

Wood-Derived Materials for Lithium-Based Batteries: Advances and Perspectives

Yizhi Lu

*School of Material Science, Beijing Forestry University, Beijing, China
luyizhi4@bjfu.edu.cn*

Abstract: In the context of growing global energy demand and raising awareness of environment, high-performance lithium-based batteries have become a research hotspot in the development of energy storage. Wood-based materials and derivatives, owing to their inherent environmental friendliness, tunable surface properties, and hierarchical porous architectures, have been extensively utilized in lithium battery devices, including electrodes, separators, binders, and electrolytes. In general, typical modification strategies involve selective components removal, precise structure control, and integration with micro/nano active units. This review highlights the advanced research progress in wood-based lithium battery, analyzing functional utilization of the intrinsic structural characteristics and three fundamental components (cellulose, hemicellulose, and lignin) as well as focusing on their modification methods and performance optimization in energy storage devices.

Keywords: Wood-derived materials, Lithium-based batteries, Cellulose, Lignin

1. Introduction

With the rapid development of global technology and increasing energy demand, people are more and more eager for green and advanced energy storage devices [1,2]. Lithium-ion batteries (LIBs), with their high energy density (up to 300 Wh kg⁻¹), long cycle life (>1000 cycles), and low self-discharge rate, have become the dominant energy storage technology [3,4]. Its derived lithium-sulfur(Li-S), lithium-oxygen(LOB), and lithium-metal batteries(LMB) also have become promising candidates for the next generation of battery technologies. As shown in Figure 1a, wood science, regarded as an eco-friendly and sustainable technology, has become a significant driving force in the global energy revolution. Moreover, Wood-based lithium batteries, due to their high energy density, long cycle life and low self-discharge rate, contributing to build a high-performance sustainable battery system [5,6].

Natural wood, serving as a renewable and biodegradable porous material, offers unique opportunities for designing eco-friendly lithium battery devices [6]. This biomass is predominantly composed of cellulose, lignin, and hemicellulose, exhibiting a hierarchical porous structure with tunable properties that facilitate rapid and efficient electron and ion transport [7,8]. Therefore, wood and its derivatives provide the following advantages for the development of lithium batteries: 1) vertical microchannels provide efficient ion transport paths; 2) nanofiber networks support highly active loadings; 3) a highly conductive carbon skeleton is formed by carbonization; and 4) a three-dimensional electrolyte network inhibits dendrite growth.

In recent years, wood-based lithium battery research has made significant progress, enabling the high-value utilization of resources while offering low cost and reduced environmental impact. Wood and for lithium battery applications can be categorized into two main strategies: 1) selective removal or conversion of components in nature wood or targeted control of its structural properties, coupled with 2) nano-engineered reassembly of wood-derived materials with micro/nano active units either during or post restructuring processes. In addition, recent advances have enabled the fabrication of wood-derived electrodes, as well as wood-based electrolytes, binders, and separators [9-10].

2. Structure and components of wood

Wood, derived from tree trunks and roots, consisting of cellulose, hemicellulose, and lignin, exhibits an anisotropic and porous hierarchical structure (Figure 1d). As shown in Figure 1c, natural wood exhibits a unique anisotropic, multi-level pore architecture: vertically aligned microchannels with diameters of 20–140 μm , while the cell walls comprise a nanoscale interpenetrating network. These structure imparts elastic moduli (15–20 GPa) and tensile strengths (100–150 MPa) to the pristine wood [8,11]. The synergistic integration of low-tortuosity pathways, high specific surface area, and a conductive carbon-enriched framework enables wood-derived materials to serve as high-performance candidates for advanced energy storage systems.

Cellulose, the primary component of wood, is a linear polysaccharide composed of repeating D-glucose units, characterized by high crystallinity, mechanical strength, and hydrophilicity [12]. It is regarded as an ideal material not only for lithium-ion battery anodes but also for separator membranes. Furthermore, its derivatives—including cellulose nanofibers (CNFs), cellulose nanocrystals (CNCs), and carboxymethyl cellulose (CMC)—have been extensively utilized in energy storage applications [11,12].

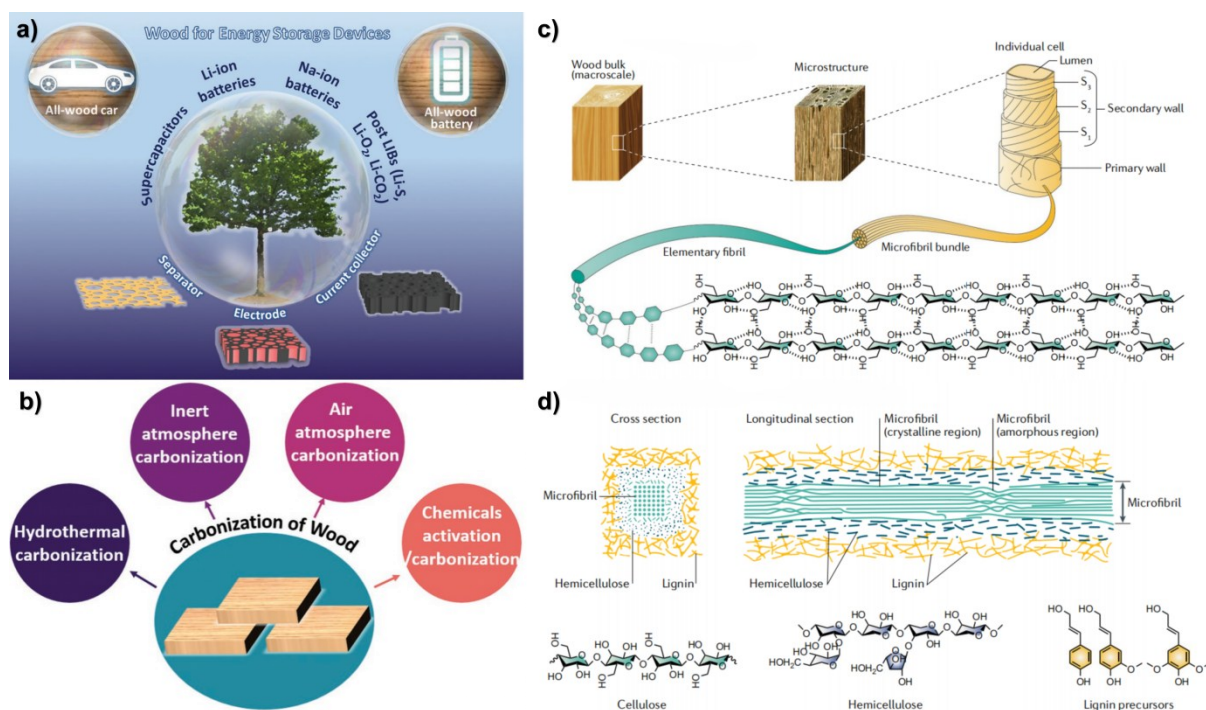


Figure 1: a) Wood-derived materials for EES devices: including lithium-based batteries; b) the carbonization/activation route of natural wood; c) the hierarchical structure of wood; d) composition in cross section and the longitudinal direction.

Hemicellulose, characterized by a low degree of polymerization (DP), are heterogeneous polysaccharides composed of diverse sugar units, exhibiting amorphous chains. Due to their low DP and structural instability, hemicelluloses have been less explored compared to other biopolymers. Although thermal processing can convert hemicelluloses into high-performance biomaterials, it also requires a lot of research [8,13].

Lignin, as the second most abundant natural polymer on Earth, forms an amorphous three-dimensional network through the cross-linking of three phenylpropane units: p-coumaryl, coniferyl, and sinapyl alcohols [6,13]. Its unique aromatic skeleton and high carbon content (60–65 wt%) endow lignin-derived carbon materials with hierarchical porosity, high electrical conductivity, and exceptional thermal stability. However, challenges such as structural heterogeneity, diverse botanical sources and unclear doping mechanisms constrain its potential application in lithium batteries [13].

3. Wood-derived materials for lithium-based battery

3.1. Wood-based electrodes

Electrode design faces multifaceted challenges, which need the simultaneous optimization of high electrical conductivity (e.g., via heteroatom doping), moderate specific surface area, hierarchical porous architectures, and cost-effectiveness [6,14]. Therefore, wood-based materials offer an innovative solution to these challenges by utilizing their hierarchical porous structure and vertically aligned ion transport pathways. In general, wood-derived electrodes are fabricated through carbonization/activation [10], followed by functional composite hybridization (e.g., conductive polymers, metal oxides) [14–18]. The carbonization/activation pathway of natural wood is shown in Figure 1b.

The research on lithium-ion wood-based electrode materials has been categorized into two aspects: pristine wood-based anodes and wood-based composite anodes[9]. In the field of pristine wood-based anode studies, ultra-thick electrodes have attracted much attention for realizing higher energy density [2,14]. Wang et al. [14] systematically investigated how different wood types (balsa, poplar, and birch) as precursors, affect the carbon pore structure and battery performance of wood-derived thick carbon electrodes (WHCTEs). Bal-W exhibited the highest specific surface area (798 m² g⁻¹) with abundant mesopores (2–4 nm), while Pop-W showed moderate mesoporosity. In contrast, Bir-W displayed scarce mesopores but a high density of micropores concentrated at 1.2–1.6 nm. After 200 cycles, Bir-W retained the highest volumetric capacity (41.03 Ah L⁻¹), attributed to its enhanced ion storage through microporosity and interfacial stability. All in all, this study establishes a critical precursor-structure-performance relationship for biomass-derived thick electrodes.

Meanwhile, wood-based composite anodes by multicomponent synergy show great potential for research[9]. For instance, Zhang et al.[15] doped SnO₂ nanoparticles within wood-derived hierarchical porous carbon (SnO₂/WFPC, Figure 2a) via hydrothermal-carbonization. The composite anode delivered a high reversible capacity of 1014.4 mAh g⁻¹ at 0.2 C with 82% capacity retention after 250 cycles. These characterization attributed to shortened Li⁺diffusion pathways, abundant active sites, and effective buffering of SnO₂ volume expansion. Similarly, Chen et al.[16] developed a ZnO-decorated carbonized wood (CW-ZnO) using microwave-assisted ultrafast carbonization. The 3D porous scaffold enhanced charge transfer kinetics through interfacial synergy, achieving dual functionality as both Li-ion anode and Li-S cathode. Another study by Zhang et al.[17] integrated Co₄N nanoparticles into wood-derived carbon plates (Co₄N/WCP) via electrochemical deposition and nitridation. With an 807.9 mAh g⁻¹ after 500 cycles at 1 C in Li-S batteries, the composite cathode demonstrates the increase of redox kinetics and uniform Li deposition.

Beyond metal doping, heteroatom incorporation (e.g., P, N) effectively enhances the electrochemical activity of wood-derived carbon. Wang et al. [18] fabricated phosphorus-doped

carbonized wood electrodes via phytic acid (PA) impregnation and carbonization. The optimized electrode exhibited low tortuosity, hierarchical porosity, and high P-doping in symmetric supercapacitors, which can be translated into lithium-ion batteries (LIBs). Chen et al. [19] introduced g-C₃N₄ as a sacrificial template and nitrogen source to synthesize nitrogen-doped porous carbon fibers (N-PCF), with the preparation process shown in Figure 2b. N-PCF-2 anode delivered a reversible capacity of 434 mAh g⁻¹ in Li-ion batteries, retaining 427 mAh g⁻¹ after 300 cycles (98.4% retention). All in all, these strategies highlight the cross-system applicability of heteroatom engineering in biomass-based carbon electrodes.

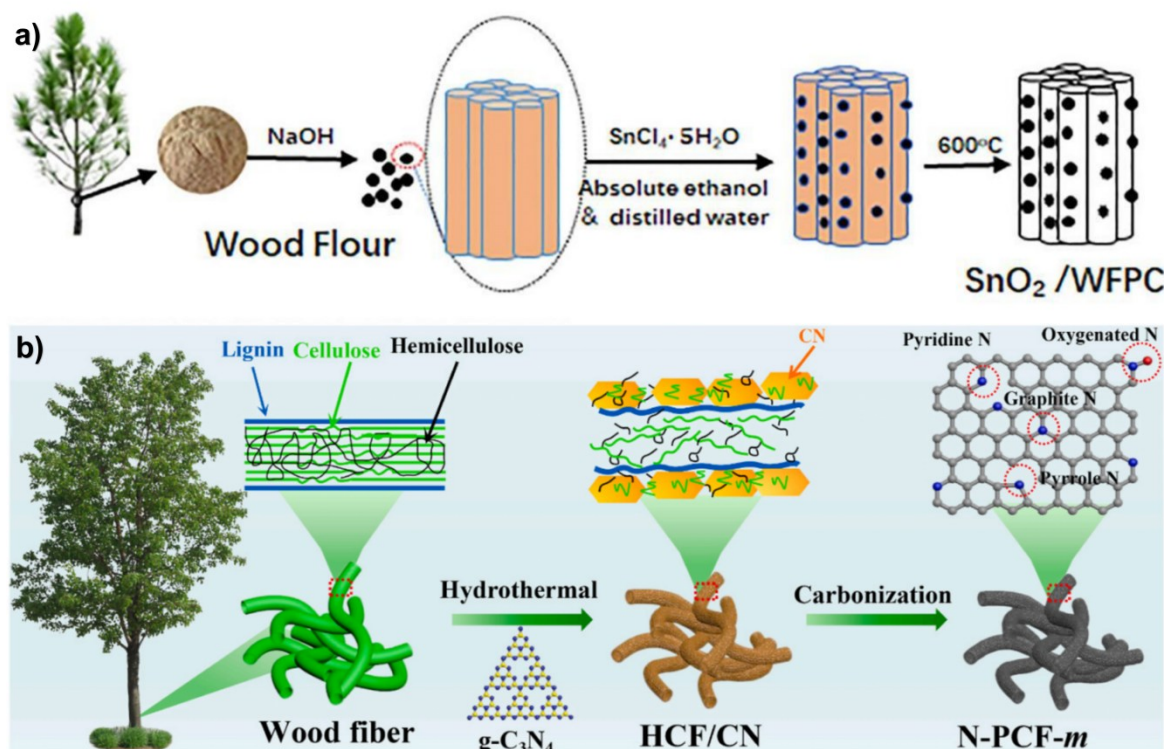


Figure 2: a) Schematic illustration of the synthesis of SnO₂/WFPC composite; b) schematic diagram of the synthetic procedure for N-PCF-m.

3.2. Wood-based separators

All the names of the authors must use the format: first name, middle name initials (optional), surname (last name). Any names that do not conform to this format will be changed by the typesetting team. If your paper has multiple authors, use commas to separate each author and use identifiers to associate an author with an affiliation and an email address (see the first page in this template for an example). Use a superscript asterisk symbol (*) to indicate the corresponding author.

Wood-derived materials have emerged as promising alternatives to conventional separators (e.g., PP/PE) in energy storage systems, addressing a several limitations such as poor hydrophobicity, electrolyte wettability and thermal instability [20-22]. There are three primary optimization strategies: inorganic coatings, electrospinning techniques, preparation of ceramic membranes [22]. Inspired by these strategies, recent studies in wood-derived separators using surface modification, electrospinning, and biomimetic mineralization to address electrochemical and thermal challenges of separators [23]. These green fabrication techniques not only reduce production costs through low-energy processing but also align with sustainable development goals, thereby pioneering novel pathways for next-generation battery separators.

Wood-derived separators have emerged as promising candidates for high-performance LIBs due to their inherent hydrophilicity, thermal stability, and sustainability. Yang et al.[20] developed a modified natural wood separator by selectively removing hemicellulose and lignin, which achieves superior dendrite suppression. The optimized separator exhibited enhanced mechanical strength (58 MPa), thermal resistance (minimal shrinkage at 150 °C), and ionic conductivity (0.48 mS cm^{-1}), outperforming commercial PP membranes in cycling stability, capacity retention, and rate capability. Moreover, its low-cost, eco-friendly fabrication method further highlights viability for LIBs and next-generation energy storage.

To address challenges in LOB, Zhang et al. [21] designed directional porous wood separators via vertical (V-NW) or parallel (P-NW) cutting (Figure 3a), thermal treatment (HW), and delignification (DW). The P-HW separator showed exceptional ionic conductivity (5.11 mS cm^{-1}) and a high Li^+ transference number (0.74). As illustrated in Figure 3b, the wood components synergistically regulated Li^+ flux, suppressing dendritic growth and side reactions (e.g., water-induced side reactions) by blocking H_2O migration. This bioinspired design leverages wood's hierarchical channels for efficient ion transport and interfacial stability. This bioinspired structure take advantage of wood's inherent channel alignment to decouple ion transport from interfacial degradation, contrasting with the disordered pathways in conventional GF separators.

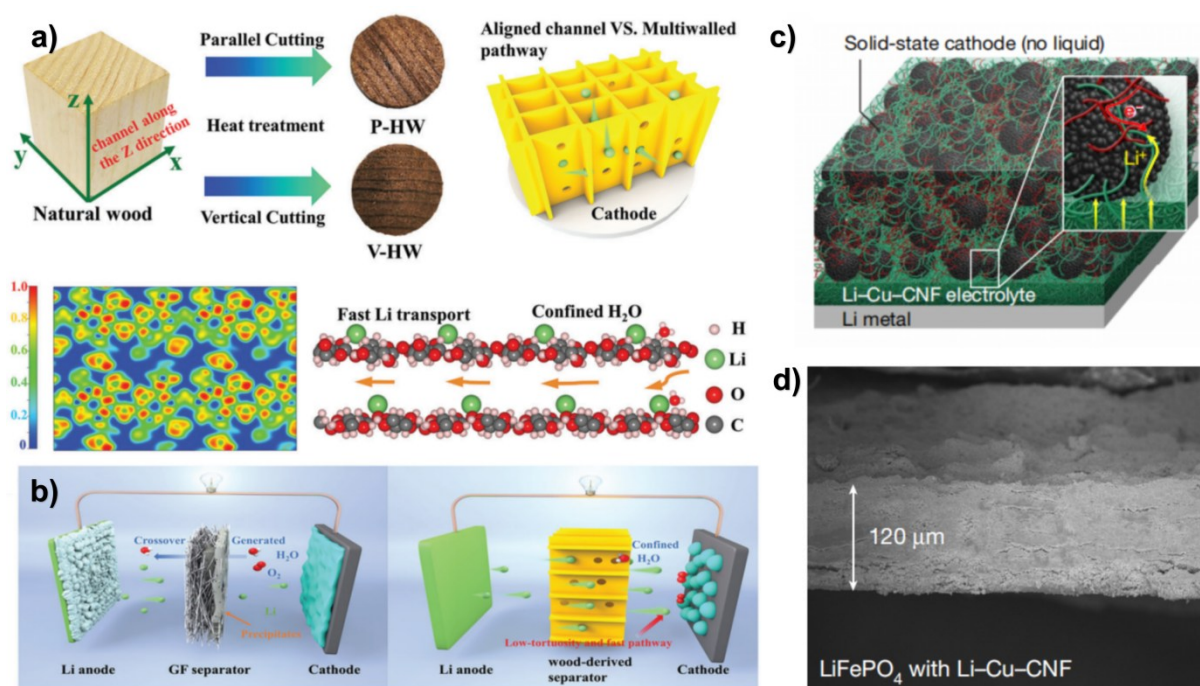


Figure 3: a) Aligned wood channels enabling lithium-ion migration, with uniform electron distribution; b) schematic of operation principle for wood-derived separator in LOBs; c) solid-state battery with Li-Cu-CNF electrolyte: li-metal anode , CNF-ion-conducting binder (green fibers), and cathode (black spheres); d) cross-sectional SEM image of a 120-μm-thick LiFePO_4 cathode made using Li-Cu-CNF and CNT additives

Jia et al.[22] designed a xonotlite nanowire/wood pulp fiber (XWP) composite separator via a papermaking-inspired strategy, integrating thermal stability (not shrinkage at 600°C) with mechanical robustness, while enhancing porosity through a hierarchical 3D network. Electrochemical evaluations demonstrated 91% capacity retention after 100 cycles, 1.148 mS cm^{-1} ionic conductivity, and stable operation within a 2.5-6.0 V voltage window, which outperforms Celgard in high-rate performance.

This sustainable approach leverages renewable wood pulp and low-energy processing, offering a viable pathway for next-generation high-safety batteries.

Lignin electrospun has become an ideal method to prepare separators due to high porosity of lignin and electrospinning unique advantage of high electrolyte wettability and nanofiber disordered stacking structure. Yerkinbekova et al.[24] developed a photo-crosslinked lignin-PAN electrospun separator (PMHP) via dual-crosslinking (UV-electrospinning process and thermal sol–gel process), which forms a 3D porous network with high porosity and electrolyte uptake while maintains dimensional stability and mechanical robustness. More important, the result shows that lignin's polar functional groups synergistically regulated Li^+ flux, suppressing dendrite growth and enabling stable LIB cycling. Furthermore, Song et al.[19] enhanced lignin-based separators by blending polyimide (PI) with lignin (L) to fabricate PI-L nanofiber membranes via electrospinning. The optimized separator exhibited 592% electrolyte uptake, Li^+ transference number of 0.787, and ionic conductivity of 1.78 mS cm^{-1} , alongside exceptional thermal stability ($>450^\circ\text{C}$). Both studies highlight lignin's pivotal role in improving separator performance, providing a green pathway for high-performance separators balancing ionic transport, thermal safety, and interfacial stability.

Apart from lignin, cellulose and its derivatives exhibit high electrolyte affinity, enabling CNF separators to achieve high thermal stability and tunable porosity. Cho et al. [25] developed a nanoporous CNF separator via enzymatic-chemical-mechanical processing of hardwood pulp. The CNF separator demonstrated superior thermal resistance and electrolyte uptake, enabling a wide electrochemical stability window and stable cycling (88.6% capacity retention after 200 cycles). Lv et al. [23] further modified commercial cellulose paper (CP) through structural tuner CNF, addressing the large-pore defects of CP while enhancing mechanical strength. Compared with PP separator, the optimized pure cellulose paper (CCP) separator exhibited higher ionic conductivity and high thermal safety. Owing to the interfacial synergy between CCP and electrolytes, LIBs shows 91% capacity retention over 100 cycles, settling cycling performance and safety issues.

3.3. Wood-based binders

While raw wood materials are not directly employed as binders, cellulose and lignin's derivatives, derived from abundant wood resources, offer sustainable alternatives to synthetic binders in LIBs. In cellulose-based binders, water-soluble carboxymethyl cellulose (CMC) remains the dominant cathode binder due to its mechanical robustness and electrolyte compatibility[12,26]. Another advanced derivatives, such as CNFs, cellulose acetate (CA) and nanocrystals (CNCs), enhance adhesion performance through inherent hierarchical nanostructures and hydrophilicity[13,27,28]. Lignin, another wood-derived component, demonstrates remarkable electrode compatibility and beneficial interfacial interactions. Its aromatic backbone and crosslinked networks facilitate π - π interactions with conductive additives, while hydroxyl and carboxyl groups enhance active material dispersion via polar bonding[29]. However, the inherent properties of unmodified lignin limit effective application in high-performance lithium battery. Key modification strategies include: chemical functionalization, graft copolymerization, plasticizer blending [13].

As a biomass-based binder, CMC can solve the electrode volume expansion problem and enhance the cycle stability of lithium batteries by virtue of its environmental friendliness, versatility and tunability. Li et al. [27] developed lithium carboxymethyl cellulose (CMC-Li) as a water-based binder for LIBs using hardwood and softwood dissolving pulp. By optimizing the degree of substitution (DS) and viscosity, CMC-Li exhibits superior structural integrity and electrochemical performance compared to traditional CMC-Na. The molecular structure of CMC-Li features as a crosslinked network of long- and short-chain cellulose molecules, analogous to reinforced concrete. This hierarchical structure enhances mechanical stability and provides efficient Li^+ diffusion pathways, reducing charge transfer resistance and ensuring uniform ion transport to active material surfaces. In

LiFePO₄ cathodes, CMC-Li demonstrates exceptional performance: initial discharge capacity (180 mAh g⁻¹), coulombic efficiency (99%), capacity retention (97% after 200 cycles).

Cellulose molecular engineering plays a pivotal role in regulating the performance of biomass-based materials. By precisely controlling the hydrogen bond network of cellulose molecular chains, researchers successfully isolated cellulose elementary fibrils (CEFs). To address the insufficient continuity in high-load lithium battery electrodes, Hong et al. [28] proposed a strategy utilizing CEFs and single-walled carbon nanotubes (SWCNTs). Through one-dimensional π - π interactions, these components form a bi-ion conduction network, which was applied to lithium-rich layered oxide (OLO) cathodes. The CEF-based binder constructs a bicontinuous ion conduction network on the OLO electrode surface while preserving the fundamental crystalline structure of CEFs. The resulting electrode shows superior performance, achieving a high area mass loading of 50 mg cm⁻² and a specific energy density of 445.4 Wh kg⁻¹, significantly surpassing previously reported OLO cathodes.

Recent studies on lignin binders demonstrate that chemical modifications significantly enhance binders performance, which is over traditional binders like PVDF. Jeong et al. [29] pioneered the use of lignin as a raw material for synthesizing crosslinked polymers via chemical modifications and atom transfer radical polymerization (ATRP). The resulting star-shaped polymer network, with a lignin core and flexible ion-conductive polyethylene glycol branches, exhibits excellent thermal stability and ionic conductivity, meeting the requirements of LMBs at a wide temperature range. Inspired by lignin's natural role in wood, Chen et al. [30] developed an ultra-low-dosage lignin binder (AL-Lys-D) for Li-S cathodes. This binder addresses compatibility issues between active materials and conductive additives by forming a robust interfacial network, inspired by lignin's function in binding cellulose and hemicellulose within plant cell walls. AL-Lys-D enables more efficient charge transport pathways. At a dosage of 2 wt%, AL-Lys-D achieves an initial discharge capacity of 864 mAh g⁻¹ at 0.5 C, maintains stable cycling for over 1,000 cycles, and supports high mass loading (4.75 mg cm⁻²) with an energy density of 484 Wh kg⁻¹. These advancements highlight lignin's potential as a sustainable, high-performance binder for next-generation energy storage systems.

3.4. Wood-based electrolytes

The inherent vertical microchannel structure in wood-derived materials provides structural advantages for addressing low ionic conductivity and high interfacial resistance in solid-state electrolytes [6]. Molecular engineering strategies, such as metal ion coordination or polymer composite integration, enable precise control over mechanical strength and ion transport efficiency, while suppressing lithium dendrite growth [31-32]. Meanwhile, these aligned microchannels act as templates for directional ion transport networks, effectively reducing ion migration resistance [33]. Although pristine wood's direct application remains limited, insights from lignin- and cellulose-based functional materials offer critical pathways for advancing wood-derived electrolyte technologies.

Li et al. [31] focused on lignin waste valorization, utilizing molecular grafting techniques to anchor flexible polyethylene glycol (PEG) chains on lignin, forming a brush-like PEG-g-lignin polymer. This rigid-flexible hybrid structure enhances film-forming capability and thermal stability. The ether-type linkages and phenolic terminal groups in lignin promote Li⁺ hopping across polymer chains and coordination effects, achieving an ionic conductivity of 6.5×10^{-5} S cm⁻¹. Incorporating LLGZO ceramic fillers further optimizes the composite electrolyte's performance. Yang et al. [32] proposed a breakthrough strategy using copper ion coordination to construct molecular channels in CNF (Figure 3c). Cu²⁺ coordination with hydroxyl groups creates 1D pathways for rapid Li⁺ transport. The Li-Cu-CNF electrolyte exhibits exceptional properties: a room-temperature ionic conductivity of 1.5×10^{-3} S cm⁻¹ (10-1000 higher than conventional SPEs), a high Li⁺ transference number (0.78) and a wide electrochemical stability window (0-4.5 V). As shown in Figure 3d, The Li-Cu-CNF enables the fabrication of thick LiFePO₄ cathodes (about 120 μ m), due to its ion-percolating network,

highlighting its potential for high-energy-density batteries. This work not only reveals the ion transport regulation mechanism through metal coordination in lignocellulosic materials but also extends the molecular channel engineering strategy to other polymer systems, offering universal principles for green energy storage materials. Moreover, Dai et al. [33] pioneered a wood-templated approach by chemically removing lignin to form a porous framework. After garnet precursor impregnation, calcination, and PEO infiltration, a garnet-wood composite electrolyte was developed. This electrolyte achieves high ionic conductivities of $1.8 \times 10^{-4} \text{ S cm}^{-1}$ at room temperature and $1.1 \times 10^{-3} \text{ S cm}^{-1}$ at 95°C . This study introduces a novel direction for biomass-templated solid-state electrolytes, laying a foundation for high-performance energy storage devices derived from lignocellulosic materials.

4. Conclusion

Recent advancements in wood-based materials highlight their transformative potential for lithium-derived batteries. Key innovations focus on wood-based composite anodes and biomimetic separators, where aligned microchannels and advanced modifications (e.g., electrospinning, surface modifications, doping) enable ultrahigh mass loading and efficient ion transport. In addition, leveraging inherent wood porous hierarchical structure and molecular engineering strategies, such as metal ion coordination and graft copolymerization, have further advanced wood-derived binders and electrolytes, achieving high ionic conductivities and thermal stability.

In the field of lithium-based batteries, wood-based materials still face several critical challenges. For instance, in order to optimize ion transport kinetics and interfacial stability, molecular-level precision control, nanostructural reconfiguration, and rational design of pore structure remain to be addressed. A fundamental gap persists in understanding the mechanistic links between hierarchical porous structures (e.g., pore size distribution, tortuosity, and connectivity) and electrochemical performance. In addition, mimicking wood's natural ion diffusion pathways offers a bio-inspired strategy to design self-healing materials for lithium batteries.

Wood-derived systems exhibit promising industrial potential in energy storage applications due to their structural tunability and eco-friendly attributes. Specifically, innovations such as molecular channel engineering and multi-scale modelling are leading to pioneering progress in the surface engineering and controllable microstructure fabrication for wood-based materials. These breakthroughs lay the foundation for next-generation energy storage devices, including solid-state electrolytes and thick-electrode composites. Although research on wood-based energy storage materials is still in initial stages, their unique structural tunability and environmentally friendly properties give them a significant advantage in lithium battery applications. Therefore, such renewable biomass materials are expected to provide transformative solutions for future sustainable energy storage systems and promote the development of green energy technologies.

Authorship statement

Yizhi Lu: Conceptualization, Methodology, Investigation, Writing, Visualization. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work is supported by the Beijing Forestry University National Undergraduate Training Program for Innovation and Entrepreneurship (No. S202410022137).

References

- [1] Ramasubramanian, B., Ling, J., Jose, R., & Ramakrishna, S. (2024). Ten major challenges for sustainable lithium-ion batteries. *Cell Reports Physical Science*, 5(6), 102032. <https://doi.org/10.1016/j.xcrp>
- [2] Wang, F., Lee, J., Chen, L., Zhang, G., He, S., Han, J., Ahn, J., Cheong, J. Y., Jiang, S., & Kim, I.-D. (2023). Inspired by Wood: Thick Electrodes for Supercapacitors. *ACS Nano*, 17(10), 8866-8898. [https://doi.org/10.1021/acsnano.3c01241](https://doi.org/10.1021/acs.nano.3c01241)
- [3] Fu, F., Jiao, X., Yang, Y., Yin, X., & Zheng, Z.-J. (2025). Wood-based materials for high-energy-density lithium metal batteries. *Nano Energy*, 133, 110464. <https://doi.org/10.1016/j.nanoen.2024.110464>
- [4] Nasajpour-Esfahani, N., Garmestani, H., Bagheritabar, M., Jasim, D. J., Toghraie, D., Dadkhah, S., & Firoozeh, H. (2024). Comprehensive review of lithium-ion battery materials and development challenges. *Renewable and Sustainable Energy Reviews*, 203, 114783. <https://doi.org/10.1016/j.rser.2024.114783>
- [5] Lu, Y., Lu, Y., Jin, C., Gao, R., Liu, B., Huang, Y., Yu, Y., Ren, J., Deng, Y., Tao, X., & Lyu, J. (2021). Natural Wood Structure Inspires Practical Lithium-Metal Batteries. *ACS Energy Letters*, 6(6), 2103-2110. <https://doi.org/10.1021/acseenergylett.1c00629>
- [6] Gomez, I., & Lizundia, E. (2021). Biomimetic Wood-Inspired Batteries: Fabrication, Electrochemical Performance, and Sustainability within a Circular Perspective. *Advanced Sustainable Systems*, 5(12), 2100236. <https://doi.org/10.1002/advsu.202100236>
- [7] Patil, R., Mishra, M., Liu, S., Jun, S. C., & Dutta, S. (2023). Wood Derived Flexible and Spongy Architectures for Advanced Electrochemical Energy Storage and Conversion. *Advanced Sustainable Systems*, 8(1), 2300275. <https://doi.org/10.1002/advsu.202300275>
- [8] Chen, C., Kuang, Y., Zhu, S., Burgert, I., Keplinger, T., Gong, A., Li, T., Berglund, L., Eichhorn, S. J., & Hu, L. (2020). Structure–property–function relationships of natural and engineered wood. *Nature Reviews Materials*, 5(9), 642-666. <https://doi.org/10.1038/s41578-020-0195-z>
- [9] Aslam, J., Ahsan Waseem, M., Zhang, Y., & Wang, Y. (2024). Eco-friendly Anode Materials for Lithium and Sodium-ion Batteries from Wood Sources. *Batteries & Supercaps*, 7(12), e202400302. <https://doi.org/10.1002/batt.202400302>
- [10] Huang, J., Zhao, B., Liu, T., Mou, J., Jiang, Z., Liu, J., Li, H., & Liu, M. (2019). Wood-Derived Materials for Advanced Electrochemical Energy Storage Devices. *Advanced Functional Materials*, 29(31), 1902255. <https://doi.org/10.1002/adfm.201902255>
- [11] de Paiva, M. V., Bettini, J., Colombari, F. M., Fazzio, A., & Strauss, M. (2022). Unveiling electrical anisotropy of hierarchical pyrolytic biocarbons from wood cellulose. *Journal of Materials Science*, 57(48), 21980-21995. <https://doi.org/10.1007/s10853-022-08033-7>
- [12] Wang, Z., Lee, Y.-H., Kim, S.-W., Seo, J.-Y., Lee, S.-Y., & Nyholm, L. (2021). Why Cellulose-Based Electrochemical Energy Storage Devices? *Advanced Materials*, 33(28), 2000892. <https://doi.org/10.1002/adma.202000892>
- [13] Mehta, S., Jha, S., & Liang, H. (2020). Lignocellulose materials for supercapacitor and battery electrodes: A review. *Renewable and Sustainable Energy Reviews*, 134, 110345. <https://doi.org/10.1016/j.rser.2020.110345>
- [14] Wang, Y., Yang, W., Zhang, C., Han, X., Han, J., He, S., Hu, J., & Jiang, S. (2023). Effect of precursor selection on the structure and Li-storage properties of wood-based hard carbon thick electrodes. *Industrial Crops and Products*, 198, 116664. <https://doi.org/10.1016/j.indcrop.2023.116664>
- [15] Zhang, W., Xu, Y., Li, H., Wang, C., Qin, B., Li, Z., Chen, Y., Jiang, K., & Zhang, H. (2020). Incorporating SnO₂ nanodots into wood flour-derived hierarchically porous carbon as low-cost anodes for superior lithium storage. *Journal of Electroanalytical Chemistry*, 856, 113654. <https://doi.org/10.1016/j.jelechem.2019.113654>
- [16] Chen, S., Nie, L., Shi, H. et al. (2023). Ultrafast Carbonized Wood of Electrode-Scaled Aligned-Porous Structure for High-Performance Lithium Batteries. *Transactions of Tianjin University*, 29(5), 387-394. <https://doi.org/10.1007/s12209-023-00365-y>
- [17] Zhang, W., Xu, B., Zhang, L., Li, W., Li, S., Zhang, J., Jiang, G., Cui, Z., Song, H., Grundish, N., Shi, K., Zhang, B., Fan, Y., Pan, F., Liu, Q., Du, L. (2022). Co₄N-Decorated 3D Wood-Derived Carbon Host Enables Enhanced Cathodic Electrocatalysis and Homogeneous Lithium Deposition for Lithium-Sulfur Full Cells. *Small*, 18(6), 2105664. <https://doi.org/10.1002/smll.202105664>
- [18] Wang, F., Cheong, J. Y., He, Q., Duan, G., He, S., Zhang, L., Zhao, Y., Kim, I.-D., & Jiang, S. (2021). Phosphorus-doped thick carbon electrode for high-energy density and long-life supercapacitors. *Chemical Engineering Journal*, 414, 128767. <https://doi.org/10.1016/j.cej.2021.128767>
- [19] Chen, Y., Wu, Y., Liao, Y., Zhang, Z., Luo, S., Li, L., Wu, Y. Q., & Qing, Y. (2022). Tuning carbonized wood fiber via sacrificial template-assisted hydrothermal synthesis for high-performance lithium/sodium-ion batteries. *Journal of Power Sources*, 546, 231993. <https://doi.org/10.1016/j.jpowsour.2022.231993>

- [20] Yang, Y., Li, N., Lv, T., Chen, Z., Liu, Y., Dong, K., Cao, S., & Chen, T. (2022). Natural wood-derived free-standing films as efficient and stable separators for high-performance lithium ion batteries. *Nanoscale Advances*, 4(7), 1718-1726. <https://doi.org/10.1039/D2NA00097K>
- [21] Zhang, G., Zhang, D., Yang, R., Du, Y., Wang, N., Guo, Z., Mai, X., & Dang, F. (2023). A Multifunctional Wood-Derived Separator Towards the Problems of Semi-Open System in Lithium-Oxygen Batteries. *Advanced Functional Materials*, 33(40), 2304981. <https://doi.org/10.1002/adfm.202304981>
- [22] Jia, S., Yang, S., Zhang, M., Huang, K., Long, J., & Xiao, J. (2020). Eco-friendly xonotlite nanowires/wood pulp fibers ceramic hybrid separators through a simple papermaking process for lithium ion battery. *Journal of Membrane Science*, 597, 117725. <https://doi.org/10.1016/j.memsci.2019.117725>
- [23] Lv, D., Chai, J., Wang, P., Zhu, L., Liu, C., Nie, S., Li, B., & Cui, G. (2021). Pure cellulose lithium-ion battery separator with tunable pore size and improved working stability by cellulose nanofibrils. *Carbohydrate Polymers*, 251, 116975. <https://doi.org/10.1016/j.carbpol.2020.116975>
- [24] Yerkinbekova, Y., Kalybekkyzy, S., Tolganbek, N., Kahraman, M. V., Bakenov, Z., & Mentbayeva, A. (2022). Photo-crosslinked lignin/PAN electrospun separator for safe lithium-ion batteries. *Scientific Reports*, 12(1), 18272. <https://doi.org/10.1038/s41598-022-23038-7>
- [25] Cho, H. W., Kim, J. W., Mugobera, S., Park, R., Jung, J., Ko, J. M., & Lee, K. S. (2023). Cellulose nanofibrils derived from pulp as a high performance separator for lithium-ion batteries. *Journal of the Chinese Chemical Society*, 70(11), 1965-1971. <https://doi.org/10.1002/jccs.202300160>
- [26] Dobryden, I., Montanari, C., Bhattacharjya, D., Aydin, J., & Ahniyaz, A. (2023). Bio-Based Binder Development for Lithium-Ion Batteries. *Materials*, 16(16), 5553. <https://doi.org/10.3390/ma16165553>
- [27] Li, J., Wang, A., Xiang, W., Liu, S., Li, L., Wu, Q., Liu, Y., Liu, Y., Nie, G., Nie, S., Yao, S., & Yu, H. (2024). Direct synthesis of a lithium carboxymethyl cellulose binder using wood dissolving pulp for high-performance LiFePO₄ cathodes in lithium-ion batteries. *Bioresource Technology*, 401, 130711. <https://doi.org/10.1016/j.biortech.2024.130711>
- [28] Hong, Y.-K., Kim, J.-H., Kim, N.-Y., Oh, K.-S., Kim, H.-I., Ryu, S., Ko, Y., Kim, J.-Y., Lee, K.-H., & Lee, S.-Y. (2025). Cellulose Elementary Fibrils as Deagglomerated Binder for High-Mass-Loading Lithium Battery Electrodes. *Nano-Micro Letters*, 17(1), 112. <https://doi.org/10.1007/s40820-024-01642-8>
- [29] Jeong, D., Shim, J., Shin, H., & Lee, J.-C. (2020). Sustainable Lignin-Derived Cross-Linked Graft Polymers as Electrolyte and Binder Materials for Lithium Metal Batteries. *ChemSusChem*, 13(10), 2642-2649. <https://doi.org/10.1002/cssc.201903466>
- [30] Chen, Z., Lu, M., Qian, Y., Yang, Y., Liu, J., Lin, Z., Yang, D., Lu, J., & Qiu, X. (2023). Ultra-Low Dosage Lignin Binder for Practical Lithium-Sulfur Batteries. *Advanced Energy Materials*, 13(17), 2300092. <https://doi.org/10.1002/aenm.202300092>
- [31] Li, Q., Cao, D., Naik, M. T., Pu, Y., Sun, X., Luan, P., Ragauskas, A. J., Ji, T., Zhao, Y., Chen, F., Zheng, Y., & Zhu, H. (2022). Molecular Engineering of Biorefining Lignin Waste for Solid-State Electrolyte. *ACS Sustainable Chemistry & Engineering*, 10(27), 8704-8714. <https://doi.org/10.1021/acssuschemeng.2c00783>
- [32] Yang, C., Wu, Q., Xie, W., Zhang, X., Brozena, A., Zheng, J., Garaga, M. N., Ko, B. H., Mao, Y., He, S., Gao, Y., Wang, P., Tyagi, M., Jiao, F., Briber, R., Albertus, P., Wang, C., Greenbaum, S., Hu, Y.-Y., Isogai, A., Winter, M., Xu, K., Qi, Y., & Hu, L. (2021). Copper-coordinated cellulose ion conductors for solid-state batteries. *Nature*, 598(7882), 590-596. <https://doi.org/10.1038/s41586-021-03885-6>
- [33] Dai, J., Fu, K., Gong, Y., Song, J., Chen, C., Yao, Y., Pastel, G., Zhang, L., Wachsman, E., & Hu, L. (2019). Flexible Solid-State Electrolyte with Aligned Nanostructures Derived from Wood. *ACS Materials Letters*, 1(3), 354-361. <https://doi.org/10.1021/acsmaterialslett.9b00189>