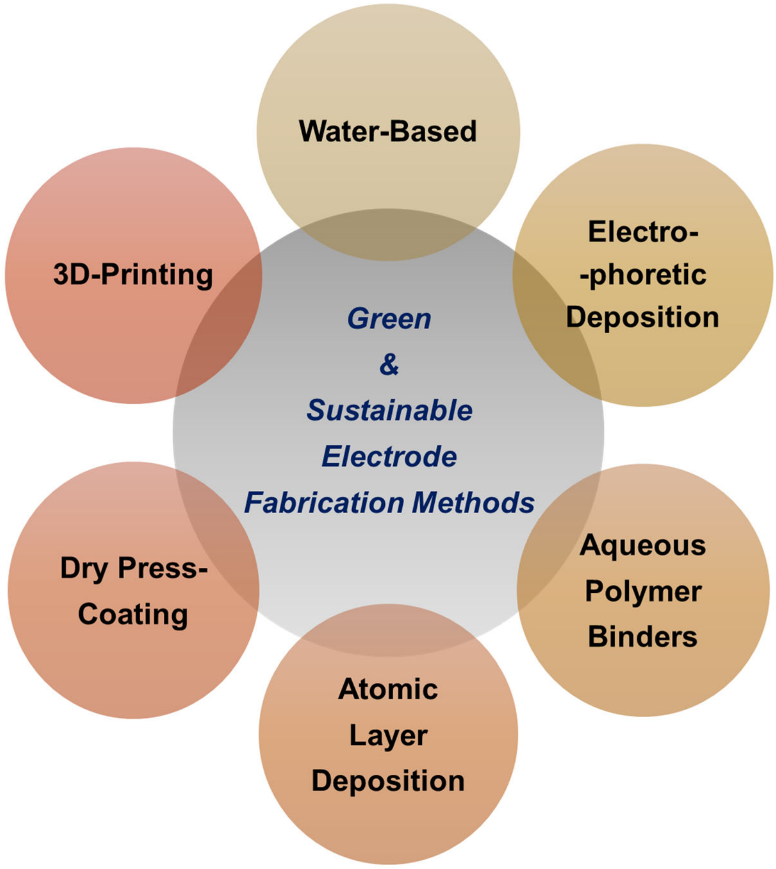

Figure 5. Fabrication methods for green and sustainable electrode.

The most commonly employed method for sustainable electrode fabrication is water-based processing. In this process, toxic solvents (like N-methyl-2-pyrrolidone (NMP)) are replaced with water or ethanol in electrode manufacturing, which significantly reduces toxicity and cost while maintaining battery performance [9–11]. For instance, in a recent study, a comprehensive green manufacturing and recycling strategy for lithium-ion batteries was demonstrated by replacing the conventional toxic (NMP) with water in electrode fabrication. Electrodes were prepared using water-soluble binders, enabling subsequent recovery and reuse of materials. The water-based process allowed efficient separation of the black mass from current collectors through simple aqueous dissolution, followed by recovery and relithiation of the active material to produce battery-grade components. Meanwhile, pouch cells (~1.6 Ah) assembled with $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ (NCM523) cathodes and graphite anodes produced via water-based processing exhibited comparable electrochemical performance to conventional NMP-based cells [11].

Secondly, the electrophoretic deposition (EPD) method utilizes green solvents (e.g., ethanol) to deposit active materials onto conductive substrates, improving adhesion and reducing environmental impact [9]. Recently, a nanocomposite anode composed of SiO_2, poly(aniline-co-anthranilic acid) (PAAA), and functionalized MWCNTs was fabricated for lithium-ion batteries. Strong interfacial interactions between the components revealed enhanced structural integrity. Using electrostatic spray deposition (ESD), the electrode was uniformly coated onto the current collector, effectively suppressing SiO_2 volume expansion during cycling and led to a high initial capacity of 1415 mAh/g, with excellent retention of 1231 mAh/g after 500 cycles, and strong rate performance, demonstrating the advantages of ESD over traditional slurry-cast methods [12].

A separate study applied ESD for fabricating $LiCoO_2$ cathodes using engineered core/shell composite particles. $LiCoO_2$ was coated with carbon nanoparticles for conductivity and PMMA nanoparticles as a binder. The surface-modified particles exhibited improved flowability and electrostatic charging, enabling stable and uniform deposition. The PMMA layer also enhanced film formation, validating ESD as a promising route for high-performance cathode manufacturing [13].

Similarly, aqueous polymer binders that include water-soluble, fluoro-free binders enable electrode fabrication and recycling without hazardous chemicals, supporting closed-loop manufacturing [10,11]. For instance, polyfluorene-based poly(2,7-9,9 (di(oxy-2,5,8-trioxadecane))fluorene) PFO binders present a novel approach to green electrode fabrication through multifunctional conjugated polymers. By integrating ethylene oxide (EO) side chains into the PFO backbone, the polymer achieved excellent solubility in environmentally benign ethanol/water mixtures. The optimized PFO-400 binder combines mechanical flexibility, surface adhesion, and efficient charge transport. Its strong compatibility with silicon oxide (SiOx) anodes enabled the formation of a conductive matrix around the active material, which effectively buffered the mechanical stress from volume fluctuations during cycling. Remarkably, the SiOx-HOS-PFO electrodes demonstrated a capacity retention of approximately 86% over 200 cycles at a current rate of 0.33 C, despite the absence of conductive carbon additives, electrolyte additives, or nanoscale materials [9]. In another fabrication technique, electrosynthesis and bipolar electrochemistry utilizes electricity instead of hazardous chemical oxidants/reductants and employs bipolar electrodes to minimize supporting electrolyte use, making the process inherently greener and more sustainable [14,15]. Atomic layer deposition (ALD) is another method in this category in which gas-phase ALD applies ultrathin, stable coatings to organic electrodes, enhancing performance and stability in sodium-ion batteries [16].

Next is the dry press-coating method, which implements a solvent-free technique for fabricating battery electrodes [17]. Instead of making a liquid slurry like in traditional methods, this process uses dry powder mixtures of the active material, conductive additive, and binder (e.g., PVDF). These powders are premixed, then evenly spread onto a metal current collector (like aluminum foil), and finally, pressed under heat and pressure to form a solid, compact electrode layer [17,18]. Recently, a fully dry electrode fabrication technique was developed using a hot-rolling press to activate thermoplastic binders without solvents. This process eliminated evaporation steps and reduced activation time, resulting in strong electrode adhesion (148.8 kPa) and improved electrochemical performance. Compatible with roll-to-roll production, the method supports fast, scalable, and eco-friendly battery manufacturing [19].

In a recent study, researchers developed dry press coated electrodes (DPCEs) using a solvent-free approach to enhance environmental sustainability and structural integrity in battery fabrication (Figure 6). The electrodes were prepared by dry mixing NCM712 (80 wt%) with multi-walled carbon nanotubes (MWNTs) and PVDF binder in varying ratios (15/5, 10/10, and 5/15), followed by vortex mixing to preserve the MWNT network. The mixture was evenly spread onto etched aluminum foil and then pressed at 180 °C under 10 MPa pressure for 30 s. This dry press coating method avoided the use of toxic solvents like NMP, reduced energy consumption by eliminating drying steps, and maintained the conductive structure of MWNTs. In comparison, traditional slurry-coated electrodes (SCEs) were prepared using NMP and required longer drying times and higher energy input. The DPCE approach demonstrated a promising alternative for green and efficient battery electrode fabrication [20].

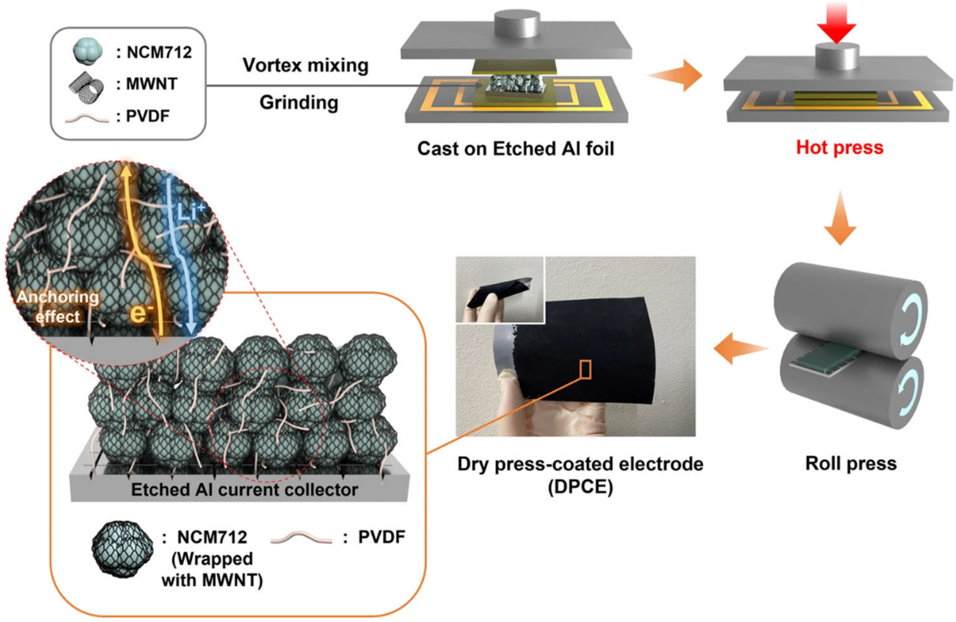

Figure 6. Schematic illustration of dry press-coating method of green electrode fabrication [20].

A solvent-free manufacturing method would represent significant progress in the development of cost-effective and environmentally friendly lithium-ion and lithium-metal batteries. Such approaches eliminate the need for toxic organic solvents, reduce energy consumption, and enable scalable, dry electrode fabrication compatible with existing roll-to-roll manufacturing [21]. In this category, one of the most industrially successful solvent-free fabrication methods to date is the PTFE-based dry electrode processing technique, which has gained significant attention due to its scalability and adoption by leading battery manufacturers. This method involves the mechanical mixing of active materials, conductive carbon, and polytetrafluoroethylene (PTFE) as a fibrillated binder to form a cohesive electrode film without the use of solvents. The resulting composite is hot-pressed onto current collectors, offering high electrode density, excellent flexibility, and robust adhesion—essential for next-generation high-energy batteries [22–24].

For instance, one promising strategy utilizes PTFE fibrillation aided by carbon nanotubes (CNTs), where CNTs serve dual functions: improving electrical conductivity and anchoring LFP particles to enable dry hot-rolled electrode films. This method results in full cells with initial coulombic efficiencies above 95% and stable capacity retention over 50 cycles [25]. Another study replaces traditional PVDF binders with phenoxy resin in solvent-free thick electrode fabrication. Phenoxy resin, with its superior ductility and low-temperature processability, ensures uniform material distribution and stronger adhesion, enabling thick electrodes with high mass loading (~40 mg/cm^2) and improved cyclability over PVDF-based or slurry-cast counterparts [26]. Additionally, solvent-free processing has extended to the fabrication of composite solid polymer electrolytes (CPEs), such as a nanofiber-reinforced polycaprolactone-based membrane plasticized with trimethyl phosphate, yielding high ionic conductivity, excellent compatibility with lithium, and enhanced thermal safety for Li//$LiFePO_4$ solid-state batteries [27]. For sulfide-based ASSBs, a continuous solvent-free fusion bonding method utilizing thermoplastic polyamide binders enables the integration of ultrathin Li_6PS_5Cl films and thick cathodes with exceptional mechanical strength, stress tolerance, and long-term electrochemical stability, achieving energy densities above 390 Wh/kg and extended operational lifespans over 10,000 h [28].

Together, these advancements highlight solvent-free techniques as viable, sustainable, and high-performance alternatives for next-generation battery technologies and industrial scalability.

Waste-derived electrode materials include different types of waste materials such as biomass waste (unburned charcoal, pomelo peel, and fungus bran) [29], industrial and electronic waste (waste glass microfiber filters, photovoltaic silicon cutting waste, and spent lithium-ion battery graphite) [30], textile and tire waste (discarded cotton cloth and waste tires) [31], and refinery and coal by-products (Semi-coke, coal gasification ash, coal tar pitch, and petroleum residues) [32].

Meanwhile the waste-derived fabrication method includes carbonization and activation in which high temperature treatment and chemical activation (often with KOH) are used to develop porous structure and enhance electrochemical properties [33]. Other effective strategies include composite formation techniques such as magnesiothermic reduction, carbon coating, and electrodeposition [29], as well as surface modification approaches like heteroatom doping (e.g., with sulfur, nitrogen, or potassium). Additionally, impurity removal through methods such as the modified Hummers process can further improve the material's purity and electrochemical performance [32].

Table 1. Sustainable fabrication methods and advantages and disadvantages of battery components.

Green Synthesis/ Fabrication Method	**Advantages**	**Disadvantages**	**Ref.**
Mechanochemical synthesis	Solvent-free, scalable, low environmental impact	Limited control over nanostructure, possible lower conductivity, scalability challenges	[34,35]
Hydrothermal carbonization	Renewable precursors, high surface area, eco-friendly	May require high energy input, batch-to-batch variability, limited scalability	[36–38]
Biopolymer-assisted synthesis	Plant extracts, biopolymer binders, high stability	Variability in biopolymer sources, potential for lower mechanical/electrochemical performance	[39]
Molten salt/in situ electrochemical MXene	No hazardous acids, direct device integration	Lower mechanical strength, binder limitations, material compatibility	[40,41]
Water/ethanol-based electrode processing	Non-toxic, cost-effective, comparable performance	Lower mechanical strength, binder limitations, material compatibility	[9–11]
Electrophoretic deposition (EPD)	Green solvents, improved adhesion	Process complexity, scalability issues	[9]
Aqueous polymer binders	Fluoro-free, recyclable, closed-loop manufacturing	Adhesion/chemical stability concerns	[10,11]
Atomic layer deposition (ALD)	Stable coatings, improved organic electrode performance	Slow deposition rates, scalability, equipment cost	[16]
Green Electrolyte Preparation	Reduces hazardous waste and environmental impact	May have lower conductivity or performance than traditional methods	[42]
(Natural solvents, green synthesis)	Uses renewable, biodegradable materials	High viscosity, cost, and scalability issues for some solvents	[42]
Sustainable Separator Synthesis	Utilizes biodegradable, renewable material	Limited data on long-term stability and performance	[43]
Biomass-based, green processing)	Reduces reliance on petrochemicals and toxic solvents	Potentially higher production costs and process complexity	[43]

Recently, a fully biodegradable, soft, and stretchable redox-diffusion battery was developed by using sustainable plant-based materials. By integrating cellulose fibers, lignin, alizarin, and biomass-derived elastomers into all battery components—including 3D porous electrodes and metal-free stretchable current collectors—the design achieves high electrochemical performance with an operating voltage of 0.6 V with a maximum volumetric capacity of 2.68 mA h cm^{-3} at a current density of 0.2 mA cm^{-2}, while maintaining exceptional mechanical softness (Young's modulus of 110 kPa). The battery demonstrated stable cycling (stable capacity retention after 200 cycles) under strain (30%) and the potential for environmentally safe disintegration at end-of-life (Figure 7) [44].

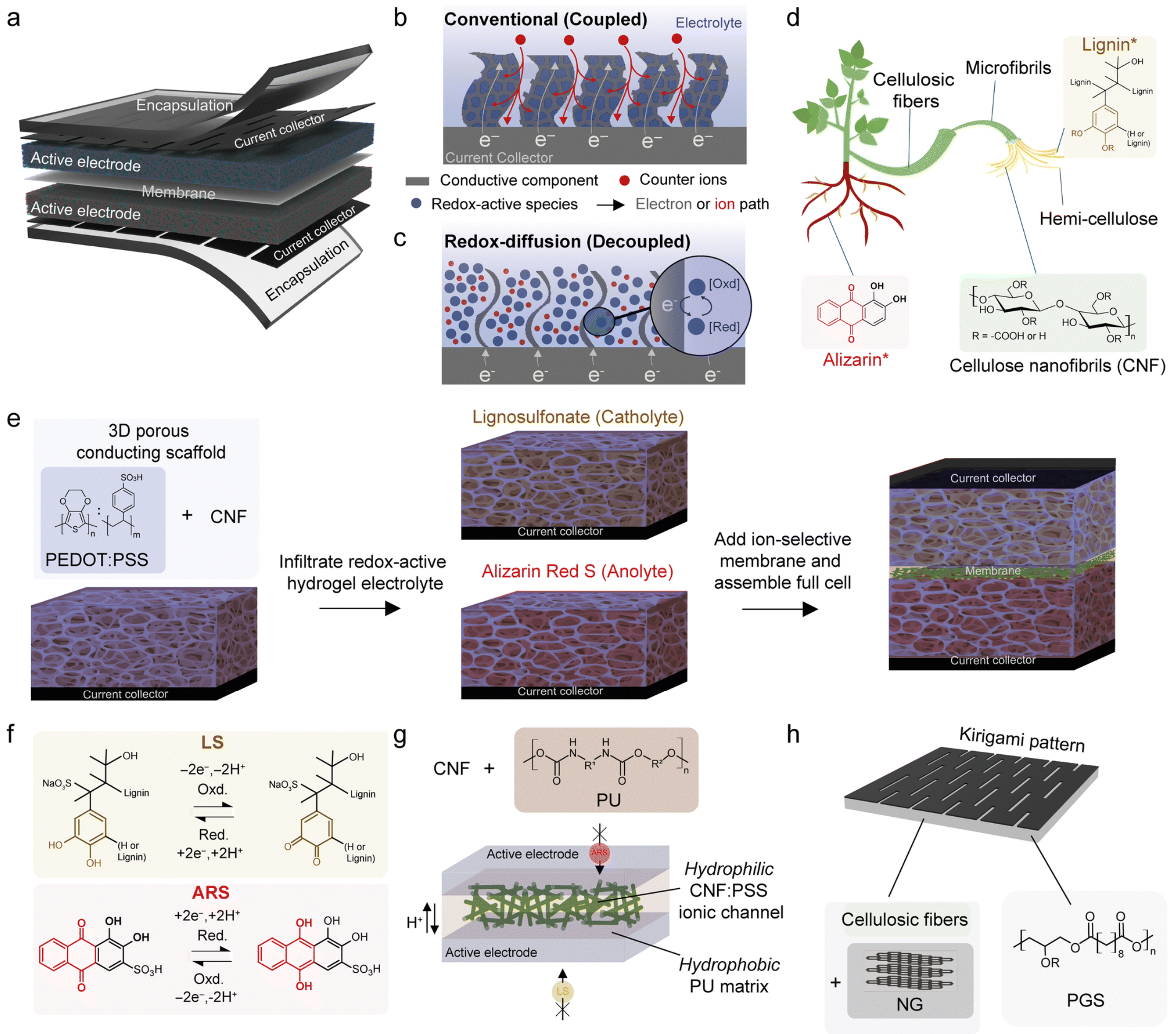

Figure 7. Schematic illustration of 3D-printed green electrode fabrication with usage of biodegradable materials (carboxymethylated cellulose nanofibrils, lignosulfonate and alizarin red sulfonate, poly(glycerol sebacate)) battery components for redox-diffusion battery [44].

Three-dimensional printed electrodes are another sustainable approach in designing and developing battery components. For instance, high-resolution, hierarchically porous, lightweight metallic electrodes are developed by using digital light processing (DLP) technology for an aqueous asymmetric nickel–iron battery, with controlled porosity and geometry, surpassing the limitations of traditional physical–chemical assembly techniques. These 3D-printed electrodes exhibit excellent mechanical strength, support ultrahigh active material mass loading, and maintain superior gravimetric and volumetric capacitance. The linear relationship between electrode thickness and areal capacitance indicates potential for further performance enhancement [45]. The electrochemical performance of waste-derived and water-based green electrolytes are presented in Tables 2 and 3.

Table 2. Electrochemical performance of waste-derived electrode material.

Waste Source	Battery Type	Electrochemical Performance	Ref.
Biomass (charcoal)	Na-ion, Li-ion	High capacity, long cycle life	[33]
Glass microfiber	Li-ion	Good cycling, high areal capacity	[46]
Silicon cutting waste	Li-ion	High reversible capacity, stable cycling	[47]
Cotton cloth	Vanadium redox flow	Higher efficiency than commercial electrodes	[48]
Tires	Li-ion	Potential for higher capacity than graphite	[49]
Pomelo peel	Zn-ion (flexible)	Outstanding electrochemical/mechanical properties	[50]

Table 3. Electrochemical performance of different water-based green electrolytes.

Electrolyte Type	Battery Type	Electrochemical Performance	Ref.
Water-in-salt (LiTFSI)	Li-ion, Na-ion, Zn	High voltage, safety, energy density	[51,52]
Semisolid (lake water)	Flexible supercapacitors	Low cost, flexibility, cycling stability	[53]
Water-in-polymer	Solid-state batteries	Recyclability, wide voltage window	[53]
Acetate-based WiSEs	Zn-ion	Corrosion suppression, long cycle life	[54]

Overall, these findings indicate that water-based green electrode processing offers a sustainable alternative with minimal compromise in electrochemical performance, particularly excelling in long-term cycling stability, thus validating its potential for environmentally friendly battery manufacturing. Green electrode fabrication brings notable environmental and economic advantages by utilizing renewable, biodegradable, and non-toxic materials such as biopolymers, plant-derived binders, and biomass-derived conductive carbons. These strategies significantly reduce greenhouse gas emissions and eliminate the need for hazardous solvents or energy-intensive processes. Additionally, the cost-effectiveness and scalability of using natural resources make green fabrication attractive for large-scale battery manufacturing. However, this approach also faces several limitations. Natural materials often display batch-to-batch variability, affecting consistency and reproducibility of electrode performance. Furthermore, the lower electrical conductivity of biopolymers and bio-carbons compared to conventional synthetic materials can compromise electrochemical efficiency unless modified. Lastly, the mechanistic understanding of how green components influence long-term battery performance remains limited, requiring further research to achieve reliable optimization and integration in commercial systems. By integrating renewable resources and clean synthesis strategies, eco-friendly electrode fabrication represents a promising direction for the development of sustainable battery technologies. However, further research is needed to address challenges related to performance optimization and scalability.

3. Green, Sustainable, and Efficient Electrolytes

The shift toward environmentally benign and sustainable energy storage systems has prompted the development of green electrolyte formulations. Green electrolytes are designed to be safe, biodegradable, non-toxic, and derived from renewable sources. They replace conventional organic solvents, which are typically volatile, flammable, and hazardous, with sustainable alternatives such as ionic liquids (ILs), deep eutectic solvents (DES), water-based electrolytes, and solid biopolymer-based systems.

3.1. Ionic Liquids and Deep Eutectic Solvents as Green Electrolytes

Ionic liquids (ILs) and deep eutectic solvents (DESs) have garnered considerable attention as green electrolyte alternatives due to their negligible vapor pressure, high thermal stability, and non-flammability. ILs, composed of bulky organic cations and various anions, provide a wide electrochemical window and high ionic conductivity, making them suitable for high-voltage applications. DESs, often formed by mixing hydrogen bond donors and acceptors such as choline chloride with urea or organic acids, offer similar physicochemical benefits with improved biodegradability and lower cost [8]. DESs, considered a distinct category within ionic liquids, are recognized as environmentally friendly and sustainable solvents. They have found broad applications across various fields, including green chemistry, drug delivery, metal processing, separation and extraction technologies, and the development of nanoscale and functional materials [55].

ILs and DESs exhibit enhanced safety, tunable physicochemical properties, and excellent chemical stability. They are non-volatile and can suppress dendrite formation in lithium metal batteries. However, ILs are often expensive and may have high viscosity, which impedes ion mobility. DESs, while more sustainable, may still suffer from limited electrochemical stability and long-term compatibility with electrode materials. Employing natural DES, bio-ionic liquids, and biomass-derived organic compounds (e.g., choline chloride, glycerol-based systems, γ-valerolactone, aloe vera) as electrolytes, which are renewable, biodegradable, and can improve battery performance by reducing unwanted side reactions and enhancing stability [43,56].

In this regard, a DES formulation demonstrated excellent cycling performance and lower overpotentials, suggesting strong potential for use as a green electrolyte in zinc-based energy storage systems. The blending of two acetamide-based DES systems results in $Ace_4(ZnTFSI_2)_x$ and $(ZnCl_2)_{1-x}$ (Figure 8). As acetamide with water acts as a green, safe, and affordable electrolyte [57], the resulting ternary DES mixtures showed significantly enhanced ionic mobility, with the optimal performance observed at a composition of $x = 0.8$, where ionic conductivity surpassed that of the individual components. However, increased ionic mobility led to fast crystallization, particularly in equimolar mixtures, posing challenges for maintaining liquid-phase stability at lower temperatures [58].

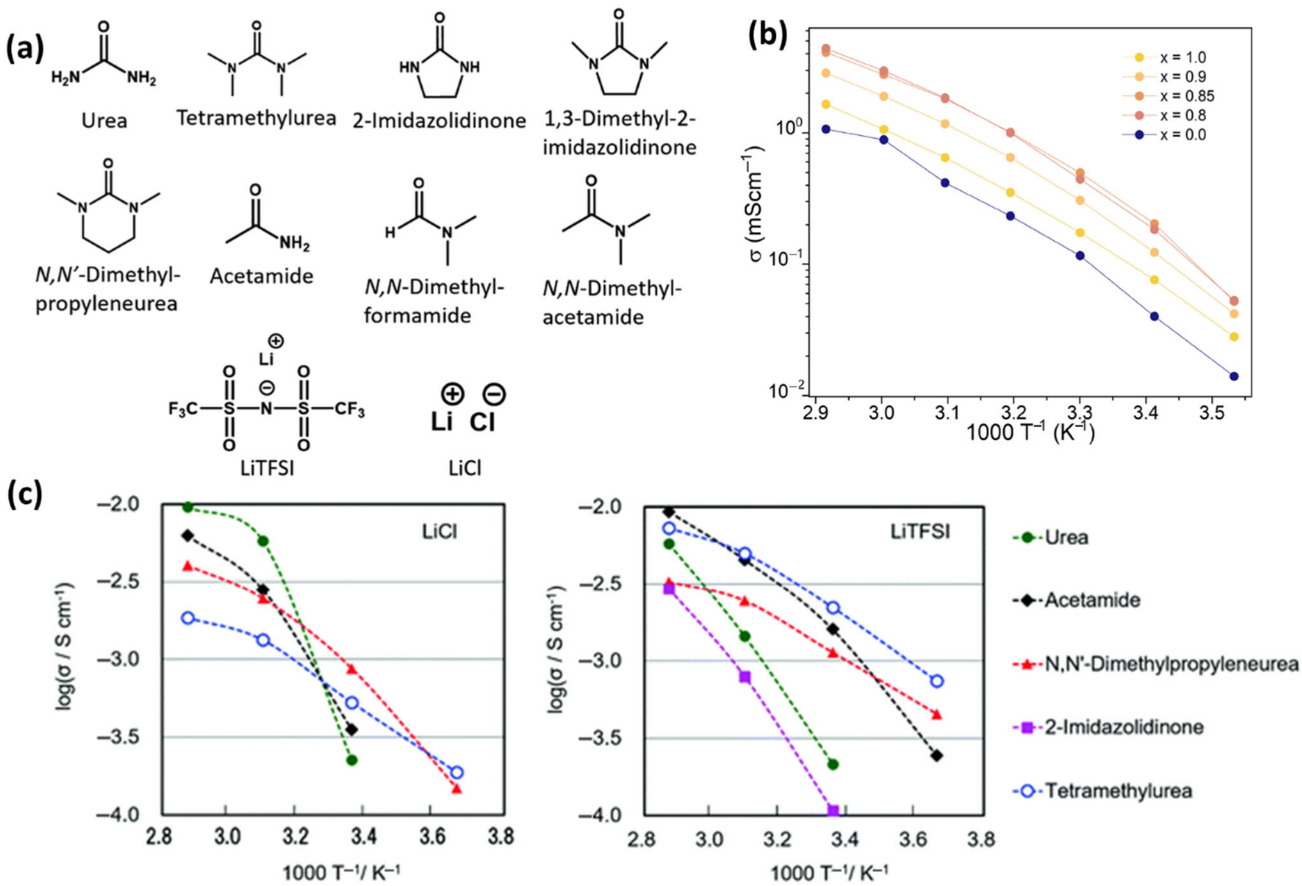

Figure 8. (**a**) Structure of different amides for DES electrolytes [55], ionic conductivity of (**b**) DES $Ace_4(ZnTFSI_2)_x$ and $(ZnCl_2)_{1-x}$ electrolyte mixtures at varying temperature with x = 0.9, 0.85, 0.8, and 0.0 [58] and (**c**) LiCl/amide and LiTFSI/amide based electrolytes, respectively [55].

3.2. Water-Based and Water-in-Polymer Electrolytes

Water-based electrolytes are essential components in modern energy storage devices, offering safety, affordability, and environmental benefits compared to traditional organic electrolytes. Water-based electrolytes, especially when optimized with additives or pH control, present an excellent eco-friendly option for aqueous batteries due to their inherent non-flammability and low toxicity [59]. These electrolytes are particularly advantageous in aqueous rechargeable batteries such as Zn-ion and Na-ion systems. Advanced variants like "water-in-salt" and "water-in-polymer" electrolytes have been developed to extend the electrochemical stability window beyond the traditional 1.23 V of water, enabling compatibility with higher voltage electrodes [51].

Water-in-salt electrolytes, with extremely high salt concentrations (e.g., LiTFSI, HCOOK, KAc), disrupt the water network, leading to isolated water molecules and extended voltage windows compared to the traditional water-based electrolytes that are limited by a narrow electrochemical stability window, restricting battery voltage and energy density. [52,59,60]. A recent study introduced a concentrated potassium formate (40 M HCOOK, water-to-salt ratio 1.38:1) as a green, cost-effective water-in-salt electrolyte with an extended electrochemical stability window of 4 V (−2.5 to 1.5 V vs. Ag/AgCl) (Figure 9). Compared to CH_3COOK, HCOOK offers superior ionic conductivity and a more stable negative potential. Additionally, a $KTi_2(PO_4)_3$ anode delivered a reversible capacity of 15 mAh g^{-1} at 0.1 A g^{-1} [51].

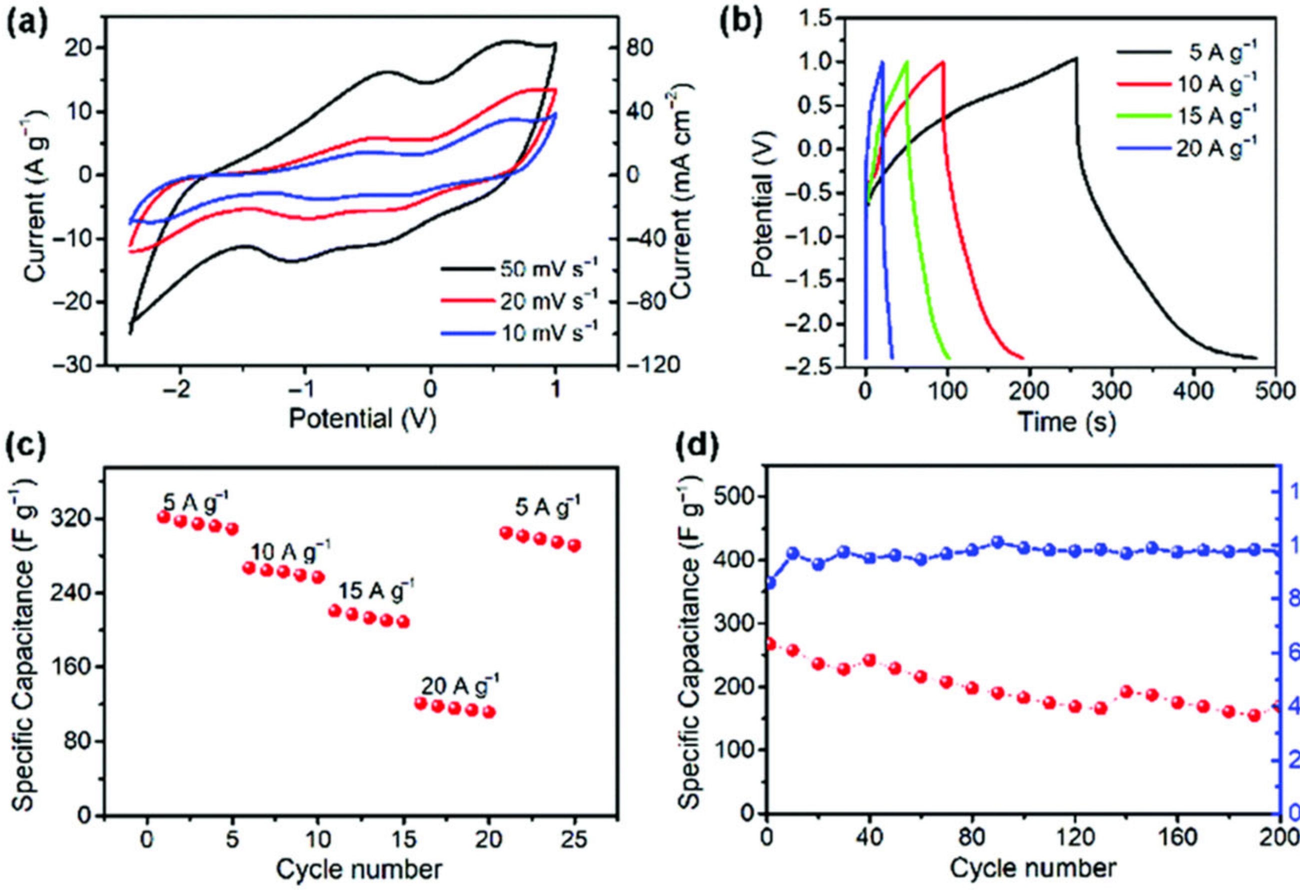

Figure 9. Electrochemical performance with water-in-salt electrolyte, 40 M HCOOK (**a**) CV, (**b**) GCD curves, (**c**) specific capacitance, rate performance, and (**d**) cycle stability at 10 A g^{-1} and Coulombic efficiency [51].

Innovations include lake-water-based semisolid electrolytes, and water-in-polymer systems are other electrolytes, which combine low cost, flexibility, and recyclability with wide electrochemical windows [53]. Relatedly, a recent study explores a water-in-polymer electrolyte using a polyacrylamide network to stabilize reactive water molecules, enabling wide electrochemical windows of 2.7 V (4.1 m, 18 wt% H_2O) and 3.7 V (7.6 m, 11 wt% H_2O)—comparable to highly concentrated 21 m and 40 m electrolytes. A solid-state $Li_4Ti_5O_{12}$//$LiMn_2O_4$ cell demonstrated stable cycling at 16 mg cm^{-2} cathode loading with a lean electrolyte of 7 g Ah^{-1}. Interestingly, the system supports up to 80% LiTFSI salt recovery and polymer regeneration, promoting electrolyte sustainability [53].

The overall electrochemical performance shows extended voltage windows: Water-in-salt electrolytes can expand the electrochemical stability window up to 3–4 V, enabling higher energy densities in aqueous batteries and supercapacitors [51–53,61]. For ionic conductivity and stability, high salt concentrations improve ionic conductivity and suppress unwanted side reactions, such as hydrogen evolution and metal corrosion, enhancing cycling stability and device lifespan [54,62]. In low-temperature operations, some water-in-salt electrolytes remain liquid and functional at temperatures below −10 °C, supporting broader operational ranges [54].

Overall, these systems offer low cost, high ionic conductivity, and superior safety. Water-in-polymer formulations also improve mechanical integrity and prevent leakage. However, their narrow operational temperature ranges and potential instability of electrodes due to water reactivity restrict its vastness. Moreover, the long-term durability of such systems under real-world conditions remains under investigation.

3.3. Biopolymer-Based Solid Electrolytes

Biopolymers such as chitosan, cellulose, alginate, and starch have been explored as sustainable matrices for solid-state electrolytes. When doped with lithium or sodium salts and plasticizers, these materials can exhibit adequate ionic conductivity and mechanical strength. Biopolymer-based solid electrolytes (BSEs) are particularly appealing due to their renewability, biodegradability, and ease of functionalization. Gel polymer electrolytes, often derived from natural polymers like starch, cellulose, or chitosan, provide a solid-state matrix with adequate mechanical strength and improved safety, utilizing plant-based chelating agents (e.g., spinach powder) for synthesizing perovskite electrolytes, which reduces environmental impact compared to conventional chemical synthesis [42].

3.3.1. Cellulose-Based Electrolytes

Cellulose, the most plentiful natural polymer, is a linear polysaccharide that forms the structural backbone of plant cell walls. It is composed of repeating D-glucose units linked by β-1,4-glycosidic bonds. Due to its biodegradable, non-toxic, and hydrophilic properties, cellulose is considered a highly suitable material for developing hydrogel electrolytes, particularly in zinc-ion battery (ZIB) applications [63,64].

Recently, a study demonstrated the introduction of high-concentration kosmotropic ions into a cellulose-based hydrogel electrolyte carboxymethylcellulose (CMC), (Con-CMC) enhances both mechanical strength and ionic conductivity via the salting-out effect (Figure 10). The Con-CMC enables dendrite-free Zn plating/stripping with a high Coulombic efficiency of 99.54% over 500 cycles in Zn/Cu cells and supports high areal capacities up to 25 mAh cm^{-2}. The hydrogel also improves Zn deposition kinetics, suppresses side reactions, and shows excellent flexibility and stability in pouch-type Zn/polyaniline full batteries, offering a promising strategy for high-performance, flexible aqueous zinc-ion batteries [65].

The use of biodegradable cellulose nanoparticles to prepare gel polymer electrolytes for sodium-ion batteries (NIBs) is explored in another study where a combination of rigid cellulose nanocrystals and flexible nanofibers creates a mesoporous structure with high liquid uptake (2985%) and ionic conductivity (2.32 mS cm^{-1}). The resulting electrolyte ensures stable Na plating/stripping up to ±500 μA cm^{-2}. Paired with a sustainable $Na_2Fe_2(SO_4)_3$ cathode, the battery achieved an energy density of 240 Wh kg^{-1} and sustained 69.7 mAh g^{-1} after 50 cycles. It clearly emphasizes the compatibility of cellulose-based materials with sustainable and high-performance NIB technologies [66]. Another study highlighting biosourced polymer electrolyte made from CMC derived from kenaf bast fiber, sodium acetate, and the ionic liquid [Bmim]Cl. Here, at 30 wt% [Bmim]Cl, the system achieves an ionic conductivity of $(4.54 \pm 1.2) \times 10^{-3}$ S cm^{-1} and an electrochemical stability window of ~2.9 V. Ion transport analysis reveals Na^+ transference numbers of 0.129. When tested in a $Na/CH_3COONa–I_2$ cell, it shows an initial capacity of 1.5 mAh with 1.6 V OCV for 200 h. This study indicates the potential of low-cost, plant-derived CMC in environmentally friendly electrolyte systems along with remarkable electrochemical performance [67].

Dendrite formation is among the most common issues that affect the overall efficiency of the battery. To resolve the problem along with corrosion, a composite Zn anode coated with a CMC-based artificial solid electrolyte interface (ASEI) was explored recently. Since CMC-ASEI facilitates fast Zn^{2+} transport via coordination with carboxyl groups and reduces desolvation energy, promoting uniform Zn deposition, the modified Zn anode delivers over 1000 stable cycles at 1 mA cm^{-2} and maintains >98% Coulombic efficiency. A Zn/polyiodide-carbon full cell further enhanced cycling and stability over 2000 cycles at

5 mA cm^{-2}. This work illustrates the dual function of CMC in improving ionic transport and extending the lifetime of aqueous Zn-ion batteries [68].

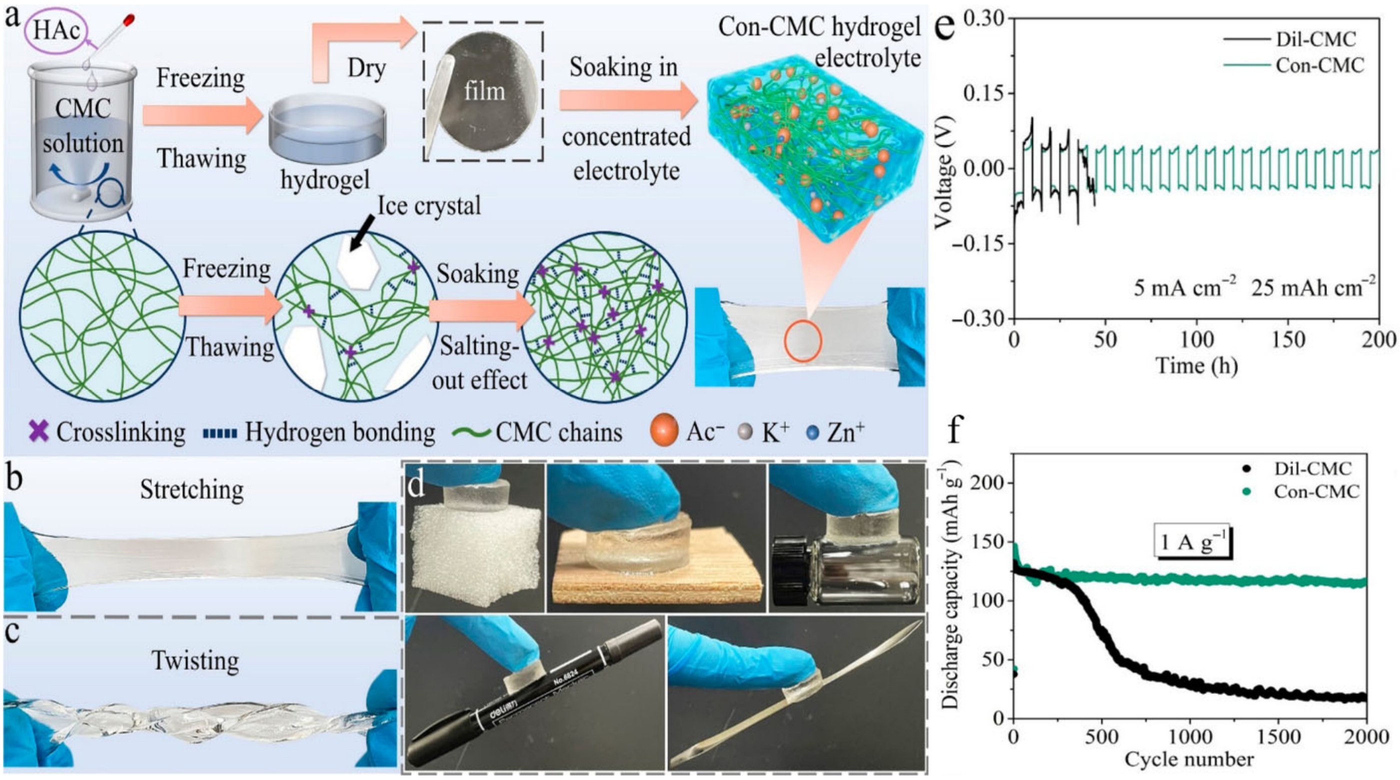

Figure 10. Schematic illustration of biopolymer-based electrolyte (**a**–**d**) (concentrated and diluted carboxymethyl cellulose hydrogel electrolyte) and their stretching, twisting, and adhesive ability. Electrochemical cycling performance of (**e**) Zn/Zn at 5 mA cm^{-2} and 25 mAh cm^{-2} and (**f**) of Zn/PANI with 2 mg of cm^{-2} PANI/CNT [65]. Reprinted with permission from [65]. Copyright 2023 American Chemical Society.

3.3.2. Chitosan-Based Electrolytes

Chitin, a naturally abundant polysaccharide sourced from fungal cell walls and arthropod exoskeletons, is composed of repeating N-acetyl-D-glucosamine units linked by β-(1→4) bonds. Its derivative, chitosan, formed through partial deacetylation (~50%), is a water-soluble copolymer of D-glucosamine and N-acetyl-D-glucosamine. Due to its biodegradability, non-toxicity, and film-forming ability, chitosan is increasingly explored as a sustainable polymer electrolyte in green battery systems, particularly for zinc-ion and sodium-ion technologies [69,70].

Recently, a biopolymeric hydrogel electrolyte (CPZ-H) based on natural chitosan (CS) and polyaspartic acid (PASP) was developed to be used in aqueous zinc-ion batteries (AZIBs) (Figure 11). The CPZ-H hydrogel forms a double-network structure that effectively suppresses zinc dendrite formation and side reactions like hydrogen evolution. Compared to bare Zn and CZ-H electrolytes, the CPZ-H significantly enhanced electrochemical performance. It extended the Zn anode lifespan from 190 h to 2200 h at 10 mA cm^{-2} with a reduced voltage hysteresis of 96 mV. Moreover, the Zn/CPZ-H cell maintained a high Coulombic efficiency of 99.6% over 850 cycles and a low plating/stripping hysteresis of 72 mV. It also showed a lower corrosion current (0.27 mA cm^{-2}) and interfacial resistance (316 Ω), confirming its strong anti-corrosion ability and fast charge transfer. Overall, this study highlights the critical synergistic role of CS and PASP in enhancing the cycling stability, reversibility, and practical viability of Zn anodes in eco-friendly energy storage systems [71].

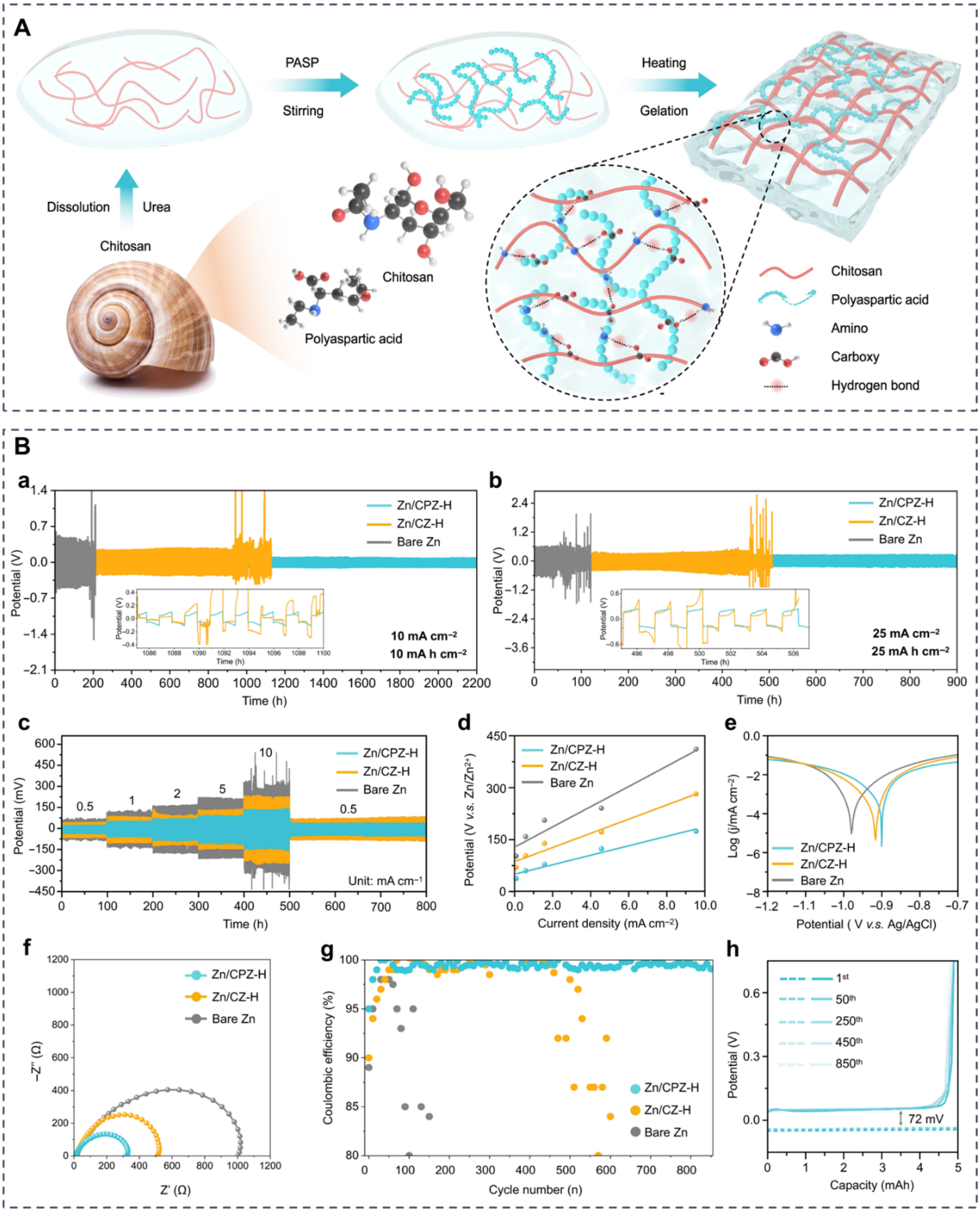

Figure 11. (**A**) Schematic illustration and (**B**) electrochemical performance of chitosan-based electrolyte for Zn-ion battery showing (**a**) voltage profile at current densities of 10 mA cm^{-2} and (**b**) 25 mA cm^{-2}, (**c**) rate performance at current densities from 0.5 to 10 mA cm^{-2}, (**d**) exchange current density, (**e**) Tafel curves, (**f**) Nyquist plots, and (**g**) coulombic efficiency and (**h**) voltage profile at 10 mA cm^{-2} of Zn/CPZ-H anode [71].

3.3.3. Other Biopolymer-Based Electrolytes

In the category of biopolymers, different biopolymers, such as alginates, starch, pectin, lignin, natural gums, carrageenan, gelatin, etc., have been explored so far as green and sustainable electrolytes in battery applications.

Alginate is a naturally occurring polysaccharide extracted from the cell walls of brown seaweed. It is composed of linear chains of β-D-mannuronic acid and α-L-guluronic acid units, arranged in block structures. Known for its excellent biocompatibility and ability to form hydrogels, alginate is widely explored in biomedical and energy applications. Alginate-based material can serve as a green alternative in battery systems, particularly as an eco-friendly binder or electrolyte [72,73]. A recent study demonstrates that sodium alginate (SA), despite being water-soluble, can be effectively used as a binder in aqueous zinc-ion batteries by cross-linking with Zn^{2+} ions to form a water-insoluble, mechanically robust network. When used in Zn||$LiFePO_4$ cells, the SA binder enables a high-capacity retention of 93.7% and nearly 100% Coulombic efficiency after 100 cycles at 0.2 C, outperforming the conventional PVDF binder. The SA-based electrode also exhibits lower redox polarization, improved ion diffusion, and enhanced electrochemical kinetics. This environmentally friendly approach eliminates the need for toxic solvents like NMP, offering a greener alternative for battery fabrication [74].

A brief chemical description of the biopolymers [75] involved in the fabrication of battery components as mentioned in Table 4 is as follows:

Table 4. Biopolymer-based electrolytes and binder for green batteries.

Biopolymer	Material Type	Battery Type	Key Electrochemical Performance	Ref.
Chitosan	Binder	Li-ion	Discharge capacity: 159.4 mAh/g; Capacity retention: 98.38%	[76]
Crosslinked Chitosan	Binder	Li-ion	Initial capacity: 133 mAh/g; Final capacity after 15 cycles: ~40 mAh/g	[77]
Carboxymethyl cellulose-epichlorohydrin	Binder	Li-ion	Specific capacity of 1054.2 mAh/g at 0.2 C following 200 cycles, capacity retention is 65.6%	[78]
Chitosan-Zn	Electrolyte	Zn-metal battery	Coulombic efficiency: 99.7%; >1000 cycles at 50 mA/cm^2; High-rate performance up to 20 C	[79]
Carboxymethyl chitosan	Electrolyte	Zn-air	Impressive discharge capacity 805.3 mAh g^{-1}, long cycle life 118 h, power density 91.04 mW cm^{-2}	[80]
Carboxymethyl chitosan-poly(ethylene oxide)	Electrolyte	Li-metal	High ionic conductivity and interface stability, long-term cycling life of 2500 h, 135.6 mAh/g capacity retention of 83.5% after 400 cycles at 0.2 C.	[81]
Glycerolized Chitosan	Electrolyte	EDLC (Supercapacitor)	Specific capacitance: 105.5 F/g (1st cycle) to 136.8 F/g (700th cycle); Energy density: up to 19.1 Wh/kg	[82]
Crosslinked Chitosan	Binder	Li-ion	Initial capacity: 2782 mAh/g; Capacity after 100 cycles: 1969 mAh/g at 500 mA/g	[83]
Chitosan	Binder	Li-ion	Discharge capacity at 10 C: ~80 mAh/g; Superior to PVdF (~55 mAh/g)	[84]
Chitosan	Modifier	Lead–Acid	First discharge capacity: 4257 mAh; After 500 cycles: 196 mAh/g	[85]
Carrageenan	Binder	Li-S	Capacity drop of ~37% after 50 cycles at 0.2–2 C	[86]

Table 4. *Cont.*

Biopolymer	Material Type	Battery Type	Key Electrochemical Performance	Ref.
Carboxymethyl Chitosan	Electrolyte	Zn-iodine	Over 28,000 cycles with narrow voltage window of 0.23 V	[87]
Carboxymethylcellulose-Chitosan	Electrolyte	Zn-Air	Power density of 117 mW cm^{-2} and a specific capacitance of 1899 mAh g^{-1}.	[88]
Gelatin/Carboxymethyl chitosan	Electrolyte	Zn-ion	High specific capacity and superior cyclic performance (2200 h at 0.1 A g^{-1}) without the formation of zinc dendrites, high recycling rate (above 80%)	[89]
Poly(ε-caprolactone)-chitosan	Electrolyte	Li-metal	Excellent stability and compatibility, ionic conductivity of 7.7×10^{-4} S cm^{-1}, and long cycling for over 1850 h	[90]
Xanthan Gum	Binder	Li-ion	Improved electrode stability and capacity retention	
Pectin	Electrolyte	Li-ion	Enhanced ion transport properties with $[BMIM][PF_6]$ ionic liquid	[91]
Pectin	Electrolyte	Supercapacitor	Specific capacitance of 879 mF cm^{-2} at 15 mA cm^{-2}	[92]
Carrageenan	Binder	Li-S	Enhanced stability and capacity retention compared to PVDF binder	[86]
Alginate	Electrolyte	Zn-ion	SiO_2-alginate-based gel polymer electrolytes with enhanced performance	[93]
Sodium Alginate	Electrolyte	Lead–Acid	Discharge capacity of 138 µAh cm^{-2} at 0.55 mA cm^{-2}; 89% capacity retention after 500 cycles	[94]
Sulfated Alginate	Binder	Li-ion	Enhanced performance for high-voltage $LiNi_{0.5}Mn_{1.5}O_4$ electrodes	[95]
Sodium Alginate–Pectin	Electrolyte	Li-ion	Ionic conductivity of 1.264×10^{-7} S cm^{-1}; breakdown voltage at 0.66 V	[96]
Potato starch (maleic anhydride esterified	Binder	Li-ion	Cycling performance capacity of 1950 mAh/g.	[97]
Keratin–Phosphoric acid	Biosorbent	Li-ion recovery	High separation factors ranging from 11.3 to 22.0	[98]
Silk Fibroin	Binder	Zn-ion	Coulombic efficiency of 99.04% under a large plating capacity for 800 cycles, full cells 20,000 cycles, >80% capacity retention at 5 and 10 A g^{-1}	[99]
Collagen–chitosan	Separator	Li-ion	Ionic conductivity is >0.49 mS·cm^{-1}, Discharge capacity 140 mAh·g^{-1} at C/8 rate,	[100]
Chitosan–Avocado starch	Electrolyte	Zn-air	Improved conductivity value of 0.61 S·cm^{-1}, specific capacity value 1618 mA h·g^{-1}	[101]
Carboxymethylcellulose	Binder	Na-Ion	Capacity retention of 90% after 300 cycles, electrode capacities of 850 and 425 mAh g^{-1} at charge–discharge rates of 20 and 2000 mA g^{-1}	[102]
Agar-Agar	Electrolyte	Li-Ion	High ionic conductivity, $3.12 \pm 0.11 \times 10^{-2}$ S/cm, 20 mol% of AA:80 mol% of LiCl	[103]

Table 4. *Cont.*

Biopolymer	Material Type	Battery Type	Key Electrochemical Performance	Ref.
Cellulose (Cladophora)	Separator	Lithium-ion	Ionic conductivity: 0.4 mS/cm; 99.5% capacity retention after 50 cycles at 0.2 C	[104]
Cellulose (Bacterial)/ZIF-67	Separator	Lithium-ion	Ionic conductivity: 0.096 mS cm^{-1}, discharge capacity retention 91.41% after 100 cycles (0.2 C), discharge capacity 156 mAh g^{-1}	[105]
Modified Cellulose (M-CDA/PEO)	Separator	Lithium-ion	Ionic conductivity: 2.83 mS/cm; 170.3 mAh/g after 100 cycles at 0.5 C; no shrinkage at 200 °C	[106]
Chitosan Nanofiber	Separator	Lithium-ion	Electrolyte uptake: 281%; superior thermal stability; higher discharge capacity over 100 cycles	[107]
Carrageenan (Iota)	Separator	Lithium-ion	Ionic conductivity: 1.34 mS/cm; discharge capacity: 145 mAh/g at C/10; 25 mAh/g at 1 C	[108]
Alginate (Calcium Alginate)	Separator	Lithium-ion	Ionic conductivity: 2.80 mS/cm at 65 °C; lithium-ion transference number: 0.55; over 1000 cycles at 60 °C with 97% CE	[109]
Guar Gum (Hydroxypropyl)	Separator	Lithium-ion	High thermal stability; no dimensional shrinkage at elevated temperatures; good electrochemical stability	[110]
Silk Fibroin (Lyophilized)	Separator	Lithium-ion	Ionic conductivity: 1.00 mS/cm; discharge capacity: 126 mAh/g at C/2; 99 mAh/g at 2 C; 72% capacity retention over 50 cycles	[111]
Cellulose (Trilayer with $BaTiO_3$)	Separator	Sodium-ion	Energy density: ~376 Wh/kg; 62% capacity retention over 240 cycles; nearly 100% Coulombic efficiency	[112]
Cellulose (Composite with PE)	Separator	Lithium-metal	Improved Coulombic efficiency; enhanced lithium deposition and stripping performance	[113]

Gelatin: Gelatin is a protein-based biopolymer derived from the partial hydrolysis of collagen, consisting of polypeptide chains primarily composed of glycine, proline, and hydroxyproline. It lacks a defined repeating unit but forms triple helices and hydrogen-bonded networks, making it suitable for film formation and ionic transport in battery systems.

Pectin: Pectin is a complex anionic polysaccharide mainly composed of α-(1→4)-linked D-galacturonic acid units with variable degrees of methyl esterification. Its carboxylic groups and branched neutral sugar side chains contribute to its gelation and metal-ion binding capabilities, beneficial for use in green battery electrolytes and binders.

Keratin: Keratin is a high-sulfur fibrous protein with α-helix or β-sheet secondary structures, stabilized by extensive disulfide bonds (-S-S-) between cysteine residues. This cross-linked structure imparts high mechanical strength and stability, making keratin suitable for binder or scaffold roles in biodegradable battery components.

Natural gums include xanthan gum, guar gum, and gum arabic. Xanthan Gum: A microbial polysaccharide composed of a cellulose-like backbone of β-(1→4)-D-glucose units with trisaccharide side chains of mannose–glucuronic acid–mannose attached at every second glucose unit. Its branched structure and charged groups enable high water retention and ionic mobility.

Guar Gum: A galactomannan consisting of a linear backbone of β-(1→4)-linked D-mannopyranose units with α-(1→6)-linked D-galactopyranose side branches. The high galactose content provides water solubility and rheological properties valuable in electrolyte design.

Gum Arabic: A highly branched arabinogalactan polysaccharide with a β-(1→3)-galactopyranosyl backbone and side chains connected through β-(1→6) linkages, containing rhamnose, arabinose, and glucuronic acid. Its structural complexity supports ion coordination and film formation for battery interfaces.

Overall, BSEs are environmentally friendly, non-toxic, and sourced from abundant natural resources. They also offer flexibility in membrane design and the potential for safe, leak-proof battery operation. Conversely, a major limitation is their relatively low ionic conductivity at room temperature compared to synthetic solid electrolytes. Mechanical reinforcement and hybridization with inorganic fillers are often required to enhance the overall battery performance.

3.4. Additive-Free and Renewable Electrolytes

The push towards complete sustainability has led to the exploration of additive-free electrolyte systems based solely on renewable and bio-derived constituents. These include naturally occurring salts, organic acids, and plant-derived solvents that require minimal processing. Such systems eliminate the need for harmful additives, fluorinated salts, or synthetic stabilizers, aligning with cradle-to-cradle design philosophies [114]. These systems represent the highest level of green chemistry, with minimal environmental footprint and low toxicity. They also facilitate easy recycling and end-of-life management of battery components. However, while promising, additive-free systems are still in the early stages of development, their electrochemical performance, particularly in terms of conductivity, voltage stability, and compatibility with electrodes, remains a challenge [115].

For instance, the performance of green organic Na-ion batteries is enhanced by addressing key limitations such as poor electrochemical kinetics, unstable interfaces, and high solubility of organic electrodes. By applying ultrathin (Å-level) metal oxide coatings (Al_2O_3, ZnO, TiO_2) via atomic layer deposition (ALD) onto perylene-3,4,9,10-tetracarboxylicacid dianhydride (PTCD) electrodes, the researchers achieved significantly improved interfacial stability and electrochemical performance. The coated electrodes demonstrated enhanced ion diffusion, a high rate capability of 71 C, and cycling stability of 89% after 500 cycles, outperforming uncoated counterparts. The study also highlights the critical role of chemical stability of the coatings in redox behavior and electrode longevity. Unlike conventional coating methods, ALD enables uniform and low-temperature deposition suitable for thermally sensitive organic materials. This strategy marks a promising step toward sustainable, high-performance organic SIBs comparable to inorganic systems [16].

Overall advantages of green electrolytes include reduced environmental footprint, improved safety due to non-flammability, and potential for biodegradability and recycling. However, limitations include lower ionic conductivity in some systems compared to traditional electrolytes, possible incompatibility with existing electrode materials, and challenges in large-scale production and long-term stability. Overall, sustainable and efficient electrolytes form a cornerstone of green battery development. While ionic liquids and DESs offer high performance and stability, water-based and biopolymer-based electrolytes prioritize safety and environmental compatibility. Additive-free systems, though nascent, represent the future of truly sustainable energy storage. Continued research is essential to overcome the existing limitations and to enable widespread adoption of these green alternatives in commercial battery technologies.

4. Green Separators for Sustainable Batteries

Battery separators are critical components that prevent physical contact between the electrodes while allowing ionic transport. Sustainable separator development focuses on replacing petroleum-derived, non-degradable polymers like polypropylene (PP) and polyethylene (PE) with materials that are biodegradable, bio-sourced, and thermally stable. The sustainable strategies for separators can be inferred by using biodegradable and renewable materials, employing natural polymers or biomass-derived materials as separator substrates to ensure biodegradability and reduce reliance on petrochemicals [43,56]. Secondly, the green processing techniques, utilizing solvent-free or low-toxicity solvent processes, and minimizing energy consumption during synthesis and fabrication [56,116]. Thirdly, integration with green electrolytes is achieved by designing separators that are compatible with natural solvent-based electrolytes to enhance overall battery sustainability [43].

4.1. Cellulose and Chitosan-Derived Separators

Similar to the electrolyte membranes, biopolymer-based separators are fabricated for green and sustainable batteries. Cellulose-based separators, derived from abundant natural resources, offer high porosity, thermal stability, and excellent electrolyte wettability. Chitosan-derived membranes are another biopolymer-based alternative with inherent antibacterial properties and film-forming capability, often used in combination with inorganic fillers like SiO_2 or $BaTiO_3$ to enhance performance. Bio-derived and natural polymer separators such as alginate, starch, and silk fibroin have also shown potential due to their renewability and low environmental impact [117,118]. For instance, a green regenerative cellulose (RC)/sodium alginate (SA) gel electrolyte membrane is recently developed via a sol-gel method, featuring a Zn^{2+}-centered dual crosslinked network. The structure offers uniform porosity and abundant polar groups, enhancing Zn^{2+} transport. The membrane delivers a high ionic conductivity of 6.30 $mS \cdot cm^{-1}$ and a Zn^{2+} transference number of 0.66. In Zn//V_2O_5 full-cells, it achieves a reversible capacity of 159 $mAh \cdot g^{-1}$ and retains 99.2% of capacity after 24 h of rest. Compared to glass fiber separators, the RC-SA membrane significantly improves coulombic efficiency and cycling stability in Zn//Cu and Zn//Zn cells [118].

A sustainable strategy utilizes chitosan micro/nanofiber membranes for lithium-ion battery separators, with tunable fiber diameters to control pore size and properties. Chitosan nanofiber separators (CSNFs) achieve high electrolyte uptake (281%), strong thermal stability, and enhanced electrochemical performance compared to conventional Celgard2325. In $LiFePO_4$/Li half-cells, CSNFs deliver greater discharge capacity and rate capability across 100 cycles, supporting their eco-friendly and bio-based potential. Among these, CSNF-M demonstrates the highest ionic conductivity and discharge capacity of 168 mAh g^{-1}, outperforming Celgard's 148 mAh g^{-1}. Superior rate capability and reversible behavior remain consistent across varying current densities. Capacity retention reaches 95.3% after 100 cycles at 0.5 C, attributed to effective Li^+ migration driven by interactions with amino groups in the chitosan matrix. These findings emphasize efficacy of chitosan as a green alternative to synthetic battery separators (Figure 12) [107].

Advantages of these sustainable separators include biodegradability, low cost, safer thermal behavior, and reduced environmental impact. However, challenges remain in achieving the necessary mechanical robustness, electrochemical stability, and scalability required for industrial application.

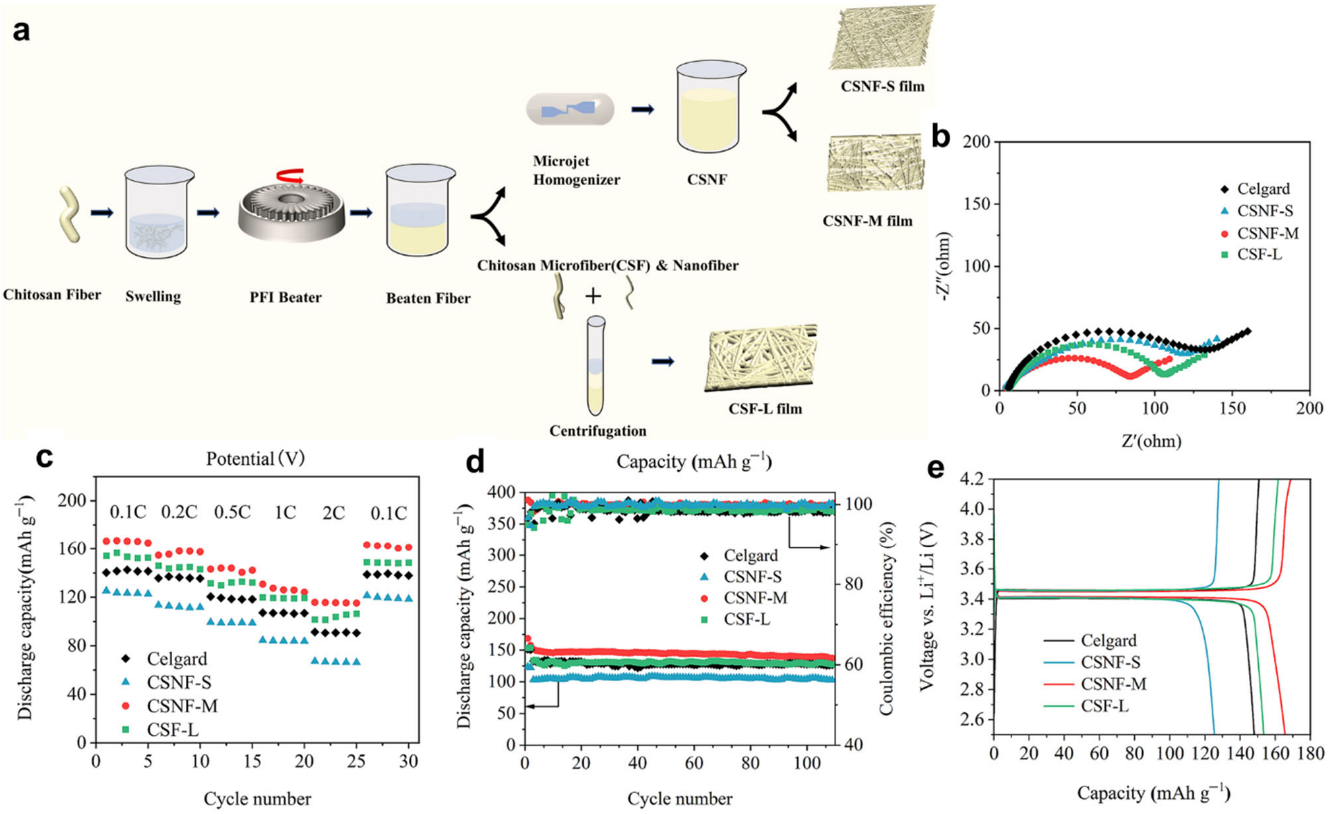

Figure 12. (**a**) Schematic illustration of chitosan-based separator through mechanical-refining process for Li-ion battery. Electrochemical performance showing (**b**) EIS, (**c**) rate performance, (**d**) cycle performance at 0.1 C and 0.5 C, and (**e**) first charge–discharge of $LiFePO_4$/separator/Li batteries [107].

4.2. Advanced Nanostructured Membranes

Advanced nanostructured membranes have emerged as promising separators in battery technologies, offering enhanced thermal stability, ionic conductivity, and mechanical strength compared to conventional polyolefin-based separators [119,120]. These membranes, often fabricated using techniques like electrospinning, incorporate materials such as inorganic nanofibers, metal–organic frameworks, or phase inversion techniques, and ceramic nanoparticles to improve battery performance and safety. Functionalization of biopolymers with nanomaterials or surface treatments can enhance their ionic conductivity and mechanical integrity [119,120]. Recent advancements in nanostructured membranes are concisely described in Table 5.

Table 5. Advanced nanostructured membranes as green and sustainable separators in batteries.

Nanostructured Membrane Type	Battery Type	Key Electrochemical Performance	Ref.
Titania nanofiber composite membrane	Li-ion	Enhanced wettability and thermal stability; lower interfacial resistance; higher ionic conductivity leading to improved discharge capacity and cycling performance.	[121]
Aramid nanofiber (ANF) membrane	Li-ion	Superior strength and modulus; excellent thermal stability; improved safety and reliability in battery operations.	[122]

Table 5. Cont.

Nanostructured Membrane Type	Battery Type	Key Electrochemical Performance	Ref.
Boron nitride nanotube-based separator	Li-ion	High thermal conductivity; chemical stability; improved cycle life and capacity retention in lithium–sulfur batteries.	[123]
Nanodiamond-enhanced nanofiber separator	Li-ion	Improved thermal stability and mechanical strength; enhanced electrolyte wettability; better cycling performance.	[124]
Polyimide aerogel separator	Li-ion	High porosity (78.35%); electrolyte absorption (321.66%); maintained capacity of 118 mAh/g after 1000 cycles at 1 C; stable performance at 90 °C over 300 cycles.	[125]
TiO_2/PVDF-TrFE composite membrane	Li-ion	High ionic conductivity and lithium transference number; discharge capacity retention of 83% at 2 C after 100 cycles; improved rate capability.	[126]
Electrospun PVDF nanofiber separator	Li-ion	Enhanced charge storage capacity; improved cycling durability; reduced polarization voltage difference (η = 0.13 V) compared to PP separator (η = 0.32 V).	[127]
Boehmite/polyacrylonitrile (PAN) composite	Li-ion	Ionic conductivity up to 2.85 mS/cm with 30 wt% boehmite; improved mechanical strength; better electrolyte uptake compared to pure PAN and PP membranes.	[128]
Core-shell nanofiber with flame retardants	Li-ion	Incorporation of over 60 wt% flame retardants; enhanced safety without compromising cycling stability or rate performance; potential for coating on commercial separators.	[129]
Carboxylated cellulose nanofibers	Li-ion	Hierarchical porous TOCN structure; improved high-temperature 94.5% of discharge capacity maintained after 100 cycles at 1 C	[130]

5. Overview of Advancements in Latest Sustainable Key Battery Technologies

5.1. Green and Sustainable Na-Ion Batteries

The future economic viability of Na-ion batteries compared to Li-ion batteries should be considered, especially in light of the rising costs and supply challenges associated with critical Li-ion battery materials like lithium, graphite, and nickel. Using extensive scenario modeling, the research finds that with strong advancements in Na-ion battery technology and targeted R&D, certain pathways may allow SIBs to become cost-competitive by the 2030s. However, achieving this depends heavily on improving energy density to reduce material usage and on stabilizing supply chains. In the short term, competing with the lowest-cost Li-ion batteries remains difficult for Na-ion batteries [131].

All-solid-state sodium batteries offer a safer and more sustainable alternative to lithium-based liquid systems, with promising potential for cost-effective grid storage. While ceramic sodium-ion conductors provide high ionic conductivity and wide electrochemical stability, their brittleness limits flexibility and miniaturization. On the other hand, polymer electrolytes are more flexible but often exhibit lower sodium-ion conductivity, limited stability, and reduced transference numbers. Their performance is closely linked to the polymer's glass transition temperature, which governs ion mobility. Although single-ion polymers with ideal transference numbers exist, enhancing their electrochemical stability remains a key challenge [132].

As far as the importance of biopolymeric material in green batteries are concerned, CMC is the most explored biopolymer, exhibiting balanced conductivity, flexibility, and environmental tolerance in ceramic-rich composite electrolytes. This indicates a mechanically robust composite solid electrolyte that was developed using 92.5 wt% Na_3SbS_4 and 7.5 wt% CMC. The CMC acts as both a binder and moisture-resistant encapsulating layer, maintaining high ionic conductivity akin to ceramic Na_3SbS_4. The composite enables over 5× improvement in Na^+ conductance due to reduced thickness and shows enhanced electrochemical stability. It also demonstrates improved cycling performance in solid-state sodium batteries (Figure 13) [133].

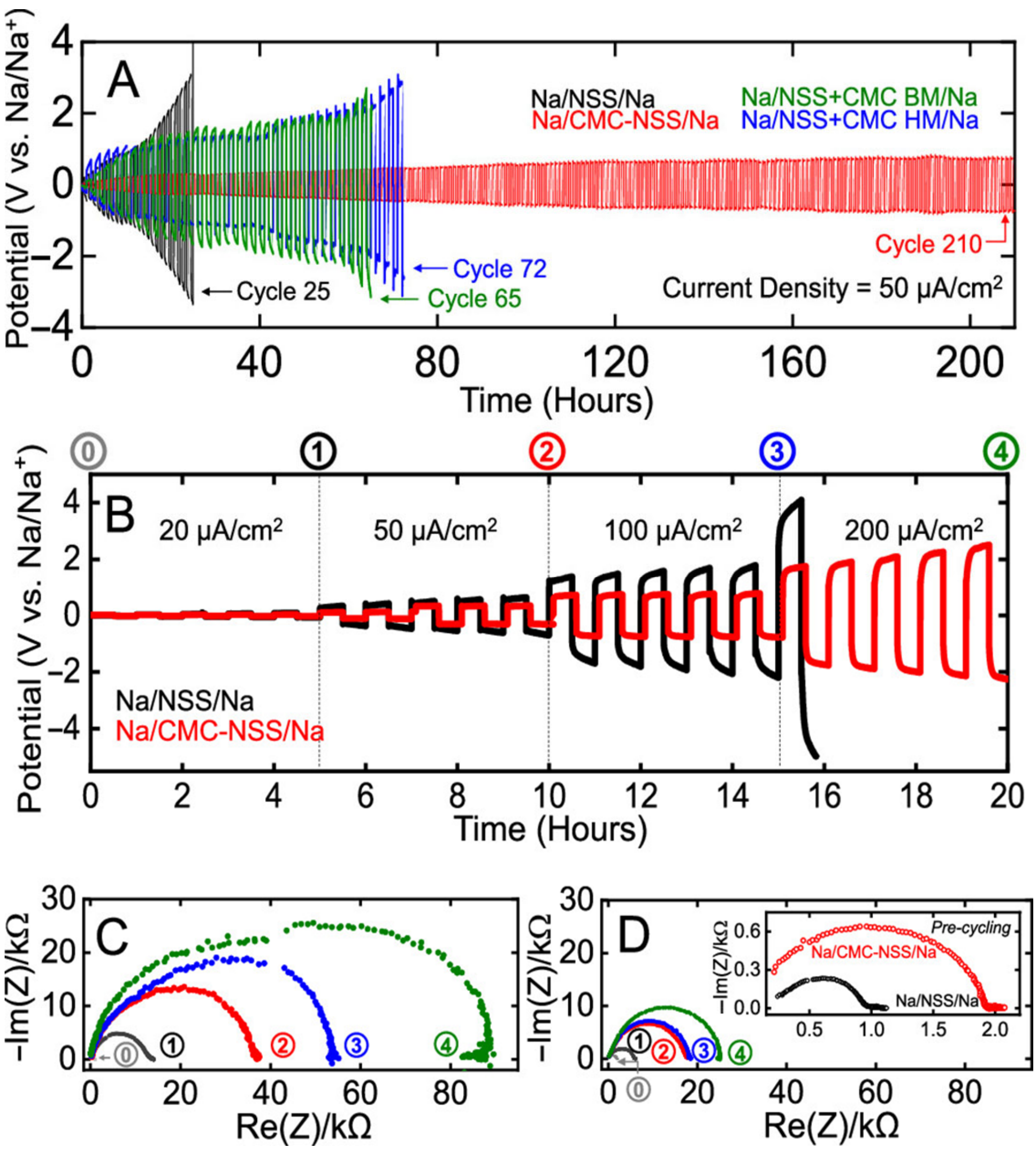

Figure 13. Electrochemical performance of green electrolyte-based Na-ion battery, showing (**A**) GCD, (**B**) rate performance, (**C**) EIS curves, and (**D**) charge–discharge cycles at each current density. Reprinted with permission from [133]. Copyright 2024 American Chemical Society.

5.2. Green and Sustainable Zn-Ion/Air Batteries

Rechargeable zinc-ion batteries (ZIBs) have gained attention as a viable alternative to lithium-ion batteries due to zinc's natural abundance, low cost, and high safety, aligning with the growing need for sustainable energy solutions [134]. A key component in ZIBs is the electrolyte, which critically influences the battery's overall electrochemical performance. Typically, ZIBs consist of a Zn^{2+}-intercalating cathode, a zinc metal anode, a separator, and an aqueous electrolyte. However, when alkaline electrolytes are used, significant challenges arise, such as the formation of zinc dendrites and unwanted by-products like ZnO and $Zn(OH)_2$ during cycling. These issues lead to low Coulombic efficiency and rapid capacity degradation. Interestingly, adjusting the pH of the electrolyte can mitigate the formation of such by-products. While neutral or mildly acidic aqueous electrolytes—such as those based on $Zn(CF_3SO_3)_2$ or $ZnSO_4$—are more compatible with Zn anodes, they still face limitations like limited Coulombic efficiency and a narrow electrochemical stability window [135].

Recently, a $ZnCl_2$–acetamide DES-based aqueous electrolyte, as a green and cost-effective solution for a sustainable Zn-ion battery, was developed, enhanced with water to form a "water-in-DES" system. By modulating the Zn^{2+} solvation structure, the added water effectively lowers the Zn^{2+} desolvation energy barrier, facilitating uniform Zn nucleation and significantly improving the electrochemical performance of the Zn anode. The optimized electrolyte composition ($ZnCl_2$:acetamide:H_2O = 1:3:1) achieved ≈98% Coulombic efficiency over 1000 cycles. Furthermore, a full cell comprising a Zn anode and phenazine cathode demonstrated excellent cycling stability, retaining 85.7% capacity after 10,000 cycles (Figure 14) [135].

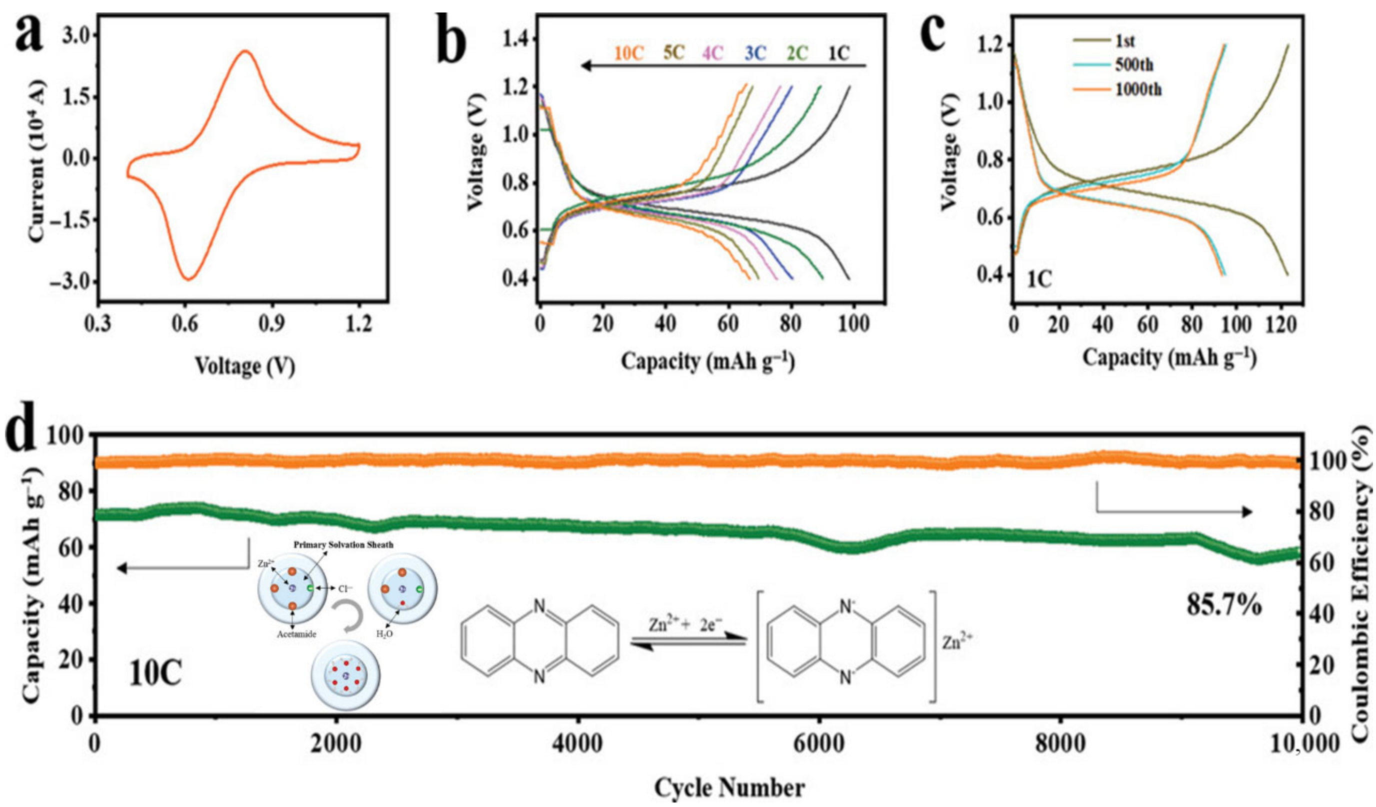

Figure 14. Electrochemical performance of green electrolyte-based Zn-ion battery, showing (**a**) CV curves, (**b**) charge-discharge in ZES-1, and (**c**) Zn//ZES-1//PNZ (**d**) Cycle performance capacity retention and Coulombic efficiency [135].

5.3. Green and Sustainable Aluminum-Ion Batteries

Among other metal green batteries, aluminum-ion batteries (AIBs) are gaining traction as a sustainable energy storage solution due to aluminum's high theoretical capacity, natural abundance, non-toxicity, and safety. While ionic liquids are commonly used as electrolytes in AIBs, deep eutectic solvents (DESs) are emerging as eco-friendly and cost-effective alternatives. However, their application remains in early stages due to limited electrochemical stability. DES-based AIBs show promise by enabling reversible aluminum plating and stripping through active ionic species like $Al_2Cl_7^-$ and $AlCl_4^-$. Unlike lithium-ion batteries, where the electrolyte solely serves as an ion transport medium, AIB electrolytes also act as a source of redox-active species, facilitating both ion transport and electrode reactions. Continued research into optimizing DES composition and improving stability is essential for advancing AIB performance and realizing their potential as a green and sustainable battery technology [136].

5.4. Green and Conventional Battery Comparative Electrochemical Performance

The transition from conventional to green battery technologies has sparked significant interest due to growing environmental concerns and the need for sustainable energy storage solutions.

Recently a comparative study between conventional NMP/PVDF-based electrodes and water-processed green electrodes (utilizing NCM523 cathodes and graphite anodes) demonstrates that water-based electrodes can achieve electrochemical performance comparable to their conventional counterparts (Figure 15). Both systems exhibited excellent rate capability up to a 1 C discharge rate, with nearly identical capacities when normalized to C/20. At higher rates, the water-based electrodes showed slightly reduced performance and increased variability, likely due to differences in binder coverage rather than material degradation. In terms of cycle life, water-processed cells, despite being subjected to higher charge–discharge rates, showed favorable long-term performance. Although they initially experienced a faster capacity fade, this trend stabilized after approximately 50 cycles. Notably, both types of electrodes retained similar capacity levels by the 668th cycle, and water-based cells maintained 80% of their initial capacity after 864 cycles. Even under accelerated testing conditions, the water-processed electrodes demonstrated resilience and were projected to outperform NMP-based cells over 1000 cycles [11].

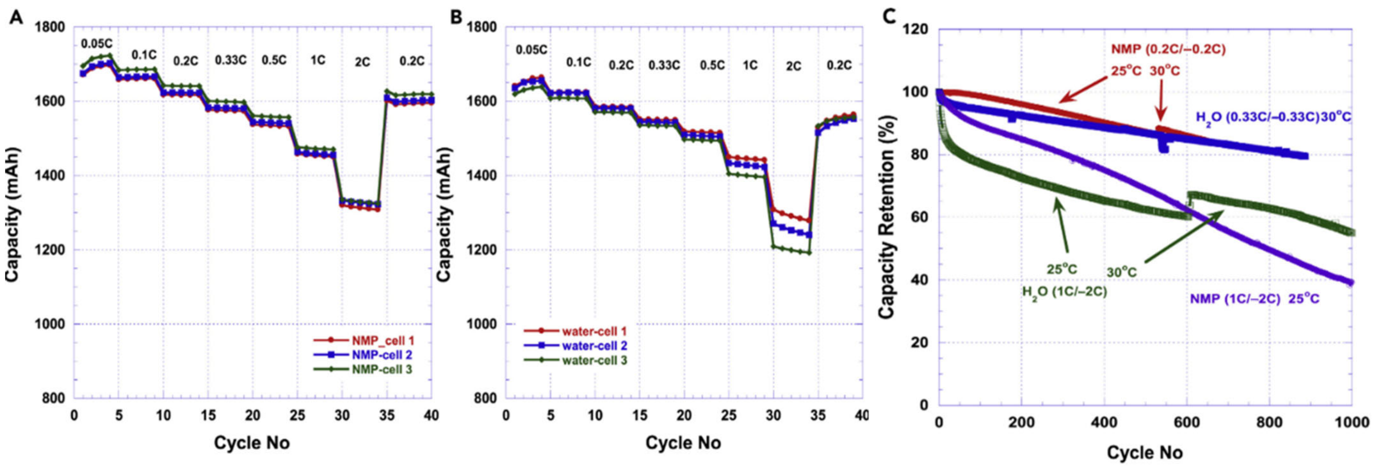

Figure 15. Comparison of electrochemical performance of conventional and water-based green electrodes: Rate capability (**A**) of NMP/PVDF cells and (**B**) water-processed cells NMC532 (composition NMC532/Denka Carbon Black/Carboxymethylated cellulose, CMC/PVDF Latex in 90/5/1/4 wt%), and (**C**) capacity retention or cycle life [11].

Conventional batteries, while offering high energy density and well-established performance metrics, often rely on toxic materials and non-renewable resources. In contrast, green batteries incorporate biodegradable, bio-derived, or non-toxic components—such as biopolymer-based electrolytes, binders, or separators—without severely compromising electrochemical performance. Comparative studies reveal that many green battery systems now achieve comparable ionic conductivity, capacity retention, and cycling stability, highlighting their potential as eco-friendly alternatives for future energy storage [137].

6. Environment Assessment

6.1. Biodegradability Test

Biodegradability testing is an essential component of sustainable battery development, as it allows for environmental impact and risk assessments that align with circular economy goals. Traditional battery components often pose environmental hazards due to toxic residues and complex recycling processes. In contrast, biodegradable materials minimize long-term ecological risks by naturally decomposing into non-toxic by-products. For instance, chitosan-based CPZ-H electrolyte, composed primarily of chitosan (CS) and polyaspartic acid (PASP), exemplifies this concept by offering full biodegradability after its service life (Figure 16). Laboratory experiments confirmed that CPZ-H degrades efficiently when exposed to *Bacillus* cultures, nearly disappearing within 90 days under controlled temperature and humidity. Microscopic observations revealed progressive bacterial colonization and decomposition, indicating nutrient assimilation by microbes. The degraded products, being nutrient-rich, can be safely released into the environment, effectively transforming waste into bioavailable fertilizer [71]. Such innovative study underscores the potential of integrating biodegradable biopolymers into battery systems, offering a greener pathway for post-use disposal and significantly reducing environmental burden. In another study, an anisotropic separator consisting of nanofibrillated cellulose (NFC) and chitosan, the V-NFC-CS separator, demonstrates superior performance with a lifespan of 1000 h at 50 °C, outperforming other separators. Biodegradability tests reveal that, unlike the glass fiber (GF) separator, which remained intact after 60 days in soil, the V-NFC-CS separator fully decomposes, highlighting its eco-friendly nature. This rapid degradation is attributed to the rich microbial environment in soil, which accelerates the breakdown of biomass-based materials. Importantly, the degradation occurs in soil, not in the electrolyte, ensuring stability during battery operation [138].

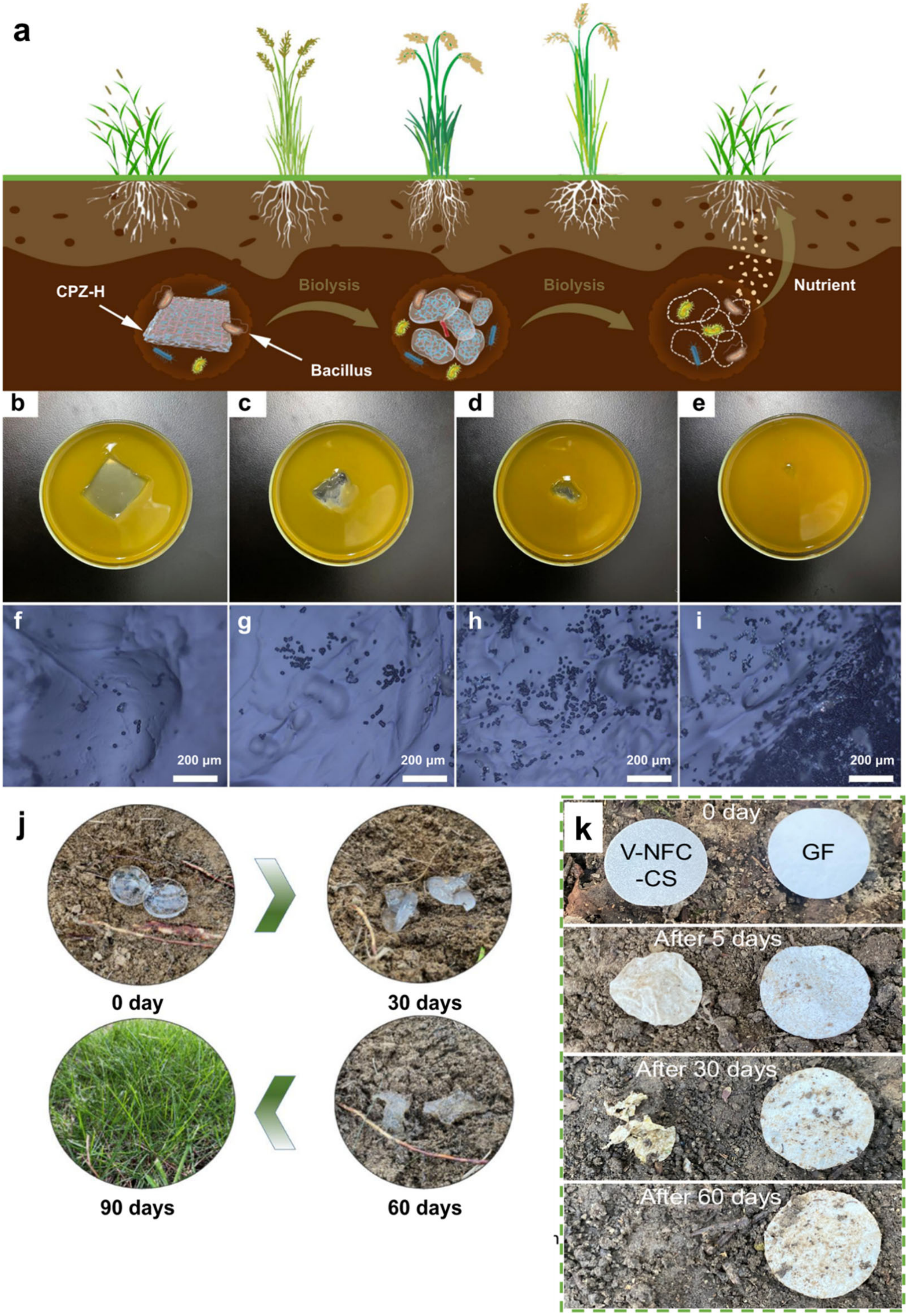

Figure 16. Biodegradability test for chitosan-based (**a**–**j**) CPZ-H electrolyte, showing decomposition process of electrolyte in *Bacillus* culture media [71] and (**k**) V-NFC-CS and GF separators [138] for green Zn-ion battery after being embedded into soil at various time intervals.

6.2. Recyclability

Repurposing used Li-ion batteries, especially from electric vehicles (EVs), for secondary applications where performance demands are lower is a practical interim solution before recycling. This approach not only extends battery life but also offers economic advantages by creating a revenue stream that can help offset recycling costs. Although the LIB recycling sector is still relatively small compared to battery production, it is expected to expand significantly, bolstered by government investments such as the U.S. Department of Energy's Battery Recycling R&D Center and the $5.5 million LIB Recycling Prize launched in 2019 [139].

Currently, the lack of standardized Li-ion batteries recycling protocols—unlike those for lead-acid batteries—poses challenges. Therefore, the development of efficient and accessible recycling infrastructure is essential to manage the growing volume of spent LIBs and to encourage broader consumer participation. In recent years, several innovative methods have emerged to improve metal recovery rates and reduce environmental impact. These include the following:

- Deep eutectic solvents, which have achieved over 90% leaching efficiency for lithium and cobalt.
- Ultrasonic-assisted leaching, reaching over 98% recovery of both metals.
- An enhanced oxalate process using hydrogen peroxide, which improves cost-effectiveness and reduces energy consumption.
- Electrolysis-based recovery, which can extract over 50% of $LiCoO_2$ in a single step without toxic reagents or high temperatures.
- Vacuum metallurgy, allowing in situ lithium recycling with over 80% efficiency.

In a recent study, a green, solvent-free recycling method was applied for Li-ion battery electrode fabrication using water-based processing. Recycled NCM523 cathode materials, recovered using a water-soluble binder, exhibited stable cycling and comparable electrochemical performance to pristine materials, despite slightly increased hysteresis and reduced capacity due to surface carbonate formation. The process successfully regenerates cathode material without using hazardous solvents. Optimization of structural properties and air/water exposure is needed to enhance performance. The recycled NCM523 delivered promising results at 0.2 C in the 2.7–4.2 V range, demonstrating the feasibility of direct recycling. Future work includes scaling for pre-pilot coating and improving the aqueous process, particularly for Ni-rich cathodes [11]. The process of direct recycling is described in a flow chart in Figures 17 and 18.

In another recent study, as discussed in the above section, a recyclable and biodegradable hydrogel electrolyte (CPZ-H) composed of chitosan and polyaspartic acid was developed for Zn/MnO_2 batteries (Figure 19). After battery use, the CPZ-H electrolyte can be recovered simply by drying, grinding, and reforming with water, yielding a regenerated electrolyte (rCPZ-H) with excellent mechanical and electrochemical performance. The rCPZ-H showed stable cycling in a Zn symmetric cell for 750 h and in a Zn/MnO_2 full cell with 86.7% capacity retention after 2400 cycles at 5 A g^{-1}. It also demonstrated high Coulombic efficiency (>97.6%) and retained functionality in practical demonstrations like powering a mini elevator and Ferris wheel, validating its robustness and reusability [71].

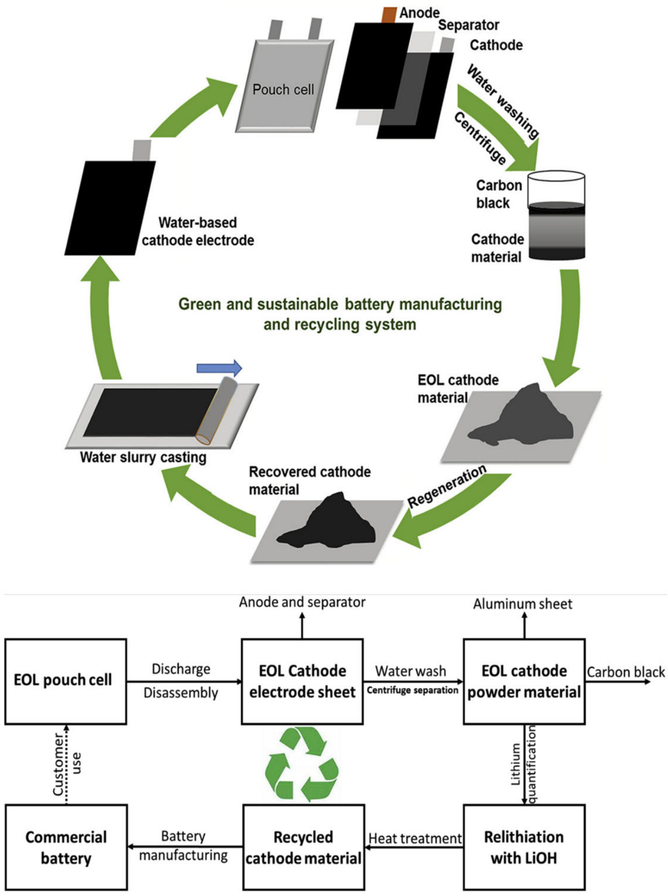

Figure 17. Flow chart illustration of process of direct recycling [11].

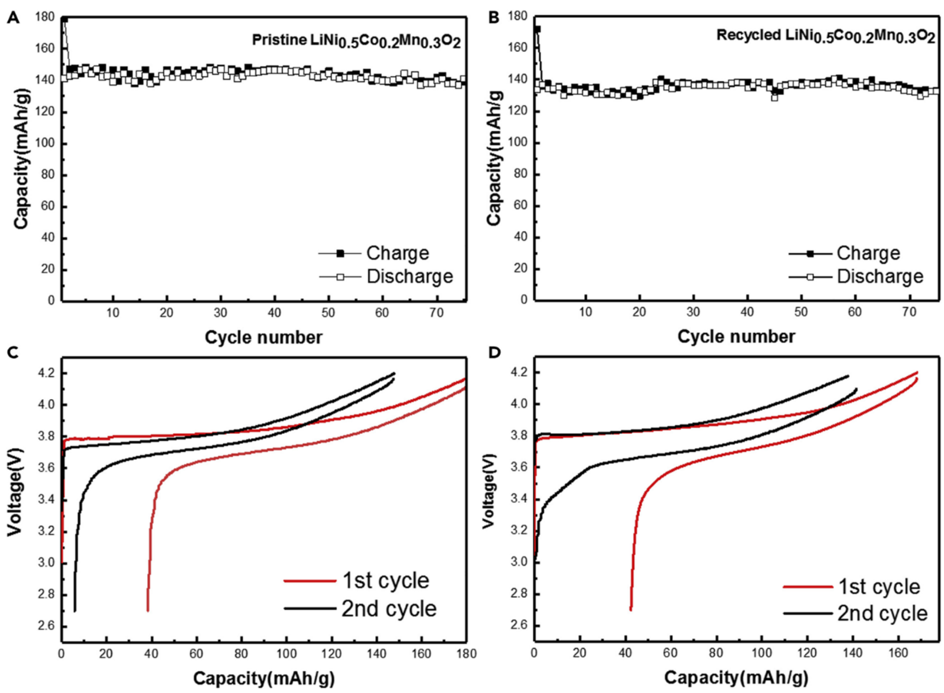

Figure 18. Electrochemical performance of NCM523 electrodes cycling performance of (**A**) Li/pristine $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ coin cell and (**B**) Li/recycled $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ coin cell at C/5. The voltage profiles of first two cycles (**C**) Li/pristine $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ coin cell and (**D**) Li/recycled $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ coin cell at C/5 [11].

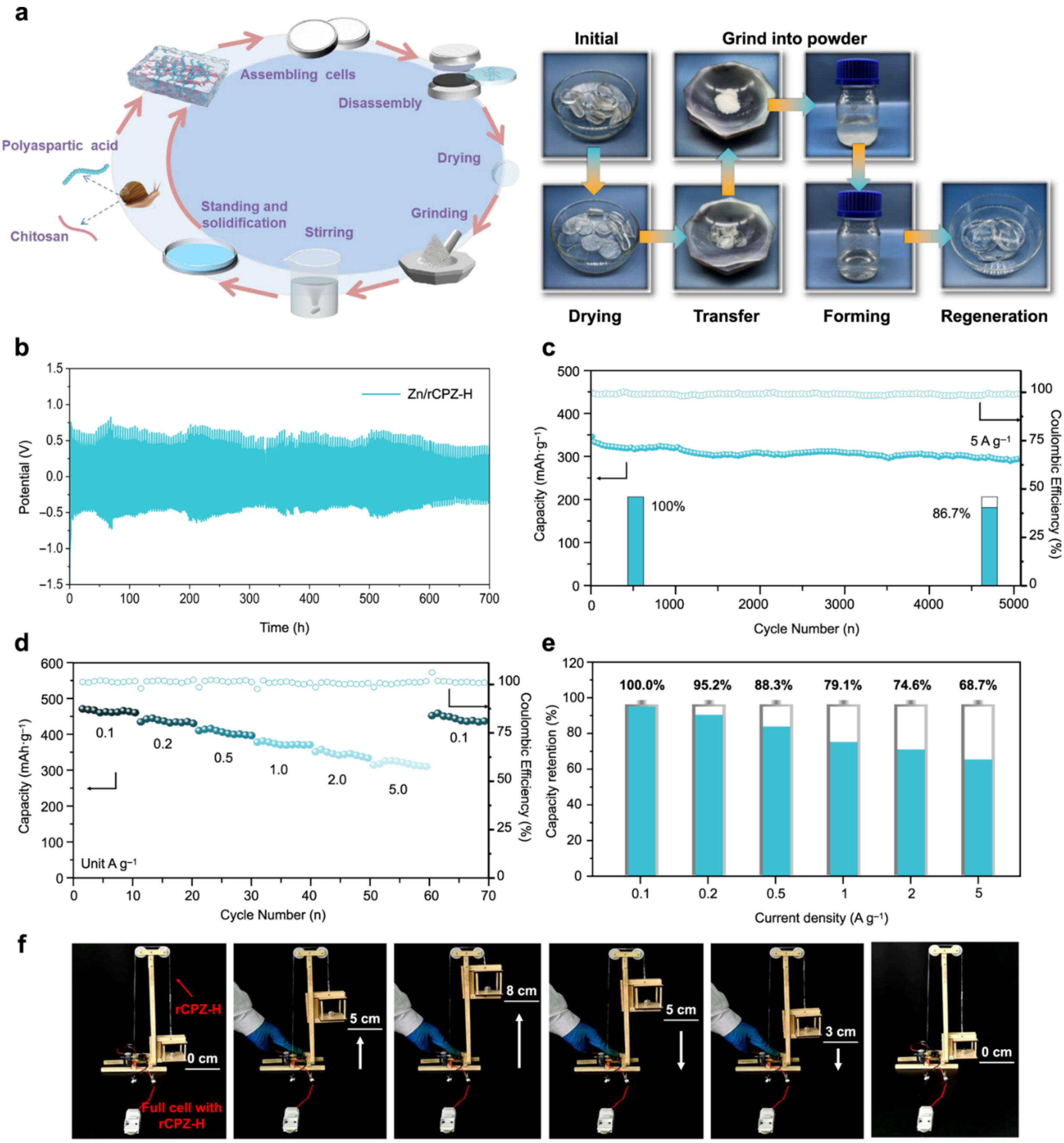

Figure 19. (**a**) Recycling process of chitosan-based electrolyte showing (**b**) voltage profile, (**c**) cycle, (**d**) rate performance, (**e**) capacity retention and (**f**) elevator device images [71].

7. Application Field Strategies for Green Battery Technologies

The transition to green batteries is critically important in sectors where environmental sustainability, human safety, and resource circularity are essential. Among the various application areas, electric vehicles (EVs), grid-scale renewable energy storage, portable consumer electronics, medical and wearable devices, and disaster-resilient energy systems stand out as the most impactful beneficiaries of green battery technologies.

In electric vehicles, which are poised to replace internal combustion engines globally, the use of biodegradable separators, bio-based electrolytes, and low-toxicity cathode materials significantly reduces the environmental burden associated with battery production and disposal. Green battery chemistries, such as sodium-ion and zinc–air systems utilizing natural polymers, offer safer, low-cost alternatives for mobility applications, particularly in regions with limited lithium resources.

Grid-scale storage systems, essential for stabilizing intermittent solar and wind energy, require sustainable batteries with long cycle life and minimal environmental impact. Here, green batteries using solvent-free fabrication techniques, recyclable electrodes, and non-flammable electrolytes enhance both safety and sustainability, making them ideal for deployment in microgrids, remote installations, and off-grid rural electrification.

In the realm of consumer electronics, where battery replacement is frequent and waste generation is high, green batteries made from renewable materials such as chitosan, cellulose, or other biopolymers offer a low-impact alternative with comparable performance. Their eco-friendly nature makes them especially attractive for single-use sensors, IoT devices, and biodegradable gadgets.

Medical implants and wearables demand materials that are not only safe and biocompatible but also degrade without toxic by-products if implanted short-term. Green batteries using naturally derived polymers and aqueous electrolytes fulfill these requirements, ensuring enhanced patient safety and compliance with biomedical regulations.

Lastly, emergency power supplies and disaster-resilient storage systems benefit from green battery chemistries with low risk of fire or explosion and easy disposal, making them ideal for field-deployable, humanitarian, and military applications.

To promote the adoption of green batteries in these sectors, strategies such as scaling up solvent-free fabrication, integrating closed-loop recycling systems, developing regulatory frameworks for biodegradable components, and incentivizing eco-certifications for battery materials are essential. Overall, green batteries are not just an alternative but a necessity in transitioning toward circular, low-carbon, and sustainable energy systems. Their integration into key fields will be instrumental in meeting global sustainability goals, reducing hazardous waste, and ensuring safer energy storage for diverse applications.

8. Market Potential and Global Regulations

The growing emphasis on sustainable battery development has prompted several countries to implement regulatory frameworks that ensure environmental compliance across battery life cycles. These global regulations aim to reduce the ecological footprint of battery manufacturing, encourage recycling, and promote the use of secondary raw materials, particularly in electric vehicle (EV) batteries.

The United States has also begun reinforcing its domestic battery industry with significant investments. In 2022, the Biden Administration announced $2.8 billion in funding aimed at strengthening battery production and launched the American Battery Materials Initiative. The U.S. also committed to achieving 50% EV sales by 2030, aligning national objectives with global sustainability trends [139].

Notably, Tesla has commercialized this PTFE-based dry electrode technology for use in its 4680-type cylindrical cells, including those implemented in the Cybertruck battery packs, highlighting its commercial viability and energy efficiency advantages. The elimination of solvent drying steps not only reduces energy consumption and capital costs but also simplifies battery production workflows, making it a highly attractive option for large-scale manufacturing [140]. Despite its technical advantages, PTFE belongs to the broader class of per- and polyfluoroalkyl substances (PFAS), which have come under increasing scrutiny due to their persistence in the environment and potential health hazards. PTFE is often classified as a non-degradable polymer, raising concerns regarding its long-term environmental footprint and regulatory acceptability. Several international agencies, including the European Chemicals Agency (ECHA) and the U.S. Environmental Protection Agency (EPA), are actively evaluating PFAS materials under potential restriction frameworks due to their bioaccumulative nature and resistance to degradation [141,142]. The inclusion of PTFE-based materials in energy storage devices thus presents a paradox—while they enable cleaner manufacturing processes, they may introduce sustainability challenges at end-of-life or during regulatory assessments. Future directions may involve the development of fluorine-free binders or biodegradable dry-processing alternatives that align better with circular economy principles.

China has taken a leading role by instituting some of the most rigorous regulations. Since 2018, the country has introduced and progressively tightened interim measures for battery reuse and recycling infrastructure. The release of the Energy in China's New Era plan in 2020 further reinforced these efforts, mandating lower carbon intensity in battery supply chains and increased recycling obligations, especially for EVs. Given that China is the world's largest EV market, these standards are shaping global supply chain practices [143].

The European Union (EU) followed suit by updating its outdated 2006 Battery Directive. In 2019, it proposed a new regulatory framework focused on ensuring sustainability across the entire battery value chain [144]. The legislation mandates the incorporation of recycled materials in batteries exceeding 2 kWh, such as those used in EVs, and enforces transparency in sourcing and lifecycle management. These rules are designed to drive circular economy practices within the European battery industry [1].

India has emerged as a significant player in the push for sustainable battery practices. The government's Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme, initiated in 2015, has been pivotal in promoting EV adoption [145]. The subsequent FAME II scheme, launched in 2019 with an increased budget, focuses on enhancing the availability of electric vehicles and charging infrastructure across the country by 2030 [2]. Furthermore, the Ministry of Environment, Forest, and Climate Change introduced the Battery Waste Management Rules, 2022, mandating producers to collect and recycle used batteries, thereby promoting a circular economy and reducing environmental hazards [146].

In a recent development, the Delhi government announced an ambitious plan to phase out petrol, diesel, and CNG vehicles, replacing them entirely with electric vehicles. This initiative aims to achieve 95% EV adoption among new vehicle registrations by 2027 and full charging infrastructure coverage by 2027. The policy also includes incentives for various EV categories and emphasizes the expansion of charging and battery-swapping infrastructure [147].

South Korea has implemented a multifaceted approach to promote sustainable battery practices. The government plans to introduce a system by 2027 that classifies EV batteries based on their potential for remanufacturing, reuse, and recycling, conducting performance evaluations without removing the batteries [148].

By 2030, the government aims to have 4.2 million EVs on the road and to increase domestic EV production to 3.3 million units annually [149]. In 2023, the Ministry of Environment amended the Waste Management Act to include standards aimed at improving the circularity of EV battery wastes [150]. This policy focuses on enhancing recycling processes and reducing hazardous chemical usage [151]. Additionally, South Korea is investing approximately $7 billion to reduce its EV battery industry's reliance on China and align with U.S. trade rules. This financial aid supports the development of lithium-metal batteries and assists companies in sourcing critical minerals from the U.S. and its free-trade partners [149].

Overall, with China and the European Union establishing stringent regulatory frameworks for battery sustainability, other countries are rapidly aligning with these high benchmarks. This global momentum signals a clear shift toward tighter regulations that mandate the integration of recycled materials, greener chemistries, and full lifecycle traceability of battery components. As these policies intensify, conventional battery chemistries with high environmental impact may become both economically unviable and legally restricted. Recent policy developments in India and South Korea further reflects this trend. India's aggressive push for complete EV adoption and battery recycling, along with South Korea's efforts to classify, reuse, and recycle EV batteries while reducing reliance on critical imports, demonstrate growing commitment in key Asian markets. These countries are not only responding to domestic environmental concerns but are also positioning themselves to meet global standards. Collectively, these regulatory advancements are catalyzing innovation in sustainable battery technologies and reshaping the future of the global battery industry.

9. Challenges and Future Perspectives

Green biopolymer-based materials such as electrolytes, binders, and separators present significant environmental advantages, yet they face several technical hurdles that must be overcome for large-scale battery integration. Biopolymer-based electrolytes often suffer from inherently low ionic conductivity, particularly at room temperature, and possess a narrow electrochemical stability window, limiting their compatibility with high-voltage electrodes. Their hydrophilic nature can also lead to moisture sensitivity and reduced shelf life. Similarly, biopolymer-based binders, while biodegradable and often water-processable, exhibit weak adhesion to electrode surfaces under thermal and mechanical stress. Their solubility in aqueous electrolytes can cause detachment from active materials during prolonged cycling, compromising structural integrity. Biopolymer-based separators, although renewable and eco-friendly, may lack the mechanical strength and thermal stability of commercial polyolefin separators. They often exhibit inhomogeneous pore structures that impede uniform ion transport and compromise cycling performance.

In additive-free solvent systems—designed to simplify battery chemistry and reduce environmental burden—the absence of functional additives can lead to poor formation of the solid electrolyte interphase (SEI), especially in lithium-based batteries. This results in unstable cycling, low Coulombic efficiency, and uncontrolled side reactions such as dendrite formation or hydrogen evolution. Moreover, these solvents often have limited flame-retardant properties and reduced electrode wettability, which negatively affects ionic mobility and rate performance.

Nanostructured membranes used as separators, while offering advantages such as tunable porosity and enhanced ion selectivity, face scalability challenges due to complex synthesis techniques like electrospinning or template-assisted casting. Their ultrathin structure makes them prone to mechanical failure, and their nanopores can become blocked by by-products from electrolyte decomposition or dendritic growth, reducing long-term stability. Additionally, maintaining a uniform three-dimensional pore network remains a significant fabrication challenge.

Recyclability of green battery components, although a major sustainability goal, is hindered by the difficulty of separating multi-functional biopolymeric layers after battery use. Degradation of structural and electrochemical properties during recycling processes often results in reduced performance. There is also a lack of standardized protocols for the effective recovery of biodegradable materials, and issues such as residual electrolyte toxicity or component cross-contamination further complicate recycling efforts.

Finally, ionic liquids (ILs) and deep eutectic solvents (DESs), though promising as non-volatile and thermally stable green solvents, pose their own limitations. ILs tend to be highly viscous, which lowers ionic conductivity, and they are often expensive and not always biodegradable. Their synthesis can also be complex and energy intensive. DESs, while easier to prepare and potentially more sustainable, share the challenge of high viscosity and tend to absorb moisture from the air, altering their electrochemical properties. Both ILs and DESs typically have a limited electrochemical stability window and still lack a comprehensive understanding of their interfacial behavior and SEI dynamics, restricting their immediate practical application in advanced battery systems.

For biopolymer-based electrolytes, binders, and separators, future developments in green batteries will increasingly leverage natural biopolymers due to their renewability, low toxicity, and biodegradability. To overcome their current limitations:

- Molecular tailoring through chemical modification (e.g., grafting ionic moieties or blending with conductive fillers) will be essential to enhance ionic conductivity and mechanical stability.
- Composite approaches, where biopolymers are integrated with nanomaterials (e.g., graphene, MXenes, or metal–organic frameworks), will offer enhanced thermal resilience, porosity control, and ion selectivity.
- Improved crosslinking strategies can yield biopolymer membranes with better electrolyte retention and long-term electrochemical stability.
- Standardization of biodegradability protocols under both aerobic and anaerobic conditions is necessary to support environmental risk assessments and ensure these materials decompose into benign by-products.
- Environmental risk perspective:
- Assessing end-of-life decomposition products and their interactions with soil and water ecosystems is critical.
- Potential allergenicity or toxicity of degradation intermediates must be systematically evaluated.
- Life cycle analysis (LCA) should become integral to biopolymer material development to validate their sustainability claims.

Additive-free solvents are attractive for minimizing toxicity and simplifying recycling processes, but future research must explore the following:

- Develop self-healing or multifunctional electrolyte systems that inherently stabilize SEI without additives.
- Investigate solvent–electrode interface chemistry to engineer stable interphases.
- Explore biologically derived solvents from lignin, glycerol, or sugars that can offer high polarity and low volatility.

However, long-term exposure data and ecotoxicological studies are required to validate these solvents as safe and sustainable. Secondly, integration into closed-loop manufacturing systems could minimize waste and improve circularity.

Nanostructured membranes offer high selectivity and tunable properties. To advance these,

- Scalable fabrication methods like roll-to-roll electrospinning or 3D printing will be pivotal.
- Future membranes may incorporate smart stimuli-responsive features (pH, temperature, or ion-triggered gating) for real-time control of ion flow and dendrite suppression.
- Biodegradable nanomaterials (e.g., nanocellulose, chitin nanofibers) will increasingly replace synthetic polymers.
- Environmental risk and biodegradability focus:
- Nanotoxicology must be rigorously studied, especially for nanomaterials released during degradation.
- Emphasis should be placed on membranes that degrade into non-toxic fragments and offer soil or marine compostability.

Ionic liquids and Deep eutectic solvents (DESs)

- Development of bio-derived and biodegradable ILs/DESs (e.g., based on amino acids, choline chloride, sugars) is critical.

- Lowering viscosity while preserving ionic conductivity is a primary research target.
- Future ILs/DESs may function as dual-purpose materials (electrolytes + binders or flame retardants).

Future research directions:

- Investigate biocompatibility and long-term environmental fate of ILs/DESs.
- Standardized testing under environmental exposure conditions (light, moisture, microbial degradation) must be established.

In summary—the key strategic directions include the following:
Biodegradability enhancements:

- Development of ISO-compliant protocols to test real-world biodegradation of battery materials.
- Integration of microbial enrichment studies to understand and optimize decomposition kinetics.

Environmental risk assessments:

- Implement predictive toxicity modeling and metabolomics to evaluate degradation pathways.
- Full life cycle assessment (LCA) to determine energy consumption, emissions, and recycling potential.

Policy and regulatory support:

- Push for eco-labeling and certifications for green battery materials.
- Encourage international green materials registries and guidelines to harmonize safety and performance standards.

10. Conclusions

The transition toward green battery technologies marks a critical step in addressing the environmental and safety challenges posed by conventional battery systems. This review highlights the integrated development of sustainable components—including green electrode fabrication methods, eco-friendly electrolytes, and biodegradable separators—that collectively promote cleaner production and safer disposal practices. The use of water-based binders, waste-derived materials, and additive-free green solvents has shown potential to significantly lower the ecological footprint of batteries. Advanced nanostructured membranes and biopolymer-based electrolytes further contribute to the enhancement of battery performance while aligning with biodegradability and recyclability goals. Nevertheless, challenges remain in scaling up these technologies, ensuring material consistency, and conducting thorough environmental risk assessments. Future research should focus on developing robust standards for biodegradability testing, optimizing recycling protocols, and designing closed-loop manufacturing systems. Ultimately, green batteries offer a viable and essential pathway toward sustainable energy storage solutions for a cleaner and more circular economy.

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