Nature’s hierarchical materials offer exceptional multifunctional properties thanks to their evolution over millions of years to reach the most optimized organization in terms of function, structure, or chemistry. Exploiting the unique features of natural materials through biomimicry offers an exciting research field with large potential for new discoveries. Wood, as one of the most fascinating biomaterials, combines unique mechanical properties, an anisotropic hierarchical porosity optimized to provide rapid, and low tortuosity pathways for nutrient/water transport, abundance, and biodegradability. Accordingly, wood has inspired scientists to mimic its outstanding properties in artificial analogues to develop batteries with remarkable electrochemical performance. For instance, its sophisticated structure can be transferred to solid-state materials through biomimetic templating to increase the lifespan and energy density of batteries, while its inherent hierarchical multi-channeled structure allows the synthesis of current collectors with enhanced ion and electron diffusivity. This Review highlights the recent progress into the application of wood as a hierarchically porous and renewable material to develop different battery components, including the cathode, the anode, the separator, and current collectors. The potential of wood-inspired batteries to lessen the pressure over critical raw materials and additional environmental sustainability benefits are highlighted within a circular economy perspective.

1. Introduction

The development of efficient and environmentally-sustainable energy storage is one of the cornerstones of a society based Circular Economy principles.[1,2] The integration of renewable energy and its efficient exploitation through electrochemical energy storage (EES) systems represent a research field in which relevant progresses are being done. Batteries, as a prominent EES example, can store and deliver on-demand power, ensuring a steady energy supply of inherently intermittent renewable-energy plants.[3] Batteries enable the transition from the current fossil-fuel based transportation model to an environmentally sustainable transportation.[4] Accordingly, EES implementation addresses some of the current global challenges, including global warming, waste management and natural resource depletion.[5–7]

Nowadays, secondary lithium-ion batteries (LIBs) dominate the market of batteries given their long cycle life, high energy density, low self-discharge and wide operating temperature.[8,9] LIBs have been widely implemented into portable electronics, hybrid vehicles and electric vehicles. Other batteries with remarkable electrochemical performance and bright potential to be commercially implemented in the near future are sodium-ion batteries (NIBs), lithium-sulfur (Li-S) batteries, lithium-oxygen (Li-O2) batteries or zinc-ion batteries (ZIBs), among others. Unfortunately, these technologies rely on the use of toxic and scarce cathodes such as LiCoO2, LiMn2O4, LiFePO4, or Li(Ni,Mn,Co)O2 (for LIBs),[10] NaCO2, NaFePO4 or Na1V2(PO4)3 (for NIBs),[11] or X2V2O7 (X = Zn, Mg, Ca, Na) for ZIBs.[12] Given their environmental sustainability and supply chain security issues, many of these
Materials have been recently (on 3rd September 2020) classified as critical raw materials (CRMs) by the European Commission (EC). Unless viable alternatives are provided, CRM scarcity may be exacerbated in the near future as the global energy demand is expected to increase by 27% from 2017 to 2040.[13]

Notable efforts are being carried out to develop novel materials and structures, either as active (anode, cathode) or inactive (separator, current collector) components, that can reduce the environmental footprint of current state-of-the-art batteries while keeping its electrochemical performance competitive (target energy densities ≥ 250 Wh kg⁻¹).[14] The large interest in developing more sustainable batteries is highlighted by the many international projects and networks contributing to sustainability requirements in batteries, such as the EU-funded Battery 2030+ initiative or the MELODY and SAFELiMOVE projects.[15] However, a simple switching from LiCoO₂ to more efficient Li(Ni,Mn,Co)O₂ cathodes, or from LIBs to higher energy density beyond Li-ion batteries could not be enough to solve material scarcity issues.

Beyond these efforts, nature has served since ancient times as an endless source of inspiration. Biological tissues have evolved over millions of years to reach the most optimized organization in terms of function, structure, or chemistry. Plants are a great natural example regarding energy production and storage, as the energy produced by photosynthesis is effectively stored thanks to their densely crammed veins efficiently transporting water.[16] Besides, the hierarchically structured characteristics resulting from the multi-scale assembly of distinct building blocks present in many biological tissues such as beetle scales provide unique optical and mechanical properties to the beetle’s exoskeleton.[17] Other hierarchical materials such as bone present a remarkable mechanical strength and toughness due to the different scales successfully maximizing energy dissipation via crack bridging, deflection, arrest and twisting processes.[18] Similarly, the dactyl clubs of Mantis shrimps are capable of withstanding repetitive impact forces up to 1500 N,[19] which originates from the layered helicoidal organization of the stomatopod dactyl club, which shows the so-called layered Bouligand structure.[20]

The transfer of the natural characteristics into synthetic materials inspired by nature is known as biomimicry or biomimetic design, and can be applied to resolve complex issues which otherwise could not be overcome with conventional approaches. One of the most widely known examples is the Gecko’s foot, which has inspired adhesives which allow people to climb walls.[21] The microscopic rough surface characteristic of Lotus leaves has inspired diverse self cleaning superhydrophobic surfaces.[22] As shown in Figure 1a, relevant natural examples having a Bouligand organization include the mechanically tough materials inspired by mantis shrimp dactyl club,[23] photonic materials derived from chitin,[24] or peptide self-assembly.[25] In comparison to these bottom-up assembly strategies, top-down approaches are more attractive as they enable replicating hierarchical structures in a simpler and more efficient fashion. In this sense, colors resulting from interference effects on nanostructures can be obtained exploiting biological materials composed by well-defined regular structures. As shown in Figure 1b, this can be achieved mimicking the ridge shape of the Morpho butterfly wings to obtain hierarchically nanostructured photonic crystals.[26]

### 1.1. Biomimicry in Energy Storage

Biomimetic approaches in energy storage hold a great potential for exploration. Inspired by biomimetic mineralization processes in which organic-inorganic materials coexist, flower-like composites consisting on multi-intercalated Mn₃O₄ nanosheets and N,P-doped carbon cores were synthesized for aqueous asymmetric supercapacitors.[27] Obtained large specific surface areas, in combination with the abundant active regions and the carbon core, provided fast electron transfer kinetics and an energy density of 76.96 Wh kg⁻¹. Embracing the internal structure of Fern leaves, the active surface area-volume ratio...
of electrodes for solar energy storage was increased by 10×.[28] The energy density increased 30 times in comparison with planar electrodes, showing the potential of natural structures in energy storage.

Natural geometries are an inspiration source to develop batteries with enhanced electrochemical performance. As schematically depicted in Figure 2a, the unique structure and work function of a sticky spider-webs inspired the synthesis of a 3D carbon nanotube network bearing γ-Fe₂O₃ nanoparticles to be applied as a LIB anode with discharge capacities of 822 mAh g⁻¹ at 0.05 A g⁻¹ (also successful for 3D freestanding NIB anodes).[29,30] Based on the nanoscale organization of

Figure 2. Biomimicry in energy storage: a) biomimetic design of spider-web-like composite web. Reproduced with permission.[29] Copyright 2017, Wiley-VCH GmbH; b) hierarchically porous carbon nanoribbons obtained from Portobello mushroom skins. Reproduced with permission.[32] Copyright 2015, Springer Nature; c) Schematic presentation summarizing the synthetic process of the biconcave structures for lithium-sulfur batteries. Reproduced with permission.[33] Copyright 2020, Elsevier; d) transmission electron microscopy image of carbon nanospheres resembling unicellular diatoms. Reproduced with permission.[34] Copyright 2015, American Chemical Society.
articulate cartilage, a solid Zn$^{2+}$ electrolyte was engineered to effectively suppress dendrite growth, enabling fast Zn$^{2+}$ transport and withstanding large bending deformations.[31] Inspired by biological tissues, Campbell et al. pyrolyzed the skins of Portobello mushroom to obtain a porous LIB anode with macro, meso, and micropores (260 mAh g$^{-1}$ after 700 cycles at C/5, Figure 2b).[32] As the natural presence of heteroatom-rich compounds plays an analogous role to KOH-activation or carbon materials, the need for harmful solvents or chemical activation agents is avoided. Zhou et al. were inspired by red blood cells to synthesize electrodes with concave structures and obtain shortened Li$^{+}$ diffusion distances (Figure 2c), resulting in a stable conversion of polysulfides to reach a capacity of 720 mAh g$^{-1}$ after 700 cycles at 2C (Li-S batteries).[33] As highlighted in Figure 2d, hierarchical porous graphitic carbon spheres with rich micro- and mesopores (resembling unicellular diatoms) guarantee smooth Li$^{+}$ transfer and high charge storage capability when applied as LIB anodes.[34] Other biomass sources have also been converted into carbon microstructures to function as LIB anodes, including allergic pollen grains (382 mAh g$^{-1}$ at C/10),[35] rice husk (400 mAh g$^{-1}$ at 75 mA g$^{-1}$),[36] or banana peel (1090 mAh g$^{-1}$ at 50 mA g$^{-1}$).[37]

1.2. Scope of the Review

Wood is formed by the assembly of cellulose, lignin and hemicelluloses,[38] from which cellulose-based,[39] and lignin-based,[40] batteries have been obtained. The good mechanical properties, low cost and electrochemical stability of cellulose has led a water-soluble cellulose derivative, carboxymethyl cellulose (2–10 € kg$^{-1}$), to be a preferred cathode binder.[41] Cellulose and lignin offer a high absorption affinity for polar solvent molecules thanks to their polar functional groups, making them good candidates for ionically conducting electrolytes.[42] The redox quinone/hydroquinone moieties of lignin serve to store charge both in the form of supercapacitors,[43] or battery cathodes.[44] These approaches generally involve bottom-up processes from nanocelluloses, or chemically-modified lignin, so the intrinsic unique structure of wood is lost. On the contrary, top-down approaches allow exploiting the inherent hierarchical multi-channeled structure of wood by incorporating novel functionalities to natural wood. This approach is often more efficient, involves fewer synthetic steps and it is feasible for scaling-up. Accordingly, in this Review we tap into the application of wood as a hierarchically porous and renewable material to develop different battery components, including the cathode, the anode, current collectors and separators (Figure 3).

Several Reviews covering the application of wood into diverse energy storage systems such as batteries and supercapacitors have been published in the last 5 years.[45–50] Though many of these works discuss the synthesis and electrochemical performance of wood-derived materials, the literature lacks a Review on how biomimetic approaches could be exploited to obtain wood-derived battery components with improved electrochemical and sustainability profiles. This work summarizes the recent advances on wood-inspired materials, linking fabrication, electrochemical performance, critical raw materials, bioeconomy, and environmental sustainability metrics, all framed within a Circular Economy perspective. Specifically, the most recent efforts (2016 onwards) to transfer the ordered arrangement of wood into solid materials for different battery chemistries (LIBs, Li-S, Li-O$_2$, NIBs, Zn-air, redox flow) are shown. The discussion is structured by the role of wood as battery component focusing on specific issues that need to be tackled, including the development of ultrathick (up to 1 mm) cathodes,[51] facilitating O$_2$ gas transport into metal-O$_2$ batteries,[52] highly conducting separator electrolytes,[53,54] or

![Figure 3. Schematic representation of the scope of the Review, highlighting the principal roles of wood-derived materials in different battery systems and their specific application into each battery component.](image_url)
providing a low tortuosity structure to facilitate fluent electrolyte transport paths in flow batteries.\(^5\) The last section highlights the future perspectives in the field, showing the need for new strategies to upgrade the electrochemical performance of the batteries as well as novel processing methods for freeform devices, together with material scarcity issues, bioeconomy, and the need for environmental impact disclosure through life cycle assessment (LCA) methodology.

2. Structure of Wood and Its Processing for Energy Storage

2.1. Hierarchical Structure of Wood and Its Use in Energy Storage

Biomimicry based on bottom-up approaches is a complex and non-environmentally friendly process. In times where establishing robust practices toward Circular Economy is crucial, there is an urgent need to provide efficient and simple synthetic top-down routes for the replication of renewable materials into battery components. Wood fulfills these requirements as it effectively functions as an abundant and biodegradable templating host to endow materials with a great level of structural complexity. Its long-range structural order composed by parallel long channels inspires novel architectures to fabricate synthetic analogues with great potential for adopting Circular Economy principles into the battery field.\(^5\)–\(^9\)

To meet the ever increasing demands of energy storage systems with higher energy density, longer cycle life, lower cost, and reduced toxicity, next generation EES devices must fulfill stringent requirements, including ability to host large active mass loadings, enhanced safety, superior mechanical performance, and should be based, as far as possible, in renewable materials. The three-dimensional hierarchical anisotropic structure and chemical composition of wood makes this renewable resource a sophisticated material remarkably fulfilling these stringent requirements.\(^10\)–\(^13\) Generally speaking, wood is a porous structural tissue found in the roots and stems of the trees.\(^13\) The anisotropic pore structure of wood is composed by abundant aligned vertical channels with micro/meso/nanopores and cellulosic fibrils.\(^14\) As schematically depicted in Figure 4a–e, the hierarchical structure of wood extends from the nanoscale of the cell wall, which in turn is composed by microfibril bundles composed by cellulose fibrils embedded within a lignin and hemicellulose matrix (Figure 4e, 40–50% cellulose, 20–35% hemicelluloses, and 20–30% lignin on a weight basis), to the microscale of the vessels and lumina and the macroscale of the wood stem (Figure 4a).\(^15\) Intermolecular hydrogen bonds and van der Waals forces between hydroxyl groups and oxygens of adjacent molecules promote the aggregation of multiple cellulose chains into fibrils. These cellulosic fibrils have crystalline regions separated by amorphous regions and are composed by d-glucose units linked through β-(1→4)-glycosidic bonds. The intra- and interchain hydrogen bonding network makes cellulose a relative stable polymer, and gives the cellulose fibrils high axial stiffness.\(^15\)

At the microscale level, the lumen (the open interior of the cell) of the tracheids, and highly oriented fibers are found. Wood cell walls have middle lamellae with primary (P) and secondary (S1, S2, and S3 layers) cell walls (Figure 4e). Micrometer-sized pits on the cell walls in trees redistribute the ion flux and function as valves between adjacent conduits to guarantee the uniform distribution of xylem sap to the whole tree. This feature can be exploited to fabricate pit-membranes working as an artificial solid-electrolyte interphase and achieve spatially homogeneous Li\(^+\) flux.\(^15\) Single vessels can run along the tree trunk over several meters with diameters in the range of tens to hundreds of microns (Figure 4b,c).\(^15\) This structure, with a straight alignment of hollow channels along the longitudinal direction, has been designed by nature over 270 millions of years to provide rapid and low tortuosity pathways for nutrient and water transport needed for the photosynthesis.\(^15\) When cut perpendicular to its longitudinal direction, the cross section of dried wood shows the opening of these capillaries constituted by aligned tracheids (known as lumens) surrounded by cell walls. The lumina can range from few to nearly 500 μm. The characteristics of the annual growth rings vary depending on the season; in the earlywood Springwood is formed, with thin cell walls and larger lumen area; while during the latewood the so-called Summerwood presents thick cell walls and narrow lumina (Figure 4d).\(^15\) The combination of hierarchical structure, anisotropy, and different biopolymers in both crystalline and amorphous forms confers the outstanding mechanical properties to the wood,\(^15\) combining the often elusive high strength and toughness characteristics.\(^15\)

2.2. Processing Wood into Functional Materials for Energy Storage

In sharp contrast with fiber disassembly processes characteristics of pulp and paper industries, the hierarchical structure orientation of native wood has been retained following a top-down approach to synthesize materials for diverse applications. For example, it has been used for the development of transparent materials (optical transmittance of 85% and a haze of 71%),\(^16\) luminescent films for optical lighting applications,\(^17\) for the fabrication of membranes for autonomous water transport and fog collection,\(^18\) to obtain highly efficient “cross-flow” filtration devices for the remediation of pollutants from water,\(^19\) oil/water separation systems,\(^19\) thermal energy storage,\(^19\) or nucleating material for metal organic frameworks.\(^19\)

In the field of energy storage, the unique 3D hierarchical architecture and open porosity structure of wood provides excellent properties to synthesize materials with large ionic/electronic conductivities, high surface area and improved mechanical stability. For instance, wood can be used as template material for the synthesis of redox active materials (LiCoO\(_2\), LiNi\(_{0.5}\)Mn\(_{0.5}\)O\(_4\)) inside the pores of wood slices, and after a calcination step where the organic part is removed, the final material presents a highly porous structure and high surface area, that promotes a better wetting with the electrolyte and therefore an improved utilization of the active material. In spite of the benefits of bare wood, depending on the source, the pore size distribution could be too small for an efficient performance (electrolyte uptake, facilitated material deposition, etc). Therefore, in order to widen the pathways for more effective material transport and profit from the large specific
area of the porous structure of wood while maintaining its aligned pores, a delignification step is often used. This process consists on the partial or total extraction of lignin part of the cell wall structure by aqueous alkali or oxidative treatment.\cite{47} Lignin is considered the “glue” that provides high mechanical rigidity to wood cell walls by joining cellulose and hemicellulose structure through intermolecular forces; therefore, after the extraction, delignified wood presents a softer, and more flexible character.\cite{47}

By depositing an electronically conductive material (e.g., carbon nanotubes) along the wall of the pores, a flexible and conductive material can be obtained for advanced flexible batteries.\cite{76}

All in all, the main strategy to provide high electrical conductivity to wood-based materials relies on the carbonization process under inert atmospheres. Wood-derived carbon significantly promotes a high ion and electron transport due to its porous anisotropic hierarchical structure and high electrical conductivity thanks to the continuous carbonaceous framework. The first examples showing the conversion of monolithic wood structures into carbons which kept the cellular structure with no pore collapse were provided by Byrne and Nagle in 1997.\cite{77,78} In commercial LIBs, current collectors and separators are \(\approx 10–25\) \(\mu\)m thick, while electrodes are \(\approx 40–80\) \(\mu\)m thick, resulting in less than the half of the battery (by weight) active for ion storage. In this sense, thick and dense electrodes are desirable to improve both the gravimetric and volumetric energy density in batteries. However, thick electrodes have
several challenges: i) a higher electrical resistance resulting in polarization; ii) slow ion diffusion through the electrode resulting in low rates for charge and discharge; iii) difficulty to make uniform electrodes free of cracks, and of uniform composition. Conversely, the straight channels with low tortuosity of wood enable ultrathick battery electrodes in the millimeter scale with good conductivity and appropriate mechanical stability, providing higher energy density by reducing the relative content of non-active components. [79] Similarly, free-standing cathodes with no binder and absence of current collector could also be obtained, providing increased energy densities. [80]

Furthermore, a simple change on the carbonization atmosphere or wet loading a heteroatom source into wood precursor can promote the introduction of heteroatoms in the carbonaceous structure. Therefore, besides the electrical conductivity, this strategy provides further functionalities to wood derived carbon such as electrocatalytic activity towards oxygen reduction reaction (ORR) and oxygen evolution reaction (OER), nucleation sites for electrodeposition or redox activity for ion intercalation.

The proper choice of different wood species for specific applications is mainly driven by its physico–chemical and cost characteristics. As structural features play a dominant role when defining the electrochemical performance of wood-derived materials, it results important to distinguish the different species according to their structural characteristics. Cell type, size, shape and the lumen/cell wall ratio varies depending on the wood species. [81] Densities as varied as 150 kg m\(^{-3}\) for balsa wood (Ochroma pyramidale) to 820 kg m\(^{-3}\) for Blue Gum (Eucalyptus) can be found, while the Young’s modulus ranges from 3.71 to 18.76 GPa, respectively (further information in Figure 5). Softwoods belong to rapid growing trees comprising needle-like leaves, and present a highly porous structure composed by water-conducting cells parallel arranged to the growth direction. On the contrary, hardwoods (generally originating from trees having broad leaves, often deciduous trees going dormant in the winter) contain tightly packed thick fiber cells together with cells that conduct water, have with lower porosity degrees (higher specific densities) and present increased mechanical strength. [82] The macrostructural characteristics also depend on the species within a specific group. Additionally, annual growth rings in the earlywood (Springwood) and latewood (Summerwood) are markedly different. [83] According to Table 1, many hardwood species have been applied into electrochemical energy storage devices in general and into batteries in particular. The potential of softwoods remains open to further development as there are still relevant softwoods which have not yet investigated as platform materials into batteries, including fir, hemlock, redwood, or cypress. In fact, a priori, softwoods may be preferred for battery applications as their inherently highly-porous character may facilitate ion/electron diffusion processes. To facilitate future follow-on works,
Figure 5 schematically summarizes the main characteristics of representative wood specifies with potential in the energy storage field. Average dried weight, pricing, Young’s modulus, grain texture (relative size of the wood-cells), orientation of wood-cell fibers, and wood sustainability are highlighted. This diversity in hierarchical structures and mechanical properties must be exploited in the near future to obtain materials with tailored and complex geometries.

### 3. Wood as Active Material

#### 3.1. Intercalation Carbon Anodes

Carbon-based materials are the predominant anodes in current and near-future battery technologies mainly thanks to their high electronic conductivity, high reversibility, and stability on the electrochemical storage of alkali metals (Li, Na, K, etc).\textsuperscript{[117–119]} Besides, the easy processing through hydrothermal carbonization of widely available precursors (sugars, polymers, epoxy resins, etc), ensures cheap and easily scalable industrial manufacturing processes.\textsuperscript{[120]} Hence, the wide availability (thus low cost), and its intrinsic interconnected porous structure offering high surface area makes wood a potential candidate as precursor for anode materials. In this context, Yoon and coworkers presented a systematic study on the effect of heat pre-treatments (prior to carbonization) of mangrove wood on the electrochemical performance as anode materials for LIBs.\textsuperscript{[121]} They observed that by varying the time, temperature, pressure, and gaseous environment, the chemical composition regarding C to H and O/C ratios could be optimized.

In this way, a synthesized hard carbon showed a discharge capacity up to 424 mAh g\(^{-1}\) with an 80% Columbic Efficiency (CE) in a half-cell configuration versus metallic lithium. Further exploring the effectiveness of wood as low-cost precursor material for carbon-based anodes, Ji and coworkers evaluated camphor-wood derived carbon electrodes for NIBs.\textsuperscript{[122]} After a simple one-step carbonization process, the carbaceous material maintained the hierarchical porous structure and a high surface area of 678 m\(^2\) g\(^{-1}\). The electrochemical performance in a slurry-processed electrode containing wood derived carbon versus metallic sodium revealed very high C-rate capability up to 5 A g\(^{-1}\) and excellent cycling stability with almost constant capacity in CE expanding up to 5000 cycles. The suitability of wood-based carbons for different battery technologies was further confirmed analyzing the effect of wood source as anode materials for LIBs and NIBs.\textsuperscript{[123]} Subjected to a first delignification reaction to obtain individual fibers, and followed with a two-step carbonization process, different woods including bamboo, pine, poplar, and paulownia were transformed into conductive carbonaceous materials maintaining the hollow tubular structure of native wood. The variety of sources, the bamboo wood showed the best performance in a LIB configuration with a discharge capacity of 435 mAh g\(^{-1}\) at 50 mA g\(^{-1}\); while reversible capacities of 320 mAh g\(^{-1}\) were obtained in a NIB at 50 mA g\(^{-1}\). The next step towards the practical performance of wood-derived carbon anodes was performed by Hu and coworkers, who used a poplar carbon derived hard carbon as anode versus Na\([Cu_{1/9}Ni_{2/9}Fe_{1/3}Mn_{1/3}]O_2\) cathode material in NIB full-cell configuration (Figure 6a).\textsuperscript{[103]} An impressive electrochemical stability after 1200 cycles at 5C delivering nearly 55 mAh g\(^{-1}\) (the 71% of the initial capacity) with a negligible

| Wood specie       | Intended application                                                                 | Ref.          |
|-------------------|--------------------------------------------------------------------------------------|---------------|
| Softwood          | Transparent wood for energy efficient buildings                                      | [83]          |
|                   | Template for LIB cathodes, Li-O\(_2\) cathode, NIB anode                              | [51,80,84,85] |
| Red cedar         | Supercapacitor electrode                                                             | [86]          |
| Spruce            | Oil/water separation, CO\(_2\) adsorption, water transport                           | [64,72,75]    |
| Chinese fir (Cunninghamia) | Separator working as artificial solid-electrolyte interphase                | [53]          |
| Hardwood          | Transparent wood, solar steam generation, supercapacitor, CO\(_2\) adsorption        | [75,87–91]    |
| Basswood          | Template for Li metal anode, current collector, Li-S cathode, Li-O\(_2\) cathode, template for Na metal anode, redox flow battery electrodes, template for solid-state electrolytes | [54,55,79,92–96] |
| Balsa             | Optical lighting                                                                     | [71]          |
| Poplar            | Luminescent transparent wood, flexible wood, flexible sponge, Li anode, Li-O\(_2\) cathode, Li-O\(_2\) cathode | [52,97–101]    |
| Fraxinus mandshurica | Li-O\(_2\) cathode, NIB anodes                                                        | [104–106]     |
| Beech             | Water purification, supercapacitors, CO\(_2\) adsorption, superhydrophobic surfaces  | [75,108–111]  |
| Eucalyptus        | Supercapacitor                                                                      | [112]         |
| Birch             | Template for LIB cathode, Li-S cathode                                               | [114,115]     |
| N.R.              | NIB anode                                                                            | [116]         |

N.R.: not reported. Non-shadowed rows correspond to batteries. The corresponding reference is provided in the right column.
CE drop of 0.8% was obtained. This work pointed out that the benefits of poplar wood derived carbon make it a suitable anode for future commercial NIBs. On the contrary to the previously described works which mainly focused on obtaining hard (amorphous) carbons from wood, Park and coworkers developed a method to produce highly crystalline graphitic carbon from bio-based precursors in a simple way. They studied the catalytic graphitization of glucose, cellulose, lignin, hardwood, and softwood by dry mixing the precursor with iron powder, heating up to 1200 °C and acid washing with concentrated HCl (37% w/w). The characterization revealed that the graphite produced from softwood exhibited the highest degree of graphite purity, which was further characterized in a half-cell versus lithium, showing high C-rate capability up to 2C, and high reversibility over 100 cycles at 0.5C.

The aligned structure and porosity that allows the natural mass transport throughout the trunk for feeding the tree is considered as one of the most interesting features of wood regarding battery applications. Laying in this concept, wood has been used as a precursor material for the fabrication of freestanding anodes, benefiting for the low tortuosity porous structure and high electronic transport through the carbonaceous structure. This feature promotes good electrolyte penetration and the associated fast ionic transport throughout the anode, allowing the fabrication of thick electrodes aiming at increasing the energy density. In this regard, Hu and coworkers presented a self-standing anode for NIBs produced directly from carbonized hardwood slices. By cutting wood parallel to the growing direction of the tree it is possible to keep the microchannels oriented directly in contact to the electrolyte; whereas if the cut is vertically aligned to the grow direction, the pores appear horizontally aligned (Figure 6b). In this way, with parallel cut wood, ultrathick electrodes of 850 µm with an aerial capacity of 13.6 mAh cm–2 were achieved, highly exceeding the current areal capacities of 3.5 mAh cm−2 offered by LIBs. Furthermore, the low tortuosity and mechanical stability proved to be beneficial for cycling performance, demonstrating a full cell comprising the ultrathick wood-based anode and Na3V2(PO4)3 cathode that maintains the 95% of the initial capacity (76 mAh g−1) over 350 cycles with a stable CE of 99.4%. Taking advantage from the high porosity of balsa wood, the lightest wood in nature, Yu and coworkers followed similar strategy to prepare freestanding carbon foam anode for potassium-ion batteries (PIBs). After delignification and two-step carbonization, microscope imaging revealed that not only the porous structure was maintained, but that carbon atoms tend to rearrange into short-range ordered structures during the second carbonization step. The X-ray photoelectron spectroscopy (XPS) experiments revealed oxygen-rich carbonaceous material, which would promote an enhanced wettability allowing fast ionic transport through the carbon foam. The electrochemical test revealed that the balsa wood derived carbon obtained at 800 °C possess the best electrochemical
performance in terms in C-rate capability, delivering a discharge capacity of 165 mAh g^{-1} at 2 A g^{-1}, as well as capacity retention along 2500 cycles, more than 1-year test, with a negligible decrease on the CE. This outstanding performance was largely ascribed to the stable 3D interconnected carbonaceous structure of balsa wood derived carbon that accommodates the volume changes during repeated deposition/dissolutions of potassium ions.

3.2. Active Materials for Metal Air Batteries

Taking into account that the main active materials of the cathode are gaseous compounds existing in the atmosphere (mainly O$_2$ and CO$_2$), metal air batteries (MABs) present a trade-off between theoretical energy density, and cost, placing them among the most promising battery system to replace LIBs.$^{[126,127]}$ Besides, the ability to couple the electrochemical reduction of O$_2$ with a variety of metal anodes (Li, Na, Zn, Al, etc) allows a high versatile energy storage system that can embrace a wide variety of applications such as small and flexible electronics, electric vehicles, or stationary applications.$^{[126]}$

However, typically the materials used are nano and/or micro sized, hindering the processability limiting the full potential of MAB performance either by causing side reactions due to their high specific area or by blocking the pores needed for the diffusion of gasses throughout the cathode.$^{[128]}$

One of the key parameters of MAB relies on the design of electrocatalyst that enhance the sluggish kinetics of oxygen redox processes (ORR and OER). The most widely used materials presenting high catalytic activity are composed on Pt or Ru, which are scarce materials, toxic, and dramatically increase the cost of the cell.$^{[129,130]}$ Alternatively carbon based materials have attracted increasing attention as electrocatalyst thanks to their intrinsic properties (high conductivity, easy preparation, modification ability, etc) as well as the large and sustainable bio-based feedstocks.$^{[131,132]}$ Till the date, plant- and animal-biomass resources have been proven efficient to synthesize advanced nanostructures for ORR.$^{[133]}$

In this regard, wood derived carbons show up as potential materials for free-standing cathodes for MABs, avoiding the use of binders and benefiting of easy construction steps. Furthermore, its intrinsic aligned porous structure enhances the transport of gases and electrolytes along the channels and electronic conductivity through the carbonaceous structure. In this regard, Luo and coworkers proved the suitability of pine wood-derived carbon as self-standing cathode for lithium air batteries.$^{[80]}$ To provide electrochemical activity for ORR and OER, the wood-derived carbon was doped introducing nitrogen atoms to the carbon structure by a high temperature carbonization step in presence of NH$_3$. Importantly, this step did not alter the structural integrity of wood-derived carbons. In actual fact, the surface area of the N-doped wood derived carbon resulted to be 10 times higher from 75 to 745 m$^2$ g$^{-1}$ than without NH$_3$ treatment, while the mechanical strength increased from 500 to 850 kPa of loading stress. The redox activity was studied in a lithium air battery, showing a discharge capacity of almost 2 mAh cm$^{-2}$ and a voltage of 2.7 V, similar to conventional cathodes. Besides, the cells were cycled at an absolute capacity of 1.5 mAh with a stable energy efficiency of 60% over 20 cycles. In order to enhance the performance of wood derived carbon as cathodes in MABs, Peng and coworkers increased the active surface area applying a partial digestion process to the cellulose walls through enzymatic hydrolysis as is shown in Figure 7a.$^{[113]}$ This approach is not only an energy saving method as it uses an incubation process at 40 °C, but also circular due to the easy recovery of the enzymes from the digestion step. After a subsequent carbonization in presence of NH$_4$Cl, the surface area increased from 750 m$^2$ g$^{-1}$ of the not-digested wood to 1040 m$^2$ g$^{-1}$. Thanks to the structure widening, a “breathable” cathode was obtained, enabling a discharge capacity using an alkaline gel polymer electrolyte (6 m KOH in PVA) of 749 mAh g$^{-1}$ at 10 mA cm$^{-2}$ and a peak power density of 36.2 mW cm$^{-2}$ at 0.7V. Nitrogen-doped wood derived carbon was remarkably stable as it could be cycled over 80 times with a stable overpotential of 0.77 V and a round-trip efficiency of 54%.

Thanks to the multichanneled structure of wood-derived carbons and the fast mass/ionic/electron transport within the electrode, wood-inspired materials have been used in additional MAB configurations. In this regard, Tang and coworkers optimized the heteroatom doping of basswood derived self-standing cathode for its use in different energy storage systems.$^{[89]}$ Figure 7b summarizes the N- and S-heteroatom doping process, that were introduced into the carbonaceous structure of a delignified basswood sample by loading trithiocyanuric acid and a subsequent carbonization process in presence of ammonia. The highly hierarchically aligned porous structure of basswood was preserved and, its catalytic activity towards ORR was studied in 6 m KOH. It was observed that the dual doping of S and N heteroatoms resulted in a synergetic effect on high electron donor nature and enhancement of charge density of carbon atoms (not specific values provided), leading an outstanding ORR activity, very close to the standard Pt/C systems. At low current densities the open structure of wood-derived carbon favors the transport kinetics to reach a peak power density of 241 mW cm$^{-2}$ at 0.7 V as opposed to the 192 mW cm$^{-2}$ delivered by the Pt/C catalyst system. This is translated into a more stable voltage plateau during galvanostatic cycling at different current densities, specially at high C-rates (regarding metal air batteries) of 50 mA cm$^2$, where the system Pt/C dropped down to 1.05 V whereas the wood-derived cathode maintained 1.12 V. Furthermore, the chemical stability of the porous carbon allowed over 100 cycles with electrolyte refilling steps at 10 mA cm$^2$ (MABs typically require continuous electrolyte filling to operate), showing a stable voltage plateau around 1.3 V. These results were confirmed in a practical zinc air battery, where wood derived carbon was used as catalyst in the gas diffusion layer cathode.

4. Wood as Ionic/Electronic Conductive Framework

4.1. Current Collector

The current collector is an essential component of electrodes, being responsible of the electrical connection of the electrode.
system with the external circuit of the battery. In other words, it is the element that collects/delivers electrons to the electrode. Therefore, it has to fulfill several requirements, namely, high electrical conductivity, electrochemical stability in the battery working voltage window and mechanical stability.\cite{134} As it is a passive material that does not contribute to store energy, it should be a low density material and its fabrication must be economically competitive.\cite{134} In this regard, carbonaceous current collectors possess many advantages over conventional metal foils (Al, Cu, Ni, etc), especially in terms of density, mechanical properties and price (Figure 8a). For example, Cu and Ni densities are as high as 8.96 and 8.90 g·cm\(^{-3}\) respectively, while native wood density typically ranges from 0.27 to 0.76 g·cm\(^{-3}\).

Nowadays, the most widely extended process to deposit the electrode materials onto current collectors relies on casting a wet mixture of active material, a conductive additive, and a binder on the surface of a flat sheet of current collector. This method, in spite of benefits such as low cost and easy scalability, presents some limitations for the development of thick electrodes, including small contact surface area and electrode mechanical collapse. As a result, the development of high energy density batteries is restricted. In this regard 3D current collectors arise as promising architectures thanks to the hierarchical structure, high surface area and high porosity that allow increased mass loading without decreasing the electrochemical performance of the electrode (Figure 8b).\cite{135}

In this context, wood turns up as a sustainable and low-cost raw material for 3D current collectors, potentially enabling high energy density batteries. Its intrinsic aligned, hierarchical and interconnected porous structure allows a high contact area for electrolyte impregnation while providing a high electrically conductive 3D carbonaceous framework. As a result, high utilization efficiency of active material could be achieved even at high C-rates and very high loadings. As a proof of concept, Chen and coworkers presented the feasibility of wood-derived carbon...
frameworks for ultrathick current collectors for LIBs. Natural basswood was subjected to two step carbonization process to obtain up to 800 \( \mu \text{m} \) thick mechanically stable and highly conductive carbon framework. The highly porous structure, with porosities up to 81\%, allowed an ultrahigh loading of active material of nearly 60 mg cm\(^{-2}\) of lithium iron phosphate (LiFePO\(_4\)). No need of inactive materials such as conductive additives or binders was required, further increasing the energy density of the final cell. As a result, outstanding discharge values of 26 mWh cm\(^{-2}\) and 323 Wh L\(^{-1}\) were obtained, comparable to the best reports on LiFePO\(_4\) cathodes so far. Besides, thanks to the fast electron conduction along the carbon framework and the efficient ion transport due to the low tortuosity structure, high C-rate capability can be achieved. Interestingly, the excellent mechanical stability of the cathode allows high stability during cycling, delivering the 76\% of the initial capacity (3.8 mA cm\(^{-2}\)) after 140 cycles at 2 mA cm\(^{-2}\) and the 61\% after 1000 cycles at 15 mA cm\(^{-2}\).

A very similar approach was followed by Li and coworkers using wood-derived carbonaceous current collectors in sulfur cathodes for Li-S batteries. Sulfur was loaded through melt-diffusion process (Figure 9a), achieving a high loading of 78 mg cm\(^{-2}\) in comparison with most of the works which remain limited to relatively modest mass loadings of \( \approx 2 \) mg cm\(^{-2}\) due to the conductive additives needed to compensate the insulating
nature of sulfur and the volumetric changes occurring during cycling.\cite{136} To avoid the rapid capacity fading of Li-S batteries arising from the sulfur shuttle effect, rGO was added to wood-derived carbon paired with a gel composite electrolyte based on a polyethylene glycol (PEG)/LiTFSI matrix and a Li$_7$La$_3$Zr$_2$O$_{12}$ ceramic filler. Although these strategies hinder the electrochemical performance of the sulfur cathode, the low tortuosity of wood-derived current collector allowed fast ion kinetics within the thick cathode, leading to very high, and stable areal discharge capacity of 6 mAh cm$^{-2}$ at 1.56 mA cm$^{-2}$ over 50 cycles, exceeding the capacities delivered from the conventional sulfur cathodes with sulfur loadings of 1.5–2.5 mAh cm$^{-2}$. Furthermore, the simplicity of the sulfur loading allows obtaining ultrahigh loading cathodes up to 21 mg cm$^{-2}$ with discharge capacities of 11 mAh cm$^{-2}$, representing one of the largest values in the recent advances of high areal capacity Li-S batteries.

Further extending the multifunctional viability of wood derived current collectors, Han and coworkers combined the low tortuosity carbonaceous materials with red phosphorous (red-P) and applied those materials in NIBs.\cite{85} The structural benefits provided by wood, as well as the high conductivity of the carbonaceous framework achieved after the carbonization process alleviate the principal drawbacks of red-P as cathode material, namely, high volume change during cycling and low electronic conductivity. The vaporization-condensation method allowed obtaining an ultrathick cathode of 800 µm with an ultrahigh-loading of 8.4 mg cm$^{-2}$. Obtained discharge capacities of 18 mAh cm$^{-2}$ at high current densities of 0.6 A g$^{-1}$ were ascribed to the homogeneous distribution of the high loading of red-P along the conductive, anisotropic, and aligned wood-derived carbon network. Besides, the structural stability of the current collector leads to improved cycling stability over 1000 cycles, delivering 3.5 mAh cm$^{-2}$ with negligible CE fading at 0.6 A g$^{-1}$. Importantly, these results are among the best reported so far in the use of red-P based cathodes for NIBs.

With the aim of increasing the energy density of alkali-ion batteries, the research stream has been mostly driven towards the use of pure metals (Li, Na, etc) as anodes, avoiding the use of intercalation based systems.\cite{128,138} In spite of the achievement of a dramatic increase of energy density, pure alkali metal anodes present several drawbacks regarding manipulation, side reactions and inhomogeneous dissolution/deposition processes that lead to non-uniform deposits that eventually evolve in dendritic structures.\cite{128} These dendrites tend to grow towards the cathode across the electrolyte and separator causing the short-circuit of the system, resulting in a dramatic failure of the cell and potential safety hazards.\cite{139} In this sense, 3D structured current collectors are attracting increasing attention for scalable and practical high energy density alkali metal cells.\cite{92} This strategy relies on the control
of plating-stripping processes through the confinement of anode materials within the high surface area and electronically conductive network, thus avoiding the evolution of undesired structures that could lead to dendrites. In this context, taking advantage of the inherent structure of wood and its proved potential as 3D current collector, Zhang and coworkers prepared a composite anode by infusing molten metallic lithium into the aligned pores of carbonized basswood. It is worth to mention that the wettability between Li and carbonized wood was enhanced by depositing ZnO nanoparticles onto the porous structure, leading into a fast flooding (>1 s) of molten Li within the pores. Electrochemical tests through symmetric cells revealed an overpotential improvement from the very first cycle (104 vs 173 mV) compared with the bare wood derived carbon, which was maintained over cycling steps at every current density, from 0.5 to 3 mA cm$^{-2}$. A similar strategy was followed by Luo and coworkers, who encapsulated metallic sodium into a wood-derived carbonaceous current collector by simply infusing it in molten Na. The electrochemical tests confirmed the improvement on the dissolution/deposition redox processes of the composite at 1 mA cm$^{-2}$, showing stable overpotential along 500 cycles, contrarily to bare metallic foil that failed at around 100 cycles due to the evolution of sodium dendrites. As infusing the current collector with a molten metal that could result in undesired metal waste formation, the electrodeposition of the anode material in the channels of the 3D structure wood based current collector is seen as a preferred approach. Taking into account that the homogeneity and morphology of the deposited metal is driven by the nucleation step which largely relates to the surface heterogeneities; “impurities” within the porous structure of wood carbons were introduced as nucleation agents. This way, several nucleation points could be induced, gaining control over the growth of Li deposits during the electrodeposition. This strategy allows the fabrication of more compact and homogeneous Li structures when compared with the bare wood-derived carbon. Accordingly, Jin and coworkers studied the effect of the composition of these nucleation agents during Li metal electrodeposition process, finding that the presence of MgO nanoparticles effectively reduced the nucleation overpotential (Figure 9b). Subsequently, a balsa wood derived carbon was loaded with MgO nanoparticles prior to the Li loading through electrodeposition. The electrochemical performance of the composite anode in a symmetrical two-electrode cell revealed that the presence of MgO nanoparticles enhanced the stability of the anode during plating-stripping processes even at ultrahigh current density of 15 mA cm$^{-2}$, with negligible CE decay over 100 cycles. Furthermore, the composite anode delivered higher capacity and improved cycling stability versus a Li foil in a full cell versus a LiCoO$_2$ cathode. This strategy showed the approach stability improvement of Li as anode materials, and was further confirmed by Song and coworkers who followed the same strategy to load silver nanoparticles as nucleating agent. This composite anode presented an improved stability at 1 and 3 mA cm$^{-2}$ over 450 and 300 cycles, respectively. No signs of failure were found as the stable plating/stripping process of lithium avoided the formation of dendritic structures. Furthermore, the hysteresis on the charge–discharge process of a LiFePO$_4$ full cell was decreased with the composite anode, allowing more stable cycling process at 1C over 200 cycles with no obvious overpotential increase (75 mV) compared with bare Li foil (200 mV).

### 4.2. Free Standing Electrodes for Metal Air and Redox Flow Batteries

The natural transport ability of wood with aligned and hierarchical porous structures aroused a notable interest for its application in battery systems where multiphase flow is required. For instance, MABs require a continuous flow of oxygen during the ORR/OER processes, while Li$^+$ is transported into the cathode through its porous structure. Therefore, wood promises a sustainable option for freestanding cathodes, benefiting from its architecture that ensures a fast diffusion of O$_2$ along thick cathodes. For instance, Song and coworkers took advantage of this structure to build thick and breathable cathodes. After loading Ru nanoparticles as catalyst for ORR/OER reactions (Figure 10a), wood-derived cathodes showed excellent stability with constant overpotential over 100 cycles at 0.1 mA cm$^{-2}$. This performance was extended to higher current densities, where the overpotential barely increases at 0.1, 0.2, and 0.5 mA cm$^{-2}$, obtaining capacities of 9, 7, and 4.5 mAh cm$^{-2}$, respectively. Besides, the open porous structure allows ultra-thick cathodes up to 3 mm, which is translated into ultrahigh capacity of beyond 65 mAh cm$^{-2}$. Those results further confirm that the fast O$_2$ transport along the cathode owing to the low tortuosity aligned porous structure provided by wood is beneficial for batteries. The suitability of wood-derived carbons for lithium-air batteries was also studied by Zhu and coworkers, that followed a similar strategy to build up a cathode filled with RuO$_2$ catalysts. Besides the impressive electrochemical results (charge terminal potential below 3.8 V and specific areal capacity of 8 mAh cm$^{-2}$ at 0.1 mAh cm$^{-2}$) with these poplar-wood derived cathodes that showed very stable cycling stability over 100 cycles with above 87% efficiency, they proved the regeneration and recyclability of the cathodes, representing a step further within the Circular Economy perfective applied into MABs. The ease to load different kind of catalyst for ORR/OER reaction and the stability of wood-derived carbon is boosting its use in related applications. For instance, Zhao and coworkers loaded Co-MOF into wood-slices, that after a carbonization process become Co$_2$O$_3$-containing wood derived carbon. The excellent electrochemical performance of these cathode compared to conventionally processed ones relies on the high surface area of the carbon network that spreads the electrolyte over the cathode through capillary forces, without flooding and obstructing the pores. These features result in extremely stable performance over 400 cycles at 1 mA cm$^{-2}$ with a cut-off capacity of 1 mAh cm$^{-2}$ with a negligible overpotential increase.

Among the variety of ESS systems aimed for large scale applications, redox flow batteries show up as a potential candidate thanks to their unique ability to decouple energy from power. Indeed, the energy density is governed by the size of the electrolyte tanks, while the power is related with the electrode engineering. Within those batteries, vanadium redox flow batteries (VRFBs) are bringing an increasing attention
for large scale storage applications as cross-contamination effects in the anolyte and catholyte are reduced. However, there are some issues related with the electrodes that limit the performance of the cells in terms of charge–discharge overpotential and power capacity. In this regard, wood offers a bio-designed porous structure optimized to provide flow pathways that could improve the specific surface area for more abundant redox reaction sites to promote improved redox reaction kinetics.

Jiao and coworkers proved the potential of carbonaceous basswood-based electrodes as cost-efficient and sustainable materials for VRFBs. Although the inherent porous structure of wood provides oriented flow pathways for the electrolyte, the vanadium reactant concentration gradually decreases along the electrode. Therefore, macroscopic holes were drilled in the wood slices to achieve an enhanced mass transfer over the entire electrode. With a remarkable electronic conductivity of 20 S cm⁻¹, the VRFB exhibited high coulombic, voltage and energy efficiencies of 93.1%, 81%, and 75%, respectively. Besides, its improved electrochemical and mechanical stability allowed highly stable efficiencies over 200 cycles at 40 mA cm⁻².

Figure 10b shows the benefits of drilling the electrodes by mathematical models, showing improved mass transfer thanks to the introduced macroscopic pores. Similarly, Yang and coworkers improved the flow over the electrode by chemically modifying the wood-derived carbon. Carboxylic acid (–COOH) groups were introduced onto pore surfaces by simple nitric acid treatment, leading to a dramatic increase of wettability of wood derived carbon, were the electrolyte was instantaneously adsorbed by the structure. As a result, an enhanced aqueous electrolyte flow within the electrode was achieved, resulting in higher conductivity and associated enhanced electrochemical performance. Precisely, the activated wood-derived carbon showed reduced overpotential and polarization (0.20 vs 0.35 V) and higher discharge capacity (16.3 vs 13.6 Ah·L⁻¹) at 100 mA cm². Importantly, these improvements were more pronounced at higher current densities, where the improved wettability offered additional charge transfer sites.

### 4.3. Separator Electrolytes

Although less attention in comparison to the active materials has been paid, wood-structures can be used to synthesize good ion conductors and electrically insulating separator electrolytes. In this context, Chen et al. reported the one of the first examples of a wood-membrane working as a separator in an energy storage system. A wood-membrane separator embedded into a poly(vinyl alcohol) gel was applied into an asymmetric supercapacitor. The direct 3D aligned
microchannels with low tortuosity offered a good compatibility with carbonized wood electrodes, resulting in a large areal capacitance of 3.6 F cm⁻².

Enhancing the inherent short life span of lithium metal batteries is one of the most urgent priorities in the energy storage area. In this regard, Lu et al. have recently designed a natural-wood-structured interface to function as an artificial solid-electrolyte interphase which enables spatially homogeneous Li⁺ flux and rapid Li⁺ transport.[53] To that end, freestanding 10 nm thick cellulose nanofilms were isolated from the interlamellar matrix of a partially removed cell wall by ultrasonication. Thanks to the nanochannels between the naturally assembled parallel cellulose chains which offer a uniform metallic Li deposition was obtained. Additionally, the lithiophilic character of wood enabled rapid Li⁺ migration as noted by the conductivity of 0.39 mS cm⁻¹, larger than the 0.13 mS cm⁻¹ of the pristine polypropylene separator and the 0.036 mS cm⁻¹ of the artificial SEI. As a result, in comparison with the battery having a commercial polypropylene separator which short-circuits after 200 cycles, a LMB with a capacity of 140 mAh cm⁻² after 800 cycles at 0.5C is obtained. Solid-state electrolytes (SSEs) are getting increasing attention thanks to their potential to limit Li dendrite growth and propagation. Dai et al. reported a wood-templating approach to fabricate a SSE composed by a highly conductive garnet framework with multiscale aligned mesostructure.[34] Poly(ethylene oxide) was incorporated into the wood-templated aligned Li₆-La₃Zr₂Al₂O₁₂ nanostructure. The multiscale aligned mesostructure derived from natural wood, which enables the unobstructed Li ion transport along the garnet/polymer interface, through garnet, and through polymer electrolyte, affording a remarkably high ionic conductivity of 0.18 mS cm⁻¹ at room temperature and a homogeneous and stable Li stripping/plating.

5. Wood as Template and Mechanical Support Material

5.1. Wood as a Sacrificial Template

In spite of the maturity of LIBs, the electrification of the mobility as well as the expansion of renewable energy is demanding a boost beyond its actual limits.[144] In this sense, the improvement of the electrolyte/electrode interface can effectively enhance the power density without sacrificing energy density. Therefore, the design of the microstructure of the electrode has been proved an efficient way to improve LIB performance through the optimization of key parameters of porosity and tortuosity to allow faster ion diffusion throughout the bulk of the electrode. The template synthesis provides a simple approach to control the shape of active materials, optimizing the structure to allow an improved electrochemical performance.[342] In this regard, wood offers its inherent aligned porous structure as ordered template scaffold for the synthesis of structured active materials. Additionally, soft templating approaches using biomaterials allow the fabrication of flexible carbonaceous electrodes.[84] As a proof of concept, Liu and coworkers synthesized a LiNi₀.₅Mn₁.₅O₄ cathode material loaded into delignified pine wood.[84] After calcination step to remove the organic part, electron microscopy measurements showed LiNi₀.₅Mn₁.₅O₄ nanoparticles in an ordered structure when synthesized by templated method, whereas the nanoparticles synthesized through the conventional approach resulted in undesired agglomerates (detrimental for electrochemical reactions). Furthermore, with 35 m² g⁻¹, the surface area of templated LiNi₀.₅Mn₁.₅O₄ exceeded 5x the surface area obtained during the conventional process. This controlled structure was translated into improved electrochemical performance, especially at high current densities, where the templated LiNi₀.₅Mn₁.₅O₄ could deliver 117 and 97 mAh g⁻¹ at 5C and 10C respectively, while the non-templated cathode started to fail at 5C with a high voltage drop and low capacity. Interestingly the templated LiNi₀.₅Mn₁.₅O₄ showed enhanced capacity retention during galvanostatic cycling, with negligible capacity drop from 0.2–2C (around 130 mAh g⁻¹) and delivering stable capacities at 5C and 10C (117 and 97 mAh g⁻¹, respectively). As regards with the long term cyclability at 1C and 10C, the highly stable nature of the templated LiNi₀.₅Mn₁.₅O₄ enabled a 90% capacity retention over 100 cycles, in comparison with the non-templated LiNi₀.₅Mn₁.₅O₄ which solely retained 22% of the initial capacity.

Similarly, Kang and coworkers proved that biotemplate synthesis could be applied to the preparation of LiCoO₂ with different shapes depending of the template source.[144] Thanks to the inherent hierarchical, interconnected and aligned porous structure of wood, the LiCoO₂ synthesized achieved the best discharge capacity of 149 mAh g⁻¹ compared with cotton-templated (141 mAh g⁻¹) and pollen-templated (67 mAh g⁻¹) materials, improving the insertion/extraction of Li⁺ over the whole bio-LiCoO₂. Based on this report, Lu and coworkers optimized the bio-templated of LiCoO₂ synthesis in presence of pine-wood to obtain ultrathick bulk electrodes (Figure 11a).[53] Prior to the sol-gel synthesis, wood slices were subjected to a delignification process to remove the organic components and widen the porous structure (no specific values were reported). This bio-template synthesis allowed obtaining up to 1.5 mm thick bulk LiCoO₂ electrodes with high mechanical integrity (flexural strength of 0.45 MPa) and 66% lower tortuosity compared with control LiCoO₂. Furthermore, this interconnected porous structure promoted enhanced conductivities, both ionic, and electronic, within the bulk electrode even in the absence of conductive additives. These features were translated into impressive electrochemical performance in LIBs, where the bio-templated electrodes showed higher capacities at 0.05–1C rate in comparison to conventional wet-processed LiCoO₂ cathode. Furthermore, the bulk and ultrathick cathodes delivered impressive areal capacities of 25 and 12 mAh cm⁻² at 0.05C and 12C, respectively. Overall, these cathodes proved to be suitable for fast charging batteries, a feature increasingly interesting for electric vehicle application, retaining 82 mAh g⁻¹ at 0.5C rate compared with the 30 mAh g⁻¹ of the control LiCoO₂.

Turning from intercalation materials to pure metallic anodes is an ongoing aim due to the extreme increase of energy density of alkali-metal-based batteries. In this regard, to avoid the major issues related to the high reactivity and instability of lithium and sodium metallic anodes, solid state electrolytes (SSEs) are a promising technology.[144] SSEs bear some pressing problems that need to be overcome. While inorganic SSEs show very high conductivities (>0.1 × 10⁻³ S cm⁻¹) and virtually a unity ion transference numbers,[145] they are difficult to process and present
a poor strength. On the contrary, SSEs based on polymers are easily scalable materials with good mechanical properties but with limited ionic conductivity ($10^{–3}$–$10^{–5}$ S cm$^{–1}$) and electrochemical stability ($<4.2$ V).\cite{146} Accordingly, the combination of both electrolyte systems could give rise to a new family of materials with combined properties of ionic conductivity and electrochemical stability with mechanical properties and scalable processing. Furthermore, the use of engineered nanostructures could not only avoid the incompatibility of both type of SSEs, but promote further improvements by providing defined and aligned channels. In this regard, Figure 11b displays how Dai and coworkers took advantage of the inherent aligned porous structure of wood to build up a structured composite electrolyte.\cite{54} An inorganic solid electrolyte, $Li_{0.33}La_{0.557}TiO_3$, was synthesized within the interconnected pores of a compressed basswood slice with a subsequent carbonization step to remove the wood template. Afterwards, a PEG-based polymer electrolyte was introduced into the structured inorganic electrolyte, resulting in a flexible membrane with a remarkable ionic conductivity of $1.8 \times 10^{–4}$ S cm$^{–1}$ at room temperature. The electrochemical performance of the composite electrolyte was characterized in a symmetric cell versus metallic Li. The electrochemical stability of the electrolyte was found to be as high as 6V versus Li/Li$^+$ and the plating stripping performance was extended up to 600 cycles with slight polarization increase. This excellent performance was related to the aligned and low tortuosity structure composite electrolyte, that promote both, enhanced ionic and a controlled ionic flux across the electrolyte, leading to homogeneous Li plating/stripping over the entire lithium surface.

5.2. Wood as Support Material

The works summarized above describe processes profiting from the porous structure of wood to obtain either hierarchically structured carbonaceous materials or sacrificial templates, usually by high temperature calcination. However, wood’s cellulosic system has been proved to be an effective source for separators and electrolytes.\cite{147} This fact, combined with the aligned structure of wood, motivated Li and coworkers to use wood as support material to obtain a highly ordered inorganic solid electrolyte for solid-state lithium metal batteries.\cite{147} Figure 12a shows the fabrication of composite solid state electrolyte through a simple sol-gel method, the agrodyte type $Li_6PS_5Cl$ was synthesized within the pores of wood slices and the resulting composite was directly applied as a solid electrolyte in a lithium metal cell. In consequence, the flux of ions was homogeneously regulated over the metallic lithium surface by ion insulating confinements, avoiding the growth of undesired lithium deposits that could evolve in dendrites. This strategy proved to be effective as the ionic conductivity of the membrane was comparable to the pure $Li_6PS_5Cl$, allowing plating/stripping of lithium at high power densities of up to 1 mA cm$^{–2}$ with limited polarization. The symmetric cell was cycled over 1000 h at 0.2 mA cm$^{–2}$ with negligible overpotential increase, confirming the stable and homogeneous Li$^+$ plating/stripping thanks to the engineered structure of the $Li_6PS_5Cl@wood$ solid electrolyte.

Unfortunately, in the majority of the cases, the inherent characteristics of wood are lost during its processing (mostly involving high temperature carbonization) aimed to obtain large electronic conductivities and increased specific areas. However, the rise of wireless and wearable technologies in the frame of Internet of Things (IoT) technology demands new device concepts, such as miniaturization, flexibility, and sustainability.\cite{148} Green materials that can match the trade-offs between mechanical flexibility, electrochemical performance, and sustainability requirements are gaining an increasing attention in this field. The recent advances on wood modification to provide novel properties such
as flexibility and optical transparency, added to the benefits of its porous structure, make wood an attractive support material for advanced EESs. In this regard, the group of Hu developed a procedure to obtain flexible wood-based cathodes for MABs. This strategy combines the modified mechanical properties of wood after delignification process with the inherent porous structure beneficial for MABs. As proof of concept, Li-CO₂ and Li-O₂ batteries were assembled using a fabric built by the deposition of carbon nanotubes as conductive material and Ru nanoparticles as catalyst along flexible wood slices (Figure 12b). For both cathode chemistries, the cathode exhibited impressive results in terms of areal capacity (up to 70 mAh cm² in O₂ and 11 mAh cm² in CO₂), overpotential at high C-rate of 1 A g⁻¹ (1.14 V in O₂ and 1.85 V in CO₂) and overpotential stability over 200 cycles (1.5 V in O₂ and 1.9 V in CO₂). Besides, the flexible character of wood support is translated into the cathode fabric, allowing advanced applications such as wearable devices or powering devices under CO₂ atmospheres, such as those required in Mars exploration missions.

6. Outlook and Future Perspective

6.1. Electrochemical Performance

Along this Review we summarized the works in which wood has been implemented as a different component in batteries. In this regard, Table 2 shows a summary of the role of wood-derived materials as different battery components together with their performance in practical full cell configuration. Overall, we highlight the benefits originating from its inherent aligned porous structure. It is also worth to point that wood has been mainly used as a precursor platform for low tortuosity and electronically conductive carbonaceous material.Benefiting for its structural stability, wood derived carbons have been used as self-standing electrodes, either as intercalation material or active material by heteroatom doping or nanoparticle deposition techniques. Its self-standing character has promoted the use of wood as 3D current collectors by infusing/depositing alkali metals (Li, Na, K) or other active materials, reaching impressive power densities due to the highly conductive behavior of the carbonaceous network and the low tortuosity provided by the porous structure. Finally, wood has been used as a template material for the controlled growth of functional material or as innovative flexible support. The outlook of the electrochemical performance of batteries containing wood we envision is summarized as:

1. Multipurpose materials: similar wood species have been processed through controlled carbonization steps to obtain conductive porous carbon materials for their implementation in batteries. Special mention deserves the electrochemical performance of wood derived self-standing 3D carbon in a wide variety of application, such as carbon anodes, current collectors, ORR/OER catalysts for MABs or electrodes in redox flow batteries. This reflects the excellent properties of wood derived materials and their potential to bring the electrochemical energy storage a step closer to sustainable economy.

2. Controlled redox processes: the aligned and oriented channels allow a guided distribution of electrons and ions throughout wood structure, improving the homogeneity of the redox reactions along the surface of the electrodes which in turn...
enhances the electrode/electrolyte interface interaction and enlarges cell lifespan as well as power density of the cell. A representative example of the ability of wood derived materials in the control of redox processes is presented by Ji and coworkers with a controlled activity towards sodium combining high cyclability at high current densities (5000 cycles at 5 A g⁻¹).[122]

3. Future perspectives: new processes and technologies are being explored to provide innovative properties to wood; these include mechanical flexibility and optical transparency. Regarding these advances, novel functionalities are being introduced in the porous walls through chemical modification of cellulose chains.[47] Therefore, engineered materials that could improve the already excellent electrochemical properties of wood derived materials can be obtained, shown by Chen and coworkers with the flexible cathode based on delignified wood and the excellent performance in both flexible Li-S batteries, limiting the capacity loss to 0.05% cycle⁻¹ after 200 cycles at 1C (776 mAh g⁻¹).[151]

The full potential of biomimicry could only be obtained when designing at the third level, as it can be used in conjunction with other two levels. Besides of fulfilling the principles of sustainability, a fully circular system could be obtained. Another approach to truly innovate and obtain efficient energy storage systems could rely on the “nature’s unifying patterns”, defined by the Biomimicry Institute as ten lessons from our natural world. Scientist, industry and designers are starting to realize that a lot of research and development time are required to get the full potential of biomimicry.

6.2. Future Biomimetic Directions in the Battery Field

The potential of biomimicry in the energy storage field is notorious, not only using wood but also other natural structures. Inspired by the multi-scale assembly of different animals having a Bouligand structure, Nguyen et al. transferred the structural chirality of cellulose to fabricate freestanding mesoporous titanium carbide,[149] and black TiO₂ (TiO₂-x)[150] LIB anodes with long operating lifespans. The physical framework provided by the mesoporous chiral network minimized volume changes arising from the local strain generated during Li⁺ insertion/extraction. A brush-like interlayer composed of ZnO was developed inspired by the brush-like membrane of cells for nutrient adsorption. This material effectively captures the polysulfides in a Li-S battery, limiting the capacity loss to 0.05% cycle⁻¹ after 200 cycles at 1C (776 mAh g⁻¹).[133]

However, most of the efforts have been focused to mimic the shape or structure of natural forms. In other words, scientists have limited their efforts to the first level of biomimicry. According to Janine M. Benyus, such three levels can be classified into: form (emulation of shape/structure), process (emulation of a series of behaviors to create an effect) and ecosystem (create and integrated system of manage material and energy efficiently into an ongoing cycle).[152] The full potential of biomimicry could only be obtained when designing at the third level, as it can be used in conjunction with other two levels. Besides of fulfilling the principles of sustainability, a fully circular system could be obtained. Another approach to truly innovate and obtain efficient energy storage systems could rely on the “nature’s unifying patterns”, defined by the Biomimicry Institute as ten lessons from the natural world that should be considered as part of a design process. Adhering to these principles ensures that the designs are implemented in a sustainable fashion that is compatible with our natural world. Scientist, industry and designers are starting to realize that a lot of research and development time are required to get the full potential of biomimicry.

6.3. Critical Raw Materials and Bioeconomy

To support the sustained and rapid growth on the use of batteries, a safe and steady supply of large quantities of valuable materials is needed. Although the type and number of raw materials depend on the battery chemistry, most of the

Table 2. Comparison of the electrochemical performance endowed by the different wood-inspired battery components.

| Battery component | Wood material          | Battery system | Working voltage [V] | Rate capacity [mAh g⁻¹]/[C-rate] | Cycling stability [mAh g⁻¹] at cycle [%] | CE: Coulombic efficiency | Ref. |
|-------------------|------------------------|----------------|---------------------|----------------------------------|------------------------------------------|--------------------------|-----|
| Active material   | Anode                  | Wood derived carbon | NIB     | 1.5–4                | 58.3/5C                                  | 50 at 1200                | N.R. [105]|
| Current collector | Anode                  | Wood derived self standing 3D carbon | Li metal | 3–4.2               | 117/1C                                   | 140 at 300                | 99 [137]|
| Cathode           |                        |                | Li-S     | 1–3.5               | 509/1C                                   | 770 at 50                 | N.R. [93]|
|                    |                        |                | Li metal  | 2.5–4.2             | 4/5°                                     | 3.5° at 150               | N.R. [72]|
| Self-standing electrode | Cathode               |                | Na metal  | 0.01–1.8            | 328/0.6                                  | 121 at 1000               | 99.7 [85]|
| Template          | Cathode                | Delignified wood | Li-O₂    | 2–4                 | 7/0.2°                                   | 0.6° at 100               | 1.5° [94]|
| Support           | Cathode                |                | Li-Co₂   | 2.5–4               | 1000/1C                                  | 200 at 100                | 1.8° [101]|
| Electrolyte       |                        |                | LIB      | 1–3                 | 70/1C                                    | 90 at 100                | >95 [147]|

CE: Coulombic efficiency; N.R.: not reported; °Capacity and current density given in mAh cm⁻² and mA cm⁻²; †Efficiency is related with the stable overpotential of charge discharge curves over cycling; ‡Capacity given in Ah L⁻¹.
batteries require scarce materials associated with high supply risks. In this context, the EC published in 03.09.2020 a list of CRMs composed by 30 materials, where the following ones are applied into batteries: cobalt, magnesium, natural graphite, platinum group metals, vanadium, bauxite, lithium, titanium, and strontium. As shown in Figure 13a, from those, cobalt, natural graphite, vanadium, lithium, manganese and copper where found the be critical due to their supply risk (defined in terms of global supply risk, European production, criticality factor, import reliance of Europe for a particular raw material, substitution and recycling). Particularly troublesome is the fact that the availability of those materials is dominated by few major global supplier countries. Figure 13b, summarizes those CRM major global supplier countries together with their share of global supply, where China, Africa and Latin America, provide 74% of all battery raw materials. For instance, cobalt supply is concentrated in the Democratic Republic of the Congo, while natural graphite production is dominated by China. However, these CRMs may find alternatives as synthetic graphite can become a substitute of natural graphite in a scenario of scarce availability and increasing prices. If the current trend is maintained regarding transport electrification is maintained, the criticality of these materials is expected to increase as, for instance, Europe will need 15× more cobalt by 2050 (compared with the current supply to the whole EU economy).

Apart from their high economical cost of raw materials which can account for up to 70% of the total cost in LIBs, their extraction needs for large mining efforts, jeopardizing environmental sustainability. Moreover, these materials tend to be highly hazardous (ignitable, reactive, corrosive, toxic, etc.), compromising the long-term environmental sustainability of the batteries when ending in land or marine environments. To ensure a sustainable development and environmental protection, there is an urgent need to look for alternative materials which can rely, as far as possible, on renewable and local resources. Renewable resources may foster a sustainable supply of materials, boosting the transition towards a greener and Circular Economy. In this sense, wood-inspired biomimetic batteries can smooth the ecological transition by introducing a new model based on circularity, contributing to the following Sustainable Development Goals (SDGs): “SDG 7: Affordable and clean energy” facilitating the access to greener energy
batteries; “SDG 12: Responsible consumption and production” reducing our dependence on non-renewable resources that negatively affect the biosphere; and “SDG 14: Life below water” and “SDG 15: Life on land” replacing durable and toxic materials widely used in energy storage systems.

In spite of the fact that the humanity has halved the mass of plants in the last 3000 years, current overall living tree and shrub biomass on Earth accounts for a \(900 \times 10^9\) ton (gigaton) of dry mass.\[156\] In this context, biomass production far exceeds the production capacity of CRMs. Figure 13c summarizes the annual production (for 2019, the last representative year due to COVID-19 pandemic) of the most representative CRMs used in batteries and compares it to biomass production. Although recycling rates are not here considered (metals such as aluminum and magnesium are widely recycled), biomass provides an unlimited amount of material in comparison with CRMs. Besides, local resources can satisfy domestic battery consumption, decoupling battery production from the imports (proven critical during the COVID-19 pandemic). As nearly 99.78% by weight of plant biomass is concentrated in terrestrial environments (marine biomass is mainly composed by green algae and sea grass),\[160\] its collection and harvesting results a relatively easy process in comparison with deep mining activities. As opposed to specifically located CRMs, trees can potentially exist in about two-thirds of the land biosphere (see Figure 13d),\[165\] providing an easy access to raw materials for battery fabrication.

Bioeconomy represents a unique approach to fulfill these sustainability issues as it “comprises the production of renewable biological resources and their conversion into food, feed, bio-based products, and bioenergy via innovative, efficient technologies.” In this regard, it is the biological motor of a future circular economy, which is based on optimal use of resources and the production of primary raw materials from renewable sourced feedstock” (The European Bioeconomy Alliance).\[164\] As biological resources are embedded in the natural biological cycle once their function has been accomplished (with no waste generation), the use of biological materials is sought to contribute to the Circular Economy.\[162\] In fact, as a sustainability-oriented concept, bioeconomy has the potential of transforming the current linear, CRM-based battery industry towards an efficient waste-using Circular Economy.\[163\]

In this framework, an ideal replacement material should also satisfy stringent electrochemical performance requisites. Given the many relevant examples shown in this Review, wood, as a forest-based ecosystem material, fulfils these requirements as it displays a highly porous character capable of providing plenty of space to hold ions (or others), can be grown naturally, is low cost and environmental benign. Additionally, the wood cascading concept enables increasing the efficiency of biomass utilization,\[164\] making wood especially attractive when compared to other biological materials. Although the electrochemical performance of wood-derived current collectors, anodes, and cathodes may slightly vary between wood samples because no two biological specimens are compositionally equal, wood-inspired approaches can lessen the use of CRMs. Thereby, the potential of forest ecosystems plays a relevant role in the policymaking, highlighted in ambitious plans implemented through actions such as the EU Green Deal or the Biodiversity Strategy to 2030 by the EC. In the same vein, EC’s Horizon 2020 program has funded several projects (SINCERE, FORESIGHT) aimed to ensure new models for sustainable forest products. Altogether, these initiatives aim at transforming current production and consumption modes into environmentally sustainable.

The valorization of underutilized agricultural residues by transforming them into high value battery components can lower the pressure on natural resources arising from mining activities, alleviating the potential supply chain bottleneck associated with the widespread use of CRMs. This could help practitioners to get ahead the future legislation on circularity and sustainability. In addition, the use of wood also has further environmental benefits as an increase in the tree plantation effectively limits the rise of CO\(_2\) concentration and mitigates climate change.\[156\] In this sense, the inherent photosynthetic carbon capture ability of plants and trees could store additional 205 gigatons of carbon (GtC), reducing the global anthropogenic carbon burden (based on the assumption that two-thirds of terrestrial land could support forest).\[156\]

### 6.4. Environmental Sustainability Considerations

Following a cleaner production concept, battery production processes should be subjected to environmentally conscious efforts so the least negative residual effect on the environment is assured.\[165\] Although the use of wood as a primary source material to develop batteries should a priori reduce the environmental impacts associated with battery manufacturing, at the present this statement cannot be fully certified. There is thus an urgent need to systematically analyze and quantify the environmental impacts of wood-inspired batteries through their whole life cycle. This should include raw material extraction and processing, their manufacturing, distribution, use, recycling, and final disposal. The LCA methodology provides means for it, allowing the analysis of the contribution of the different life cycle stages or battery components to the overall environmental load.\[166\] Specifically, LCA accounts for the energy and resources consumed during each life cycle stage (identified as inputs), and calculates the emitted pollutants and wastes (outputs) originating from such processes. The general principles and specific requirements are addressed in the international standards ISO 14 040 and ISO 14 044.\[166\]

The potential environmental sustainability benefits originating from biomimetic wood-inspired batteries are schematically summarized in Figure 14. Biomimicry offers a means to reuse the waste in a way that the new material presents an improved multifunctionality in comparison to the original one. This process, known as upcycling,\[167\] increases the materials circularity avoiding undesired leakage of waste into the environment.\[168\] Accordingly, wood carbonization can render environmental benefits including biowaste upcycling/valorization,\[169\] carbon sequestration,\[170\] and energy coproduction.\[171\] Avoiding landfilling of resources is one of the cornerstones of the Circular Economy, turning waste into a valuable resource. For instance, it has been shown that activated carbon production from wood waste presents an environmental credit of 163 kg CO\(_2\)-eq per ton (carbon dioxide equivalents, CO\(_2\)-equiv.) for reducing the global warming potential (GWP) when comparing with the same amount of wood wastes disposed by
However, special care should be given to the selection of wood source as the relatively slow growth rate of the specific species, together with their long rotation cycles, can result in increased impacts in atmospheric acidification, eutrophication, depletion of abiotic resources, human toxicity, ozone layer depletion, and eco-toxicity. In any case, thermochemical conversion routes (combustion, pyrolysis) are preferred for lignocellulosic biomass valorization in comparison with biochemical conversion approaches, which are time consuming and present poor conversion efficiencies.

There is a need to establish solid routes for wood carbonization through highly efficient and safe processes. For instance, primary wood carbonization can render hazardous CO₂, CO, CH₄, N₂O, or particulate matter by-products, contributing to the global warming through atmospheric photochemical reactions. During conventional pyrolysis the heat is transferred through convection, conduction, and radiation, causing heat lost and maintaining a temperature gradient. Therefore, depending on the source and conditions (temperature, time), biomass hydrothermal carbonization processes at plant level require a specific energy ranging from 1 to 6 kWh kg⁻¹hydrochar. Other carbonization alternatives could be explored to lessen the overall energy requirements. For example, microwave-assisted pyrolysis is an energetically efficient process which provides a uniform heating, avoiding undesired secondary reactions. However, biomass feedstock cannot efficiently absorb microwave radiation and requires the addition of exogenous microwave absorbents for improved outputs. Other alternative is the energy recovery during carbonization, allowing to save more than 50% of the consumed energy while reducing GWP, acidification, and eutrophication potential impacts by 1.4–2.0× in comparison with the process with no heat recovery. These facts highlight the need of future works that should address energy and environmental impacts of wood carbonization to inform decision making in developing sustainable processes.

Even if there are no LCA reports on wood-derived batteries, the data originating from LCA studies of different battery systems can provide some clues on the potential environmental impacts of wood-derived batteries. The replacement of currently dominant cathode materials for LIBs (LiCoO₂, LiMn₂O₄, LiFePO₄, or LiNiMnCoO₂), or for NIBs (NaCO₂, NaFePO₄, or Na₃V₂(PO₄)₃) comprising toxic metals such as cobalt, nickel, manganese, or vanadium, can reduce the fresh water aquatic ecotoxicity and human toxicity potentials. Specifically, avoiding mining activities related to Li, Co, Mn, or V mining can notably reduce the GWP of battery production and protect human health, as 26% of global CO₂ emissions and 20% of health impacts from air pollution are related to the extraction and primary processing of metals and other minerals.

However, it should be taken into account that natural wood carbonization and/or activation require several energy-demanding treatments (mostly heat and mechanical treatments) and need large nitrogen gas quantities to ensure an inert atmosphere, substantially increasing the GWP. Additionally, large amounts of biomass are needed to obtain carbon as for example, 11 kg of sugar are required for 1 kg of hard carbon, making carbonization process far from efficient. One of the advantages provided by wood-inspired batteries is the ability to fabricate thick electrodes with low amount of “dead weight”. This ensures lighter batteries for a given energy density, reducing the overall impacts resulting from the battery. Certainly, avoiding the need of current collectors to function would represent a clear benefit environmentally speaking. Given the large electric conductivity of the electrodes, some wood-derived materials do not require additional current collectors, circumventing the use of aluminum and copper and reducing the metal depletion caused by mining, freshwater
ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, and human toxicity.\[183\]

The end-of-life (EoL) management of batteries is becoming an increasingly foremost environmental issue. The unprecedented increase of disposed waste electrical and electronic equipment (WEEE) has resulted in enormous amounts of hazardous battery waste generation. In spite of the notable efforts to implement recycling measures, only 17.4% of the worldwide WEEE was recycled in 2019.\[184\] resulting in large amounts of hazardous battery waste being disposed without control. In this framework, transient batteries are a plausible solution to avoid the leakage and consequent accumulation of hazardous substances into marine, river, or land environments. Transient devices are able to disintegrate, dissolve, degrade, or be resorbed leaving behind harmless residues.\[185,186\] Following the pioneering work of Chen et al in 2017, who showed an all-wood-structured supercapacitor with a high degree of biodegradability,\[91\] biomass-sourced batteries represent a unique opportunity to obtain high-performing biodegradable batteries. Moreover, given the achieved high electronic conductivities, wood-inspired batteries do not require heavy and inactive current collector foils, making their biodegradation faster and safer.\[187\]

To date, wood-inspired batteries have been designed to provide large energy densities and long life cycles, setting aside some of the basic concepts of the Circular Economy. Therefore, in the future, researchers should bear in mind aspects such as resource/energy efficiency during carbonization process, overall process simplicity and avoid, as far as possible, the multicomponent nature of batteries. These aspects not only would reduce the environmental impacts during battery fabrication, but also may enable a more efficient recycling/disposal once their reach their EoL.

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Conflict of Interest

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