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Agricultural waste-derived carbon electrodes for sustainable lithium-ion batteries: environmental and economic assessment

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The demand for effective and sustainable energy storage solutions has increased globally due to the rapid growth of renewable energy systems and electric vehicles. Despite being the industry leader, lithium-ion batteries are increasingly being challenged for their dependence on non-renewable resources, high production costs, and environmental issues related to mining and disposal. The possibility of using materials obtained from agricultural waste as sustainable substitutes for the fabrication of electrodes for lithium-ion batteries is investigated in this review. It is possible to thermochemically transform a variety of agricultural leftovers, such as husks, stalks, and shells, into high-performance carbon compounds with advantageous electrochemical properties. The viability of using these bio-derived components in the production of lithium-ion batteries was assessed by a thorough economic and environmental analysis. When compared to traditional graphite-based systems, the findings of the life cycle assessment show notable decreases in waste production, energy usage, and carbon footprint. From an economic perspective, utilizing agricultural waste cuts down raw material expenses and promotes while aligning with circular economy principles by enabling the valorisation of biomass residues into high-value products. The results show that electrodes made from agricultural waste may perform competitively while significantly improving sustainability. This review highlights a viable pathway toward more cost-effective, resource-efficient, and environmentally sustainable lithium-ion battery technology.

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Environmental significance

The rapid expansion of renewable energy and electrified transportation has led to increased dependence on lithium-ion batteries, raising concerns about resource depletion, emissions, and the environmental impacts of conventional electrode materials. This study highlights the environmental benefits of using agricultural waste as a sustainable alternative for battery electrodes. Biomass residues, such as husks, stalks, and shells, are valorised into carbon materials, reducing reliance on non-renewable graphite while addressing waste-management challenges. Life cycle assessment shows significant reductions in carbon footprint, energy consumption, and waste generation relative to the results for conventional materials. Additionally, converting low-value residues into high-performance materials supports circular economy principles, enhancing resource efficiency. Overall, this approach offers a sustainable, cost-effective pathway for greener energy-storage technologies and cleaner energy transitions.

1 Introduction

Global economies are experiencing a shift towards technological advancement, driving the transition towards clean energy while boosting the demand for energy and storage devices.[1,2] According to Khandekar *et al.*,[3] the intensified use of resources and the constant mounting pressure on fossil fuel reserves have increased the demand for more advanced battery solutions to support the growing portable electronics industry and to reduce rising carbon emissions. As studied by Wasesa *et al.*,[4] the increased use of portable electronics has driven a surge in battery demand, leading to a sudden increase in production levels. The energy and storage sector has found that lithium-ion batteries (LIBs) are an effective alternative. LIBs are found to have a high capacity, good energy efficiency and a low production cost, becoming a popular choice for manufacturers globally.[5] Beyond smartphones and electric vehicles (EVs), LIBs are used in a wide variety of energy-storage devices, which leads to increased consumption.[6] According to Iqbal *et al.*,[6] with the increasing amount of discarded lithium-ion batteries, it has contributed to the growing electronic waste, which has toan increase in the demand for important battery metals, including cobalt (Co), nickel (Ni), manganese (Mn), and lithium (Li).[7] Due

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to the presence of hazardous components and the challenges involved in their disposal, lithium-ion batteries pose a significant environmental risk.[8] Spent LIB waste contains different hazardous metals, which contribute to environmental pollution when mismanaged.[9] As reported by Jin *et al.*,[10] the presence of different valuable metals in LIBs offers an opportunity for recycling them as secondary resources, thereby reducing the reliance on the depleting primary raw materials.[1] LIB recycling has recorded significant growth recently due to its role in efficiently supporting ongoing demands and strengthening the supply chain.[11] According to Dagwar and Dutta,[12] it has been observed that 6% of LIB waste gets recycled, and the rest ends up in landfills, posing the risk of metal toxicity and environmental contamination.

1.1 LIB recycling and technological advancements

The recovery of resources from secondary raw materials has risen sharply with the evolution of recycling technologies, offering the potential to decrease dependence on primary raw materials.[4] Recent studies have focused on LIB recycling due to rising waste levels, and recycling techniques have rapidly evolved to meet the surging demand for important raw materials, ensuring a sustainable environment and supporting closed-loop economy objectives.[6] Advancements in different techniques, such as pyrometallurgy, hydrometallurgy, biometallurgy, direct recycling, and novel separation technologies, have improved artificial intelligence integration for process enhancement and have significantly upgraded the recycling sector.[13] According to Dagwar *et al.*,[14] pyrometallurgy has the ability to enable bulk metal recovery using high-temperature treatment, while hydrometallurgy helps in the recovery of precious and base metals using green and sustainable solvents, such as ionic liquids (ILs) and deep eutectic solvents (DESs), where 100% leaching efficiencies can be achieved for elements like lithium (Li), cobalt (Co), nickel (Ni).[15] Although direct recycling is limited by changing cathode chemistries, it shows promising results for electrode regeneration and closed-loop reuse.[16,17] Innovations such as zig-zag air separation, ultrasound-assisted leaching, and hybrid bioleaching techniques have enhanced recovery yields while lowering energy intensity and contamination. Fig. 1 describes the processes involved in LIB recycling and the application of different recovery methods.

Emerging methods, such as deep eutectic solvent and bio-assisted processes, have achieved up to 99% lithium recovery, while cobalt and nickel recovery efficiency routinely exceed 95%, and copper recovery surpasses 90%.[18] Although manganese recovery remains variable between 20% and 99%, ongoing optimization continues to close these gaps. Regulatory frameworks, such as the EU's 2027 and 2031 recovery targets, are largely aligned with current technological capabilities, further driving innovation and industrial adoption.[19] On the global scale, the LIB recycling sector has experienced rapid growth and technological advancements from 2025 through early 2026, driven by increasing electric-vehicle retirements and stringent regulations.[20] As described by Premathilake *et al.*,[21] with the growing demand for crucial metals such as Li, Co, Ni and others, global recycling capacity reached approximately 1.6 million tonnes per year in 2025 and is projected to exceed 3 million tonnes in the near future. Tembo *et al.*[22] claimed that the worldwide market has grown significantly, with projections indicating that it would reach USD 56.87 billion by 2032 from USD 16.23 billion in 2024. Southern Asian nations, including China, have a policy-driven formal recycling channel with a significant recycling capacity, whereas India's recycling capacity has surpassed 60 000 tonnes annually, with targets exceeding 100 000 tonnes by 2027.[23] While novel methods, like direct recycling, have developed as a potential low-energy option capable of cutting emissions by up to 70%, traditional recycling routes, like pyrometallurgical and hydrometallurgical, are still widely employed, with hybrid systems increasing their efficiency.[24,25] Despite the progress, various challenges related to safe pretreatment, scalability, and standardization persist, with future efforts focusing on design-for-recycling batteries, digital traceability, and collaborative frameworks to enhance sustainability and supply security.[20] When considered as a whole, these

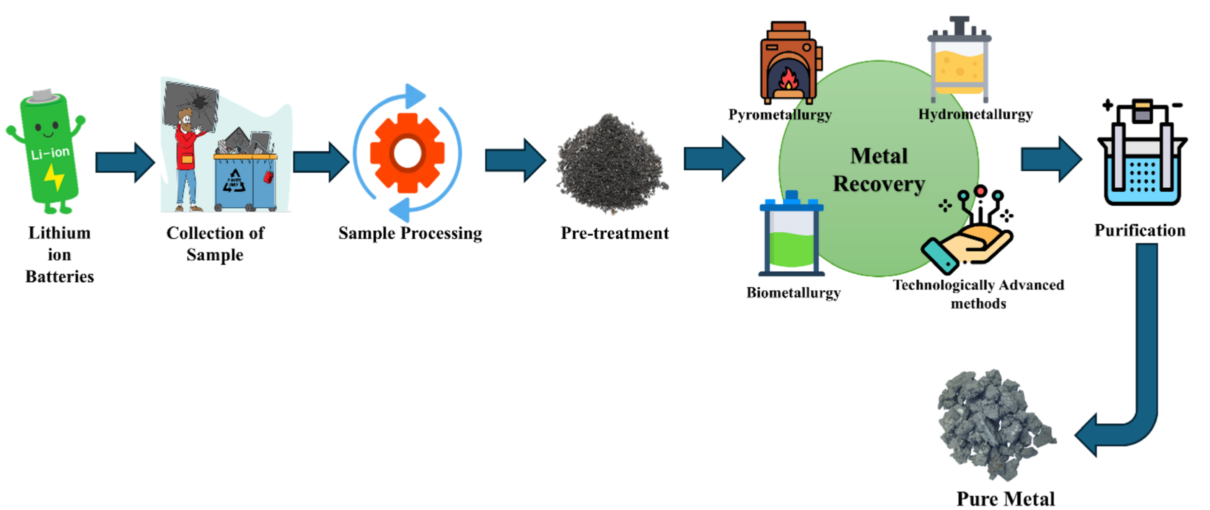

Fig. 1 Metallurgical processes involved in LIB recycling.

developments not only produce high essential metal recovery rates but also lower carbon emissions, conserve resources, and enable the reintegration of materials into new LIB production, thereby strengthening sustainable supply chains and advancing global circular economy goals.[16] Collectively, it can be established that current LIB recycling technologies can achieve high recovery efficiencies for critical metals; however, high energy requirements, process complexity, and environmental challenges are key limitations. These findings highlight the necessity of integrating green materials and circular resource strategies into battery design to reduce downstream recycling challenges.

1.2 Agricultural waste and resource utilization

Agricultural debris has been established as a global concern due to its adverse effects on the environment.[16] According to Acevedo *et al.*,[26] agro-industries, crop leftovers, livestock, and the aquaculture industry are some of the sources of agricultural waste. Agricultural-waste treatment methods offer significant advantages over conventional treatment methods, including incineration and landfill disposal, owing to their cost-effectiveness, reusability, high adsorption efficiency, reduced generation of biochemical waste, and potential for metal recovery.[26] Agricultural waste biomass has a strong adsorption capability, which can be attributed to the presence of different functional groups, including acetamido, carbonyl, phenols, amido, hydroxyl, amino, and sulfhydryl groups. Cellulose is a biopolymer and a primary component of leftover crop waste and agro-industrial waste; along with lignin and hemicellulose, it constitutes the total lignocellulosic biomass.[27] Agricultural waste comprises different materials, including rice husk, wheat bran and husks, fruit peels (such as lemon, lime, orange, apple and banana peels), tree bark, groundnut shells, coconut shells, hazelnut and walnut shells, waste tea, and *Cassia fistula* leaves.[26] Various studies have focused on different agricultural wastes, such as maize cobs, deoiled Jatropha cake, sugarcane bagasse, soybean hulls, and other plant residues (including grape stalks, cotton stalks, and water hyacinth).[28] A systematic classification of agro waste for resource optimization is shown in Fig. 2. Various studies published in 2025–2026 have identified agricultural debris as a critical source for valorisation, enabling the transformation of residues, such as crop stalks, husks, peels, and bagasse, into biofuels, bioplastics, composites, and construction materials, thereby advancing circular economy frameworks and reducing environmental pollution.[29,30] As per Ray and Dave,[31] India alone generates nearly 620 million tonnes of agricultural waste annually, of which only 25–30% is currently utilized, highlighting the urgent need for efficient and scalable valorisation strategies.[32] Due to the increasing volume of spent LIBs, recycling activities have witnessed a significant rise, supporting both environmental protection and economic benefits.[33] Metal extraction from spent LIBs using eco-friendly organic acids has attracted substantial attention because of the environmentally benign nature of this approach compared to traditional recycling methods.[34] Growing research across the globe has sparked interest in agricultural debris as a source of redox-active compounds, with various studies exploring its potential as a non-toxic and eco-friendly reducing agent.[35,36]

Recent research has explored multiple pathways for utilizing agricultural waste, including biorefinery, thermal, nanotechnological, and biotechnological approaches, to produce value-added materials, including reinforced structural composites, sustainable asphalt, and other compounds.[37] Despite the promising advances, challenges, such as feedstock variability, processing costs, and scalability, remain significant

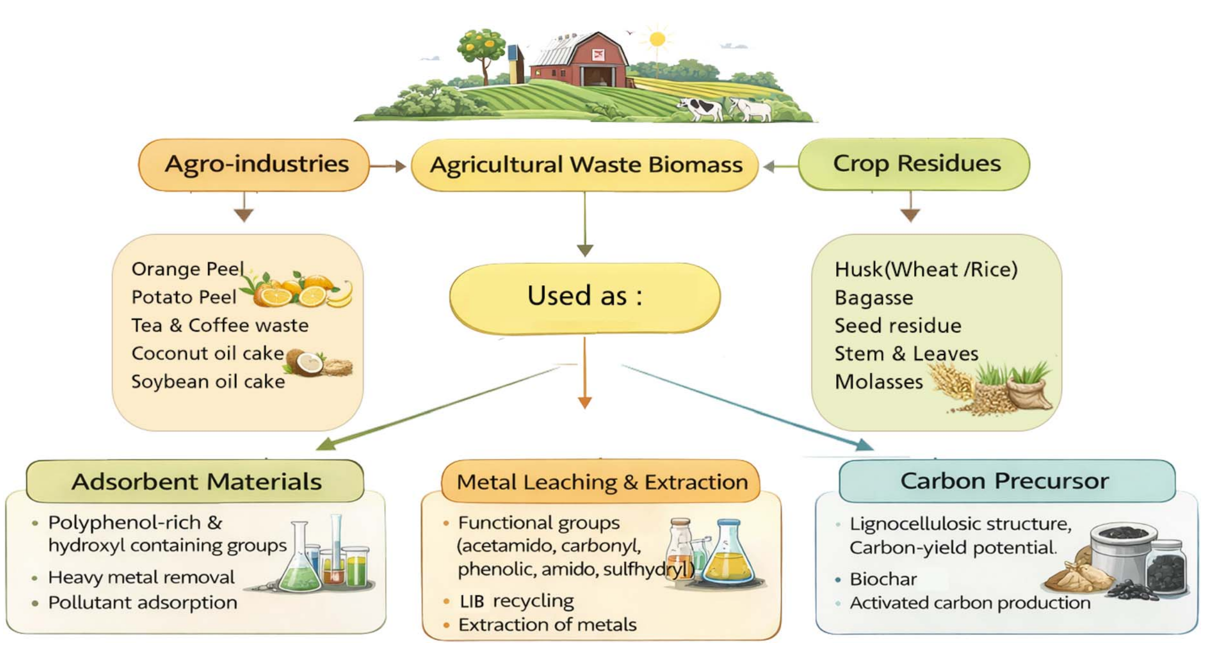

Fig. 2 Systematic classification of agro waste for resource optimization.

barriers.[38] As noted by Capanoglu *et al.*,[39] it has been estimated that the sector is projected to witness substantial market growth, with an estimated USD 31.22 billion addition by 2032, at an annual average growth rate of 8.74%, influenced by regulatory support and technological innovation. The literature consistently shows that agricultural waste possesses abundant functional groups and carbon-rich structures that enable adsorption, reduction, and material recovery applications.[40,41] Compared to conventional activated carbon and organic resins, the use of agricultural waste as a substitute material for the leaching and recovery of key components has been shown to be a sustainable strategy.[26] The literature consistently shows that agricultural waste possesses abundant functional groups and carbon-rich structures that enable adsorption, reduction, and material-recovery applications. However, most studies emphasize environmental remediation rather than energy storage, indicating an underexplored opportunity to valorise agricultural waste as functional materials for battery technologies.

1.3 Bibliometric analysis of sustainable lithium-ion batteries

Bibliometric analysis is a quantitative literature evaluation method that provides insights into research trends, strategies, key journals, publications, research quality, and demographic patterns while tracing the evolution of a research domain and its interdisciplinary linkages, particularly in science and engineering.[14,42] Lithium-ion battery recycling activities have increased significantly over the past few years, driving technological advancements, while resource recovery from secondary waste has proven effective for sustainable waste management.[43,44] In this review, bibliometric analysis was conducted using the open-source visualization software VOSviewer (version 1.6.20; Java 1.8.0_481) to generate network, overlay, and density maps through cluster analysis, examining relationships among authors, publications, journals, countries, and keywords.[45] Bibliometric data were retrieved from the Scopus database on 20 February 2026, including information on authors, titles, abstracts, keywords, sources, countries, citations, and publication dates. Scientific works published between 1980 and 2026, which include research and review articles, book chapters, and conference proceedings, were considered in this review. Keyword selection was based on recent research trends, and the number of publications identified using different keyword combinations is presented in Table 1.

The keyword co-occurrence analysis highlights the structural maturity and thematic evolution of research linking lithium-ion batteries with sustainable material pathways.[44] The first keyword group exhibits the highest number of clusters and strong link density, indicating a diverse and extensively interconnected research landscape that integrates biomass-derived carbon, agricultural waste, and environmental and economic assessments, including life cycle analysis.[46] The second group shows fewer clusters but the highest total link strength, reflecting a highly consolidated and mature research focus on energy-storage technologies, electric mobility, and renewable energy integration. Fig. 3 illustrates the co-occurrence network of keywords, highlighting major thematic clusters and research developments in the field.

The third and fourth keyword sets demonstrate moderate clustering and connectivity, representing focused yet expanding research streams centered on agricultural-waste valorisation, circular economy principles, resource efficiency, and cost-effective biomass-based electrode materials. Collectively, these patterns indicate increasing interdisciplinary convergence and a shift toward sustainable and circular approaches in lithium-ion battery research.[14] Fig. 4 provides a visual representation of keyword co-occurrence, demonstrating the thematic structure and evolving research focus within the domain.

Finally, the annual publication trend shows a pronounced progress in research output over a decade, indicating increasing scientific interest in the domain. A modest number of

Table 1 Different keyword combinations for bibliometric analysis

Keywords	No. of clusters	No. of link	Total link strength
Lithium-ion batteries; agricultural waste; biomass-derived carbon; environmental assessment; economic assessment; sustainable energy storage; life cycle assessment	43	102 290	115 735
Lithium-ion batteries; energy storage technologies; electric mobility; renewable energy integration; battery electrode materials	16	120 665	165 275
Agricultural waste; biomass residues; bio-derived carbon materials; husk stalk and shell waste; waste valorisation	31	34 979	37 881
Lithium-ion batteries; circular economy; cost-effective materials; resource efficiency; sustainable manufacturing; value-added biomass products	27	33 302	34 981

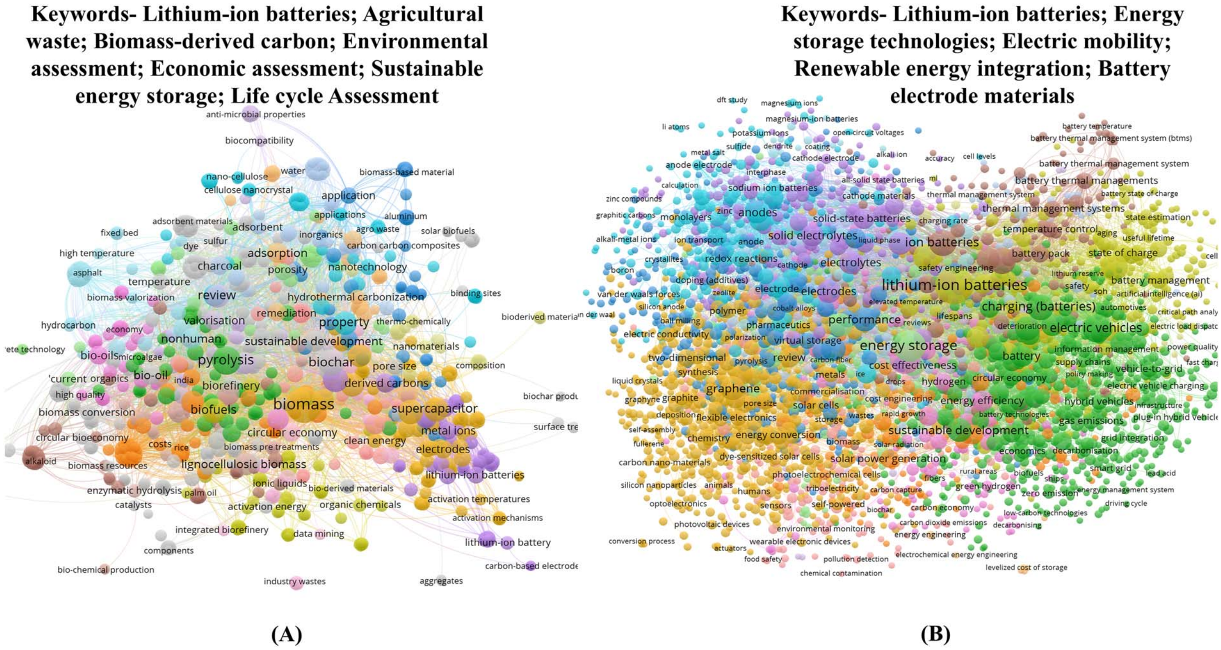

Fig. 3 Keyword co-occurrence network visualization generated using VOSviewer, showing thematic clusters related to (a) agricultural waste-derived carbon and environmental assessment in lithium-ion battery research and (b) energy storage technologies, electric mobility, and battery electrode materials.

publications was recorded prior to 2020, reflecting an early and exploratory phase of research. From 2021 onward, a steady rise is evident, followed by a sharp surge between 2023 and 2025, with 2025 emerging as the peak year of publication activity. This rapid increase highlights the growing relevance of the field, driven by advancements in sustainable materials, energy-storage technologies, and circular economy frameworks. Fig. 5 provides a visual representation of annual publication trends, illustrating the growth of research output in the studied domain between 1982 and 2026. The publications recorded in 2026 further suggest sustained momentum, emphasizing that the research area continues to evolve and attract significant attention.

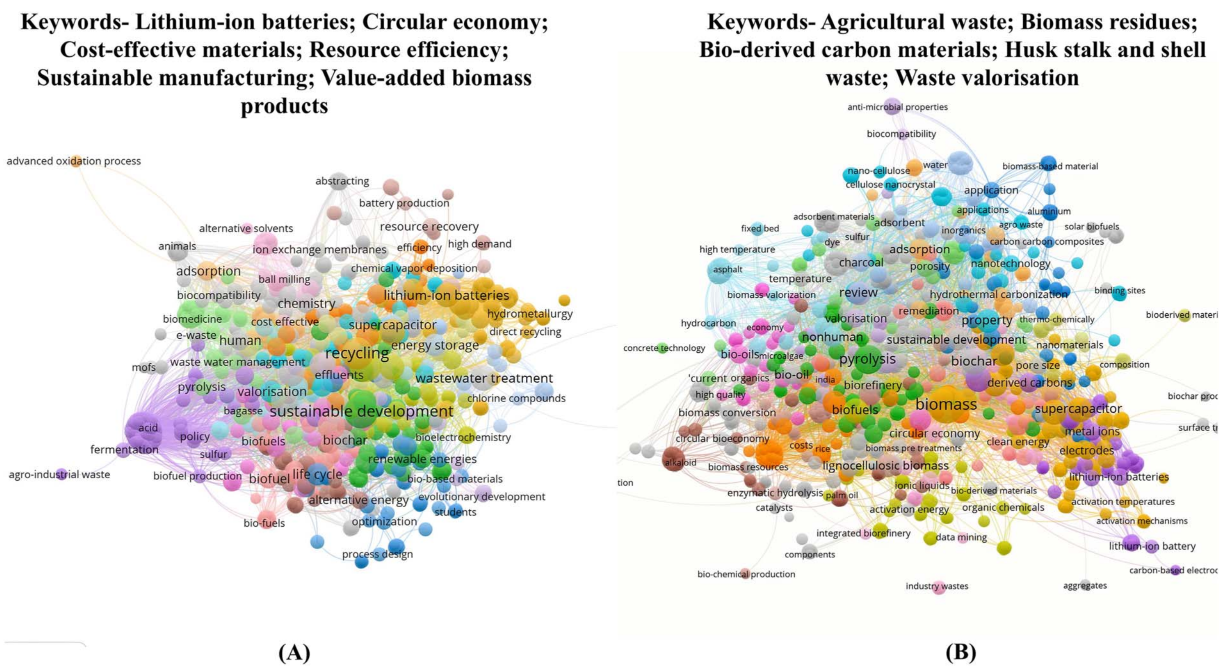

Fig. 4 Comparative bibliometric visualization, highlighting the interconnected research domains of (a) resource-efficient lithium-ion battery systems within circular economy frameworks and (b) biomass residues as precursors for bio-derived carbon materials.

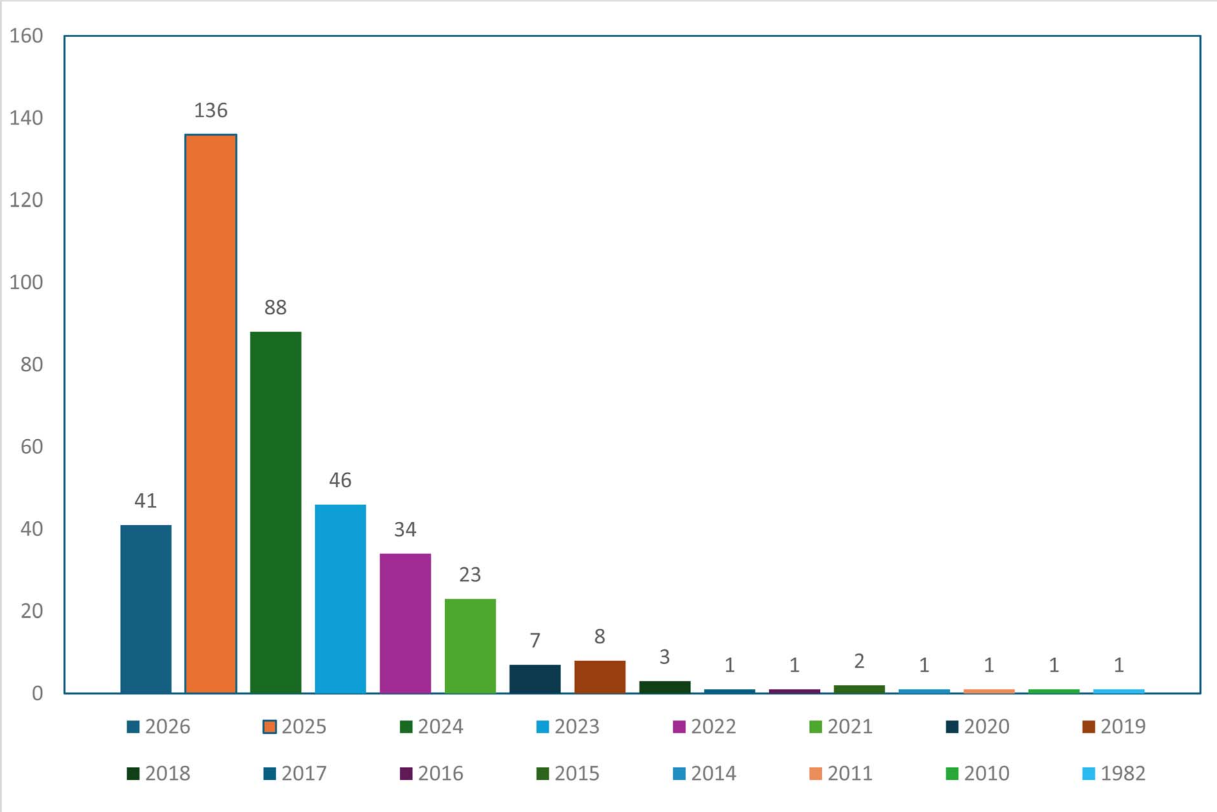

Fig. 5 Year-wise distribution of publications, illustrating the growth trend of research output in the studied domain (1982–2026).

1.4 Significance of environmental and economic assessment

Environmental and economic assessments are considered critical for evaluating the true impact and viability of LIB recycling technologies, ensuring alignment with sustainability goals, policy frameworks, and investment strategies.[46] Various traditional recycling techniques for LIBs employ different approaches aimed at improving resource recovery from spent LIB waste. According to Moganti and Dutta,[15] LIB recycling can reduce carbon footprints by up to 85.9%, leading to a significant reduction in water and energy consumption, compared to primary mining, while mitigating pollution, toxicity, biodiversity loss, and land degradation.[47] Environmental assessment frameworks, such as Life Cycle Assessment (LCA), evaluate current impacts, while prospective LCA (pLCA) incorporates future energy decarbonization and technological advancements, whereas material flow analysis (MFA) complements these approaches by mapping material and energy flows to assess resource efficiency and circularity.[48] Concerning the economic aspect, according to Pilapitiya and Piyathilaka[49] cost-effectiveness is measured using techniques like Life Cycle Costing (LCC), Cost-Benefit Analysis (CBA), net present value, and long-term payback, accounting for market volatility, infrastructure costs, and investment risks. However, a triple-bottom-line approach highlights that LIB recycling remains economically advantageous even with low commodity prices, reinforcing its role in supply chain circularity.[13] It has been studied that there are advanced multi-objective frameworks, such as SliRec, which integrate environmental and economic metrics to provide insights, with sensitivity analysis enabling stakeholders to balance trade-offs between ecological benefits and financial returns.[50] According to the United Nations (2025) report, The Global Assessment of Environmental-Economic Accounting, recent studies from 2025–2026 have described the critical role of integrated assessments in informing policy, driving technological innovation, and enabling large-scale deployment of low-carbon solutions. These approaches quantify environmental impacts, such as greenhouse gas emissions and resource use, alongside economic indicators, including cost, revenue, and employment metrics, thereby revealing key trade-offs between upfront investments and long-term environmental benefits.[51] Again, as described by Islam *et al.*,[51] their different applications across sectors, such as energy, waste management, water treatment, and circular design, demonstrate their importance in guiding investment, regulation, and research priorities. Despite challenges related to data limitations, technological uncertainty, and limited social impact integration, methodological advances such as LCA-TEA integration, life cycle sustainability assessment, and AI-assisted modelling are improving analytical robustness and transparency.[52] Overall, these frameworks provide a strong evidence base for climate-aligned strategies and informed decision-making at national and global scales. Existing environmental and economic assessment studies collectively confirm that LIB recycling and material substitution strategies can substantially reduce carbon

Table 2 Frameworks applicable for LIB recycling

Framework	Assessment approach	Key evaluation metrics	System boundary	Primary application	Social metrics	Technical metrics	Policy alignment	References
Environmental	LCA, pLCA, MFA	GHG emissions, water footprint, energy consumption	Full life cycle, including cradle-to-grave and future scenarios	Technology evaluation, policy formulation	Worker safety, community health risks		Emission standards, waste management directives	55
Economic	CBA, LCC	Total cost, NPV, profitability index	Project/system lifetime (10–20 years)	Investment decisions, economic feasibility	Job creation potential	Process scalability	Incentives, subsidies	56
Integrated	Multi-objective optimization (*e.g.*, SliRec)	Combined environmental and economic indicators	Dynamic, cross-system, flexible boundaries	Strategic research, innovation, optimization	Equity, stakeholder impacts	Recovery efficiency (>90% metals)	EPR, circular economy policies	57
Social	Social LCA (S-LCA)	Labor conditions, human rights, local employment	Stakeholder-focused, full supply chain	Equity assessment, facility siting	Fair wages, health and safety		Social standards (*e.g.*, ILO)	58
Techno-economic	TEA (techno-economic analysis)	Cost per kWh, IRR, payback period	Lab-to-commercial scale	Process optimization, scaling	Workforce training	Yield (80–95%), purity	Export restrictions on critical metals	59 and 60

emissions and resource depletion.[53] However, disparities in functional units, system limits, and future scenario assumptions underscore the necessity of standardized evaluation frameworks for new bio-based battery materials.[54] Table 2 provides an understanding of different frameworks applicable for LIB recycling.

Collectively, these frameworks support evidence-based decision-making for technology upgrades, regulatory compliance, and sustainable investment, advancing LIB recycling as both an environmentally sound and economically viable strategy within the circular economy. Existing environmental and economic assessment studies collectively confirm that LIB recycling and material substitution strategies can substantially reduce carbon emissions and resource depletion. The inconsistencies in system boundaries, functional units, and future scenario assumptions highlight the need for harmonized assessment frameworks when evaluating emerging bio-based battery materials.

Fig. 6 presents a conceptual diagram that shows how agricultural biomass may be transformed into useful carbon compounds and used as sustainable anodes for lithium-ion batteries in a circular bioeconomy.

The objective of the present review is to give a thorough economic and environmental assessment of lithium-ion batteries fabricated using sustainable electrode materials made from agricultural waste. In particular, the work explores how agricultural leftovers are thermochemically converted into carbon-based electrode materials and assesses the structural and electrochemical viability of these materials for use in LIBs. Furthermore, these bio-derived materials' environmental performance is evaluated using LCA and contrasted with traditional graphite-based systems to measure possible reductions in waste production, energy use, and carbon footprint. To ascertain their practicality for widespread use, the economic viability and market potential of incorporating agricultural waste-based materials in LIB manufacture are assessed. The review intends to demonstrate the potential of agricultural biomass as a resource-efficient route toward sustainable and affordable energy-storage technologies, considering combined environmental and economic approaches.

2 Lithium-ion batteries: fundamentals and applications

LIBs, which are extensively used in fixed grid applications, electric cars, and portable devices, are the cornerstone of contemporary energy storage.[61] LIBs are essential for stabilizing power production from sporadic sources like solar and wind energy in the context of renewable energy integration.[62] To improve safety, energy density, and long-term stability for large-scale renewable energy-storage systems, cutting-edge innovations, including all-solid-state batteries and sustainable electrode materials, are being investigated.[63,64] LIBs, which are extensively used in fixed-grid applications, electric cars, and portable devices, are the cornerstone of contemporary energy storage.[65] High energy density, extended cycle life, and comparably lightweight design are all thought to be appropriate for everyday consumer electronics and industrial electronics.[66] The reversible intercalation and deintercalation of lithium ions between the cathode, which is usually layered between transition metal oxides like $LiCoO_2$, NMC, or $LiFePO_4$, and the anode, which is typically graphite due to its higher theoretical capacities, control how LIBs operate according to Walter *et al.*[67] Lithium salt is used as an electrolyte in organic solvents,

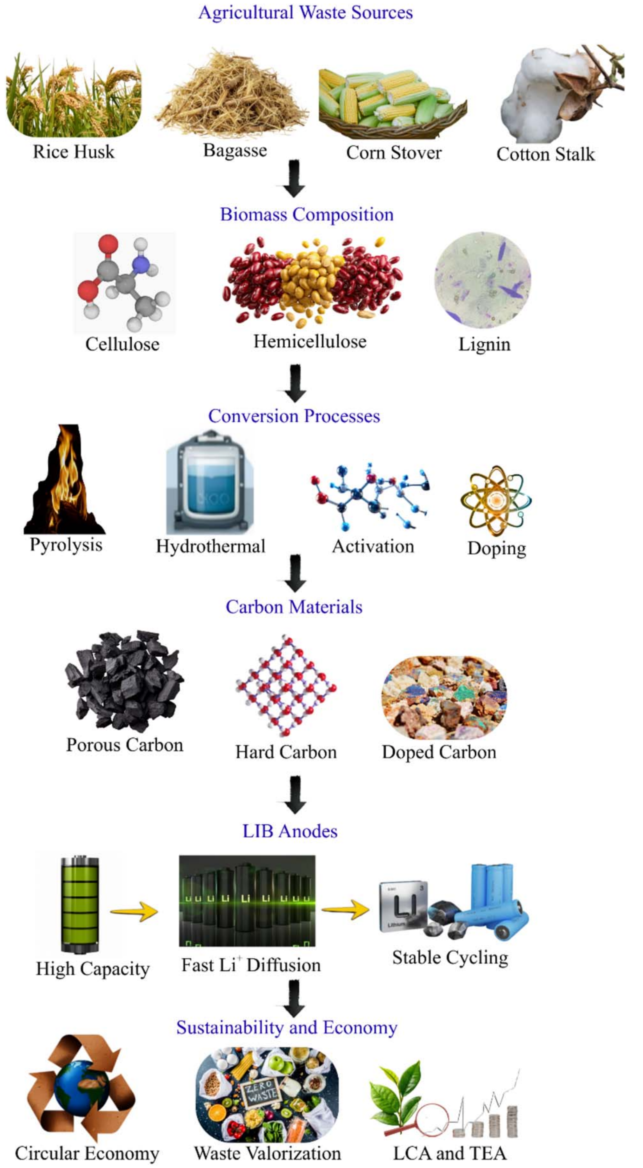

Fig. 6 Conceptual schematic illustrating the conversion of agricultural biomass into porous carbon materials and their application as sustainable anodes for lithium-ion batteries within a circular bioeconomy framework.

polymer development, and solid-state electrolytes to impart ionic conductivity while preventing electrical shorting with the separator.[68] According to Zhang *et al.*,[69] during the discharge of LIBs, lithium ions migrate from the anode to the cathode, accompanied by electron flow *via* the external circuit, and the reverse process occurs during charging. Fig. 7 provides an understanding of the working mechanisms of a LIB.

Heidrich *et al.*[70] state that by reducing side reactions and electrolyte breakdown, the formation and stability of the solid-electrolyte interphase (SEI) on the anode and the cathode-electrolyte interphase (CEI) regulate the coulombic efficiency, cycle life, and safety.[71] In LIBs, the advanced material engineering focuses majorly on optimizing electrode microstructure, particle size, and different strategies to enhance ion diffusion by mitigating capacity fading caused by electrode fracture, unstable interfaces, and high-voltage degradation.[72] As Liu *et al.*[68] reported, despite the significant advancements in high-capacity materials, solid-state electrolytes, and thermal management systems, LIBs still encounter major challenges, such as critical metal scarcity, thermal safety concerns, and inefficient recycling pathways. The reversible flow of lithium ions between the cathode and anode during cycles of charging and discharging is the fundamental mechanism by which LIBs function.[73] The main mechanism, according to Maruyama *et al.*,[74] is intercalation and deintercalation, through which lithium ions enter or exit electrode materials' crystal lattices without seriously disrupting their structural integrity. While electrons go *via* the external circuit powering devices during the discharge phase, lithium ions move from the anode to the cathode *via* the electrolyte.[69] Lithium ions, on the other hand, go back into the anode host material during charging, reversing this process. The battery's overall capacity for energy storage and conversion is governed by these redox processes, which also highlight how it functions.[73] Heidrich *et al.*[70] claim that the solid electrolyte interphase (SEI) and cathode electrolyte interphase (CEI), which develop on the anode and cathode surfaces, respectively, drive the essential electrochemical activity in the LIBs. It is critical to stabilize electrode–electrolyte interfaces by passivating electrodes to prevent continuous electrolyte decomposition, thus ensuring battery longevity and safety.[75] SEI specifically is formed during initial cycles and is a complex, dynamic layer influencing ionic transport and electronic insulation.[76] The stability of the SEI affects capacity retention and cycle life, but it can introduce resistance and impede lithium-ion flux if not well-formed. Conversely, the CEI contributes to cathode protection, particularly under high voltage operation, thereby helping mitigate parasitic reactions that can degrade battery performance.[77] Since these interphases directly affect efficiency, cycle stability, and safety, comprehending their creation, composition, and evolution continues to be a major challenge in lithium-ion battery research.[66] Ion mobility begins at the electrolyte, where lithium ions are solvated and transported between electrodes. The fundamental electrochemical reactions in LIBs involve both charge transfer at interfaces and the bulk transport of lithium ions within electrode materials.[70] Recent advances in LIBs have aimed to enhance energy density using high-voltage lithium-rich and nickel-rich layered cathodes; however, these materials suffer from structural instability and interfacial degradation during cycling.[78] Silicon has emerged as a high-capacity anode, but its severe volume expansion causes mechanical failure and an unstable solid electrolyte interphase (SEI), necessitating nano-engineering and composite strategies. Electrolyte development remains critical, as conventional carbonate-based systems pose flammability risks, prompting the development of thermally stable and non-flammable alternatives. Additionally, surface modification and solid-state electrolyte approaches are increasingly explored to stabilize SEI/cathode electrolyte interphase (CEI) layers and improve safety and long-term performance.[78]

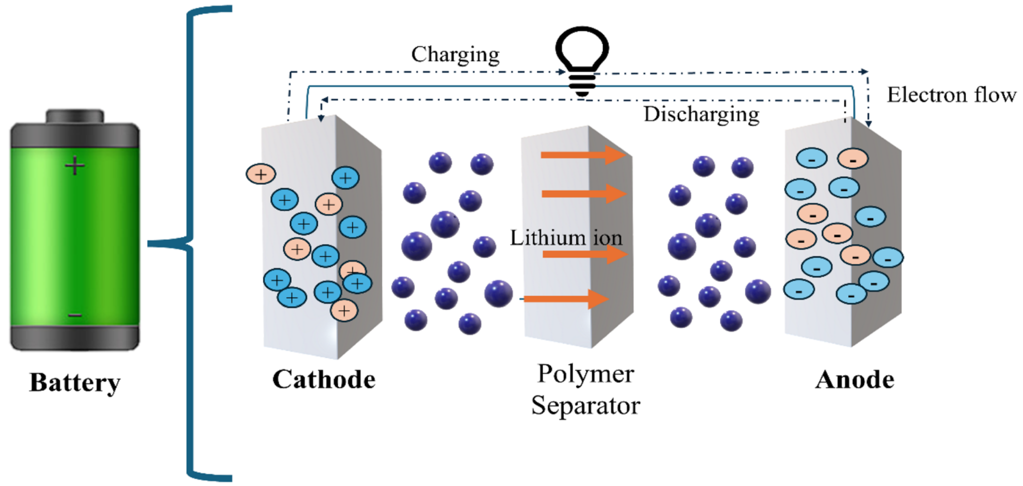

Fig. 7 Working LIB with an outline of its components.

2.1 Key components of lithium-ion batteries

Combinations of various transition metal oxides, adopted for the cathode and anode, are used to build LIBs.[79] The total voltage and energy density of LIBs are mostly determined by the cathode materials, which come in a variety of classes, with distinct crystal structures and electrochemical behaviors.[69] According to Wang *et al.*,[80] layered transition metal oxides, such as nickel manganese cobalt oxides (NMC) and lithium cobalt oxide ($LiCoO_2$), are commonly employed because of their relatively mature production techniques and high energy density. Although the layered structure facilitates effective lithium-ion intercalation, capacity fading may result from structural instability and transition metal dissolution during cycling, particularly at high voltages.[67] Spinel oxides, such as $LiMn_2O_4$, offer three-dimensional lithium-ion diffusion pathways, affording higher rate capabilities but often at the cost of lower capacity and voltage.[81] Meanwhile, olivine-type cathodes, such as $LiFePO_4$, are known for their superior thermal stability and longevity due to their robust structure, but they exhibit low operating voltages and modest capacities.[82] The lattice dimensionality and bonding directly influence the lithium-ion mobility and structural stability, making these key factors in cathode selection and optimization. Each cathode class presents unique challenges, including synthesis complexity, cycling stability, and safety concerns.[66] Because of its strong structural integrity, adequate low-voltage functioning, and good cycle stability, graphite is the industry standard anode material for LIBs.[83] The theoretical capacity of graphite is about 372 mAh g^{-1}. However, graphite's comparatively low capacity restricts the volumetric and gravimetric energy density of LIBs as energy needs rise, spurring extensive research into other materials. According to Wang *et al.*,[80] silicon, tin, and germanium-based anodes have garnered significant interest because of their significantly greater theoretical capacities, with silicon having a capacity of about 4200 mAh g^{-1}. Their significant volume increase during lithiation and delithiation results in mechanical deterioration, electrical connection loss, and cracking, which shorten cycle life and speed up capacity fading.[84] Although these liquid electrolytes offer excellent ionic conductivity at room temperature, they have several disadvantages, such as thermal instability, restricted electrochemical stability windows, and flammability.

2.2 Graphite and its derivatives in energy-storage applications

Because of its high cycle life, low lithiation potential, and structural stability, graphite is still one of the most used anode materials in commercial LIBs.[85] However, its relatively low theoretical capacity (372 mAh g^{-1}) and limited rate capability have motivated extensive research into advanced graphite derivatives and alternative carbon-based architectures.[86] Among them, graphene-based materials, especially graphene aerogels, have garnered a lot of interest because of their exceptional electrical conductivity, interconnected porosity networks, and extremely large surface area. Graphene aerogels are a possible substitute for high-performance energy-storage devices because they allow for quick ion movement and offer a large charge-storage capacity.[87] However, large-scale production remains constrained by complex synthesis routes, high energy demands, and elevated material costs, which consequently restrict industrial implementation.[85] Together with graphene, two-dimensional materials like transition metal dichalcogenides (TMDs) have drawn a lot of interest as cutting-edge electrode materials for upcoming supercapacitors and battery technologies.[88] MoS_2 and WS_2 are among the TMDs with layered structures that provide effective ion intercalation and significant pseudocapacitive behaviour. However, their poor long-term durability, structural instability during cycling, and relatively low electrical conductivity make it difficult to use them in lithium-ion systems.[89] Black phosphorus (BP) has also been identified as a multifunctional electrode material owing to its tuneable bandgap, high carrier mobility, and exceptional theoretical capacity.[90] The puckered layered architecture enhances lithium-ion diffusion kinetics, enabling improved

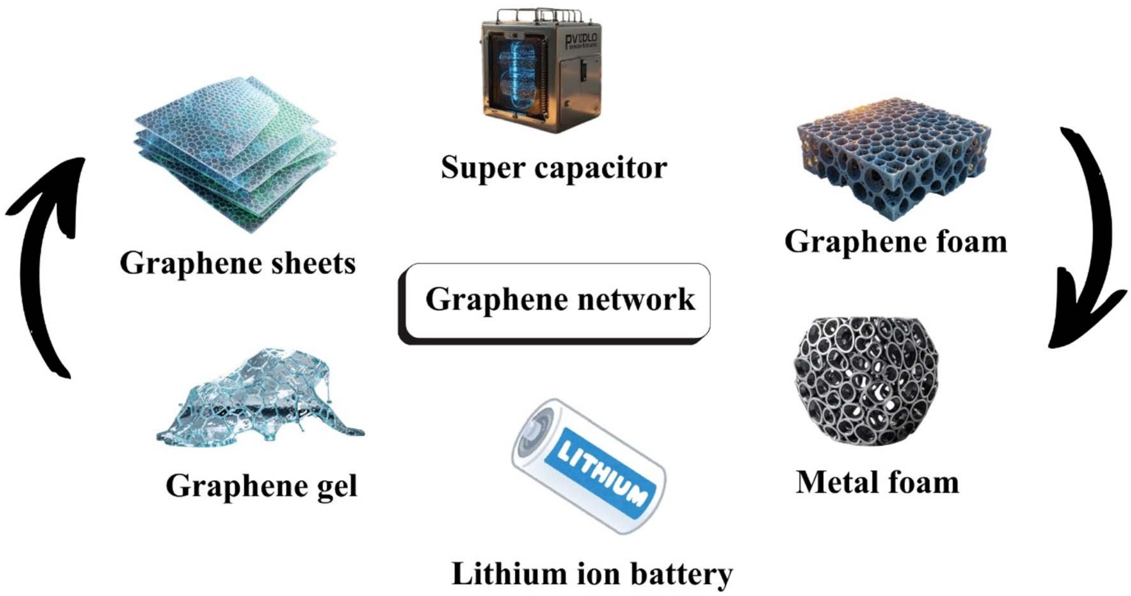

Fig. 8 Structural configurations of graphene networks and their integration into supercapacitors and lithium-ion batteries.

electrochemical performance relative to that achieved with the conventional graphite anodes.[91] Fig. 8 provides an illustration of graphene network structures and their role in high-performance energy-storage devices.

Despite its promising electrochemical properties, black phosphorus is limited by its instability under ambient conditions, susceptibility to oxidation, and high production costs, which restrict large-scale implementation.[92] Conversely, agricultural waste-derived carbon materials provide a sustainable and economically viable alternative without compromising functional performance.[93] While advanced materials like graphene aerogels, TMDs, and black phosphorus demonstrate remarkable laboratory-scale performance, their scalability is limited by environmental and economic constraints.[94] Biomass-derived carbons overcome these barriers by combining structural tunability, hierarchical porosity, and reduced production costs, thereby offering a sustainable alternative for next-generation lithium-ion batteries when assessed through life cycle and techno-economic perspectives.[95,96]

2.3 Waste-derived carbon anodes as sustainable alternatives to graphite

The rapid expansion of the LIB market, projected to grow at approximately 30% CAGR by 2030, has intensified global concerns over graphite supply security, particularly due to its highly concentrated production in China and the environmental impacts associated with graphite mining.[97] As described by Orilonise *et al.*,[98] agricultural waste-derived carbon materials have emerged as sustainable and economically attractive alternatives to commercial graphite anodes. Globally, more than 1.5 billion tons of agricultural residues are generated annually, offering an abundant and low-cost carbon precursor that can reduce material costs by an estimated 50–70% compared to mined graphite, which is approximately \$10 000–15 000 per ton.[99] As reported by Yokokura *et al.*,[100] the biomass-derived carbons, with their hierarchical porous structures, facilitates a faster lithium-ion diffusion, offering a clear advantage over the more compact nature of conventional graphite. The presence of intrinsic defects and heteroatom functionalities, such as nitrogen and oxygen doping, improves electrolyte wettability and contributes to additional pseudocapacitive storage, enabling increased rate capability and, in some cases, providing capacities exceeding the theoretical limit of graphite (372 mAh g^{-1}).[97] While improvements in long-term cycling stability and initial coulombic efficiency (ICE) are still required, waste-derived carbons have shown competitive or superior capacity and rate performance compared to graphite at high current densities.[98] These attributes position agricultural waste-based carbons as promising, scalable anode materials aligned with the circular economy and sustainable battery manufacturing strategies.[101] Table 3 presents a comparative assessment of conventional and biomass-derived anode materials, highlighting performance trade-offs and sustainability implications. It has been noted that biomass-derived carbons often exhibit 1.5–2× higher capacity at high rates due to the significant pseudocapacitive contributions (up to ∼50%).[102]

2.4 Advancements in lithium-ion battery technologies

Recent developments in lithium-ion battery electrodes are motivated by the need to improve the cycle stability, power capability, and energy density of the batteries.[103] On the cathode side, novel high-energy materials are synthesized with tailored nanostructures to optimize ion accessibility and structural stability during cycling.[83] Nano-structuring also aids in mitigating strain and phase transformations that can degrade the electrodes.[104] Silicon-based anodes have seen significant

Table 3 Comparative electrochemical performance of graphite and waste-derived carbon anodes[98–101]

Material	Initial capacity (mAh g^{-1} @ 0.1C)	Capacity retention (100 cycles)	Rate capability (1C/5C)	Cost and sustainability	Key limitation
Commercial graphite	320–350	>95%	250/150 mAh g^{-1}	High cost; supply chain risks	Limited theoretical capacity (372 mAh g^{-1})
Waste-derived carbon (*e.g.*, avocado seed, rice husk)	315–500+	85–95%	300+/200+ mAh g^{-1}	Low cost; waste valorization	Initial coulombic efficiency <80%
Si/graphite composite	500–800	70–90%	400/250 mAh g^{-1}	Moderate	~300% volume expansion
Biomass-derived Si/C	600–1200	80–92%	500+/300+ mAh g^{-1}	Very low; renewable precursor	Feedstock heterogeneity

development, with strategies focusing on controlling volumetric changes through nanoscale engineering and carbon encapsulation.[70] These innovations upgrade mechanical fracturing and stabilize the SEI, prolonging cycle life while maintaining high capacity.[69] Conversion-type anodes and alloying materials represent alternative approaches to intercalation-type electrodes, offering higher theoretical capacities but requiring careful management of volume changes and electronic conductivity.[80] Systematic research balances experimental fabrication with advanced characterization to optimize electrode architectures, targeting simultaneous improvements in capacity, rate performance, and safety. Advances in electrolyte chemistry have been pivotal in expanding the operational window, enhancing safety, and improving the cycling performance of LIBs.[66] Recent studies on liquid electrolytes have focused on developing non-flammable formulations to enhance battery safety. Strategies to mitigate thermal runaway while maintaining high ionic conductivity include optimized salt selection, solvation structure engineering, and molecular design, enabling lithium-ion batteries to operate safely without compromising their cycle stability.[105] Designing electrolytes with low melting points, strong lithium-ion affinity, and the ability to form favourable interphases permits improved performance at both minimum and maximum temperatures.[67] The use of film-forming additives has shown promise in stabilizing high-voltage cathode interfaces by constructing robust and conductive CEI layers that reduce parasitic reactions and transition metal dissolution.[79] These advances highlight the importance of electrolyte–electrode interactions for overall cell durability and safety. Electrode fabrication methods substantially influence battery microstructure, electrochemical performance, and scalability.[104] Techniques, such as slurry mixing, coating, drying, and calendaring, have evolved to optimize electrode density, porosity, and mechanical integrity, all of which affect ion/electron transport and battery kinetics.[106] Understanding the microstructure evolution during these processes informs the design of electrodes with controlled thickness, porosity, and particle distribution, advancing ion diffusion and electron conduction.[4] Novel electrode architectures incorporate multiphase systems, defect engineering, and tunnel regulation strategies to accelerate lithium-ion flux and maintain mechanical strength during cycling.[107] These processes not only improve fast-charging ability but also enhance long-term stability, addressing critical commercial requirements for LIB technology deployment.[106]

2.5 Global market trends and demand for lithium-ion batteries

LIBs dominate the energy reserve landscape across portable electronics, electric vehicles (EVs), and grid storage systems.[108] Lithium supply is vulnerable due to its concentrated production in China, Chile, and Australia amid rapidly growing demand. Supply faces long lead times, high extraction costs, and geopolitical uncertainties, while short-term lithium demand remains relatively inelastic. To mitigate these challenges, supply chain diversification, recycling, and innovative extraction technologies are essential.[109] The widespread adoption is driven by continuous cost reductions, energy-density improvements, and enhanced safety profiles.[110] The electric vehicle sector has particularly catalysed LIB growth as governments implement stringent emission regulations and consumers demand cleaner transportation alternatives.[111] Grid-scale storage requires batteries with rapid response and long cycle life to stabilize renewable sources, such as solar and wind power. Modularity and flexible installation further support LIB integration into energy infrastructures.[4] Broadly, market expansion is shaped by technological advancements, environmental policies, and regulatory frameworks, promoting green energy solutions.[112] Despite their widespread use, lithium and cobalt resources face constraints due to geographic concentration and limited reserves, raising concerns over supply security and cost volatility.[113] The elemental constraint has triggered exploration into sustainable sourcing, improved recycling practices, and the development of alternative battery interactions less reliant on limited metals. Recycling efforts aim to recover critical metals and reduce the environmental impacts of LIB waste.[114] Scientific investigations focus on multi-ion strategies and new materials to mitigate dependency on conventional elements, integrating environmental supervision with technological innovation.[115] The surging adoption of EVs worldwide, combined with expanding stationary energy-storage installations, represents substantial markets for LIBs.[112] Rapid advancement in fast-charging infrastructure and consumer electronics further drives demand for high-performance batteries.[108] Additionally, emerging technologies beyond lithium-ion technologies promise to diversify the market by addressing the limitations of current LIB technology, such as resource scarcity and specific energy density bottlenecks.[116] The constantly evolving ecosystem requires continual innovation in materials, manufacturing, and recycling to meet increasingly stringent performance, safety, and environmental criteria.

3 Agricultural waste as a sustainable resource for battery materials

Agricultural activities have observed a steep rise in the 21st century, leading to production amounts exceeding those in the preindustrial era.[117] With the rapid population expansion, industrial development, and increased economic activity, the global demand for energy has expanded drastically in recent decades.[118] The amount of agricultural waste produced has grown due to the quick expansion of agricultural output, comprising residual by-products produced during crop cultivation and food production processes. Depending on the source and kind of plant, agricultural waste can have different characteristics. Generally, it is made up of lignocellulosic biomass, which is mostly made up of cellulose, hemicellulose, and lignin.[14] On a dry weight basis, these residues typically have 40–50% cellulose, 25–35% hemicellulose, and 15–20% lignin. Table 4 provides an understanding of the lignocellulosic structure present in different agricultural wastes. These biopolymers form the structural matrix of the plant, including cellulose providing crystalline fibres for mechanical strength, hemicellulose acting as an amorphous polysaccharide filler, and lignin serving as a complex aromatic crosslinker contributing to rigidity and hydrophobicity.[119] The geographic distribution and availability of agricultural waste are closely tied to regional agricultural practices and crop types, as studied rice husks and wheat straw dominate in Asian and European farming areas, while corn cobs and sugarcane bagasse are abundant in the Americas and tropical regions.[120] The spatial heterogeneity directly influences the potential sourcing and scalability of agricultural waste for material applications. Leveraging regionally abundant residues can alleviate supply chain complexities and reduce transportation-related environmental footprints.[117] Agricultural biomass derived from different sources, such as rice straw, sugarcane bagasse, and corn stover, exhibits significant variability in lignocellulosic composition.[121] According to Yan *et al.*,[122] the compositional heterogeneity arises from differences in regional climate, soil characteristics, seasonal weather conditions, plant species, maturity stage, and harvest timing. This variability directly influences the properties of biomass-derived carbon materials, affecting carbon yield during pyrolysis, pore-structure development, crystallinity, and ultimately electrochemical performance in lithium-ion battery anodes.[123] As described by Yan *et al.*,[122] variations in feedstock composition may result in uneven heteroatom doping, which causes irregular pore structures, capacity degradation, and reduced rate capability, thereby compromising batch reproducibility and hindering large-scale commercialization. With the variations in physical properties, including grindability, flowability, and bulk density, the electrode fabrication may find inconsistency and reduced cycling stability.[124] According to Chyuan Ong *et al.*,[125] different mitigation strategies, including feedstock blending across regions, with controlled preprocessing, such as torrefaction and milling, help to regulate moisture (<10%) and particle size.[126] Additionally, robust supply chain management with controlled storage conditions and region-specific sourcing can further enhance feedstock consistency and improve scalability.

The valorisation of agricultural residues is attracting growing interest towards reducing waste footprint, as its lignocellulosic nature offers rich carbon content suitable for conversion into value-added materials, like battery electrodes.[127] The residual use aligns with broader resource recovery efforts, supporting renewable, circular economy frameworks. According to Rajak *et al.*,[128] a significant portion of biomass waste is generally burned or disposed of improperly, which

Table 4 Illustrating the lignocellulose structure components in different agricultural waste and its application[117,119,120]

Component	Structure	Key properties	Content range (% dry wt)	Extraction methods	Applications	Significance in circular bioeconomy	Environmental benefits
Cellulose	Linear biopolymer of D-glucose units (β-1,4-glycosidic linkages)	High mechanical strength; crystallinity (50–80%); biodegradable	35–50% (rice straw, sugarcane bagasse)	Acid hydrolysis; enzymatic treatment; steam explosion	Bioplastics; nanofibers; biocomposites	Structural backbone for sustainable polymers replacing petrochemical plastics	Reduces plastic pollution; enhances carbon sequestration
Hemicellulose	Branched heteropolymer (xylose, mannose, arabinose units)	Hydrophilic; low molecular weight (10–30 kDa); easily degradable	20–35% (wheat straw, corn stover)	Alkali extraction; hot water treatment; autohydrolysis	Biofilms; biopolymers; coatings; bioethanol production	Flexible matrix for producing value-added biochemicals in biorefineries	Reduces landfill waste; enables cascade biorefinery utilization
Lignin	Amorphous aromatic polymer (phenylpropane units: *p*-coumaryl, coniferyl, sinapyl alcohols)	Hydrophobic; phenolic-rich; thermally stable (>200 °C)	15–30% (sugarcane bagasse, rice husk)	Organosolv process; kraft pulping; ionic liquids	Carbon fibers; resins; adhesives; phenol substitutes	Source of renewable aromatic compounds for chemicals and advanced materials	Promotes biomass valorisation; reduces fossil fuel dependence (20–40%)

Table 5 Different lignocellulose component percentages in different agricultural wastes[133]

	% Cellulose	% Hemicellulose	% Lignin
Sugarcane	48	—	—
Corn stover	41	31	11
Lignocellulosic biomass	40–50	25–35	15–20
Maize husk	38.2	44.5	6.6
Rice straw	35	27	24
Soybean straw	83	—	—

degrades the environment and increases greenhouse gas emissions. Crop stalks, fruit and vegetable peels are examples of agricultural residues that provide significant potential as renewable feedstocks for clean energy and high-value bi-oproducts. According to Blasi *et al.*,[129] cellulose, hemicellulose, and lignin are three of the most abundant natural polymers on the planet, and these substances are prized for their biodegradability, biocompatibility, and renewable nature, which make them perfect for a variety of sustainable and commercial uses.[130,131] However, the mechanical and chemical properties of these polymers, including chain length, orientation, and concentration, significantly influence their behaviour, necessitating thorough characterization and testing.[132] They are unbranched, crystalline polymers composed of glucose units that repeat themselves.[133] Type I (native), Type II (chemically regenerated), Type III (ammonia-treated), and Type IV (heat-treated) are the four allomorphs of cellulose.[26] Table 5 highlights the percentage of different lignocellulosic components in agricultural waste.

The branched heteropolymers are composed of pentose and hexose sugars, including xylose, mannose, and glucose. When compared with cellulose, they hydrolyse more readily, enabling the production of ethanol and other valuable compounds widely used in food, cosmetic, and pharmaceutical applications.[134] However, 5–35% of biomass is made up of lignin, which functions as a structural glue to give materials rigidity, water resistance, and resistance to decay.[135] The alcohols *p*-coumaryl, coniferyl, and sinapyl are used to create this amorphous aromatic polymer. Biofuels, catalysts, carbon compounds for energy storage, and pollution adsorbents are all made from lignin.[136] Fig. 9 provides an understanding of the lignocellulose structure component in different agricultural wastes.

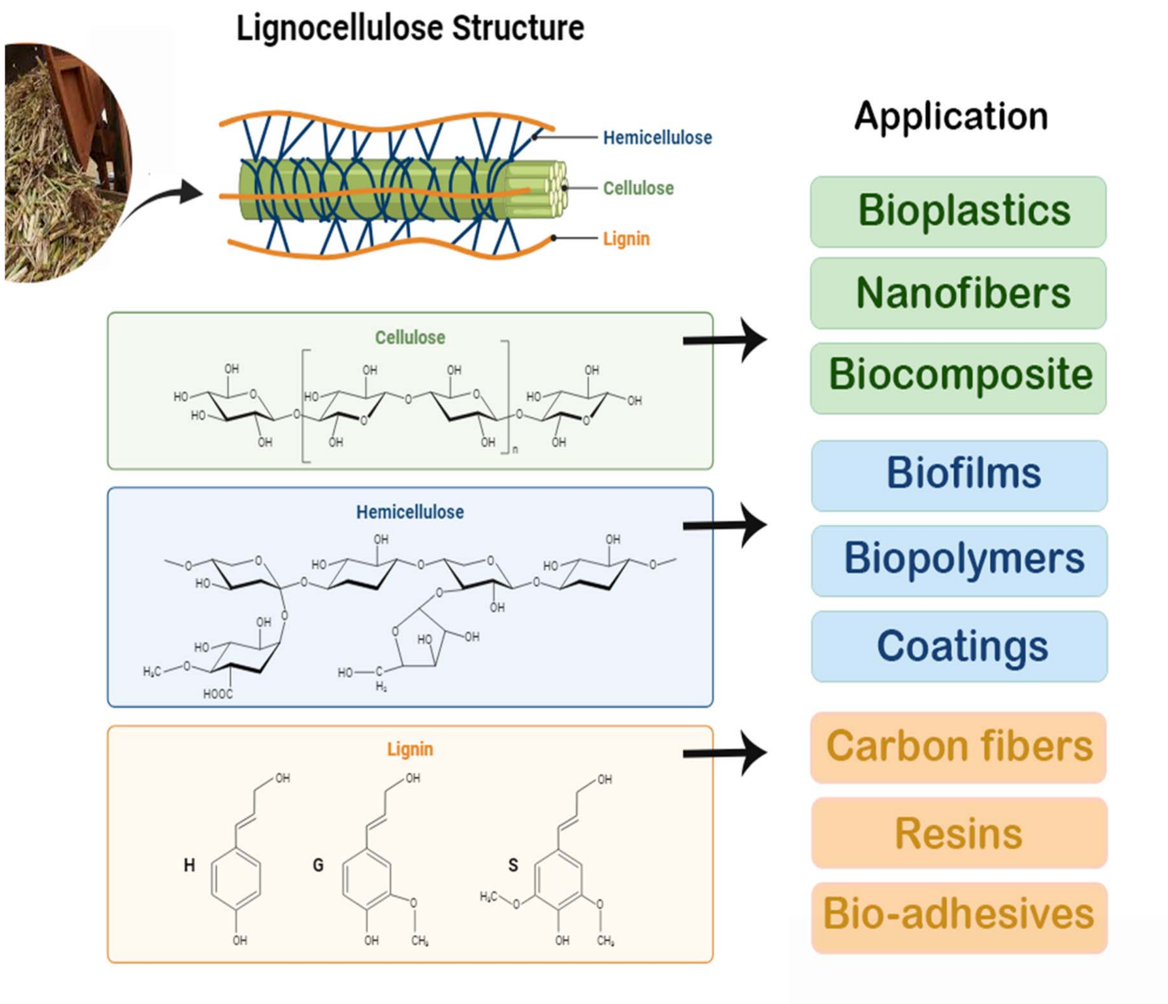

Fig. 9 Lignocellulose structure component in different agricultural wastes and their applications.

The intrinsic composition of biomass plays a decisive role in determining the microstructure and lithium storage behaviour of derived hard carbons used as LIB anodes.[137] Variations in the relative proportions of cellulose, hemicellulose, and lignin significantly influence the development of graphitic structures, pore sizes, density, and heteroatom functionalities during carbonization.[138] As studied by Hong *et al.*,[139] the cellulose-rich biomass can be characterized by its linear and crystalline structure, which tends to promote the formation of structuralized graphitic layers and closed pores when carbonized at temperatures between 600 and 1000 °C, thereby contributing to enhanced plateau capacity associated with low-voltage lithium intercalation. Conversely, in contrast, hemicellulose, which is structurally branched and thermally less stable, decomposes more readily to generate open pores and structural defects, leading to expanded interlayer spacing and improved sloping capacity through surface adsorption and pseudocapacitive storage.[140] Lignin, which is an aromatic and highly cross-linked polymer, tends to promote turbostratic carbon structures and closed pore formation, which can enhance structural stability during repeated cycling.[141] In addition to lignocellulosic composition, naturally occurring heteroatoms, such as nitrogen, oxygen, sulfur, and phosphorus, influence the electrochemical properties of biomass-derived carbons by creating active adsorption sites and improving charge-transfer kinetics.[139] According to Cai *et al.*,[140] nitrogen functionalities, such as pyridinic and quaternary N, can enhance lithium adsorption and diffusion, while inorganic constituents present in certain biomass sources, such as silica in rice husk, may contribute to the formation of porous Si–C composite structures that further improve capacity.[142] However, excessive ash content can introduce impurities and promote unstable solid-electrolyte interphase (SEI) formation, thereby reducing initial coulombic efficiency. Consequently, the compositional diversity of biomass feedstocks directly governs the structural and electrochemical characteristics of derived carbons, emphasizing the importance of feedstock selection and controlled processing for achieving reproducible performance in LIB anode applications.[143]

3.1 Potential of biomass-derived carbon for battery electrodes

Biomass waste conversion into carbon compounds for high-value applications, such as rechargeable batteries and sensors, has been emphasized by various studies.[144] According to Zhou *et al.*,[145] global biomass production exceeds 10–15 billion tons annually, representing an abundant and renewable carbon resource that is frequently underutilized and often improperly disposed of, leading to environmental degradation. Numerous investigations have shown that thermochemical techniques, like pyrolysis and hydrothermal carbonization (HTC), may transform biomass into porous carbon compounds with improved electrochemical characteristics.[146] Pyrolysis breaks down the organic matrix and creates holes by using high temperatures (often less than 1000 °C) under inert conditions, while HTC can process wet biomass and produces stable aromatic carbon structures by operating in water at moderate temperatures (180–250 °C).[147] The activation of biomass with chemicals, such as HCl, KOH, or NaOH, assists in improving pore structure and surface area while facilitating the HTC of different agricultural wastes, like corn straw, hemp stems, wheat straw, pomegranate peels and others.[148] According to Pistone and Espro,[146] carbon generated from biomass provides a high-performance, affordable, and environmentally friendly substitute for traditional electrode materials. For scalable, industrial-grade production, the combination of HTC with chemical activation has been considered as a promising method.[149] Fig. 10 describes the method of using agricultural waste to make activated carbon.

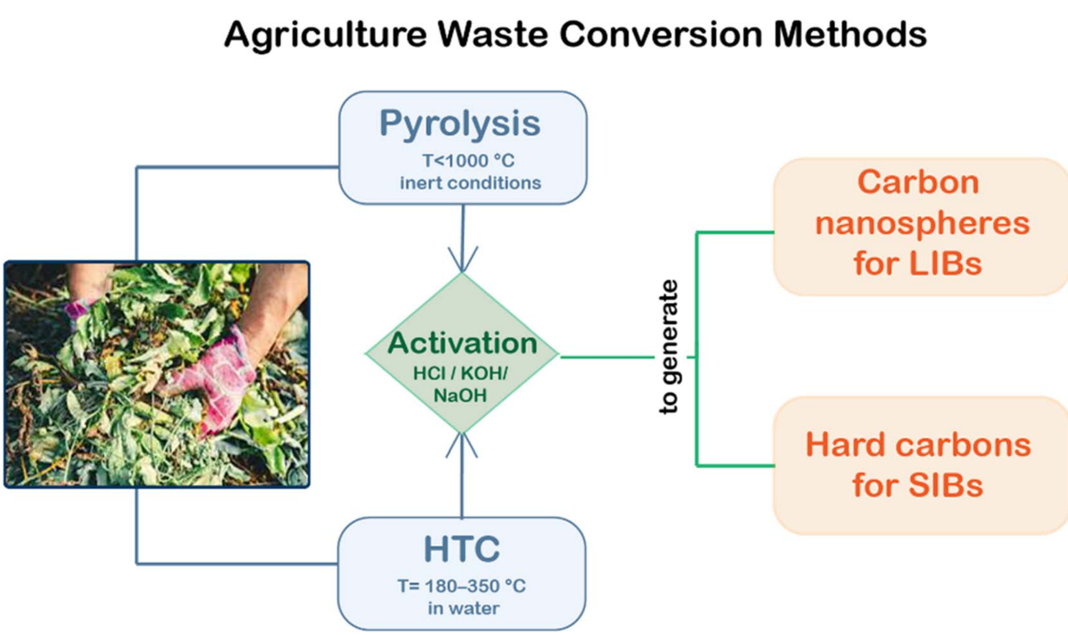

Fig. 10 Process of producing activated carbon using agricultural waste.

Yang *et al.*[150] state that biomass-derived carbon compounds show promise as sustainable and high-performing electrode materials for a range of secondary batteries, such as solid-state lithium metal batteries (ASSLMBs), LIBs, sodium-ion batteries (SIBs), and potassium-ion batteries (KIBs). Carbon materials are often created by pyrolysis or carbonization at temperatures between 500 and 1200 °C in inert atmospheres; this process has also helped construct porous structures.[127] Structural stability and storage capacity are enhanced when silicon, red phosphorus, or metal oxides are added to carbon composites; doping with heteroatoms further enhances electrical conductivity and electrochemical performance.[120] The incorporation of these materials has shown good results in a range of battery systems. For example, carbon obtained from wheat straw generated more than 1400 mAh g^{-1} in SIBs, while carbon extracted from litchi peels produced 474 mAh g^{-1} at 1 A g^{-1} in LIBs.[151] These results demonstrate the potential of biomass-derived carbons as affordable and sustainable substitutes for traditional synthetic carbon materials in next-generation energy-storage systems. These advantages include high surface area, hierarchical porosity, adjustable surface chemistry, and reduced environmental impact.[152] The lignocellulose structure component in various agricultural wastes is explained in Fig. 11.

The development of sustainable battery technology has been observed to be increasingly reliant on agricultural waste as

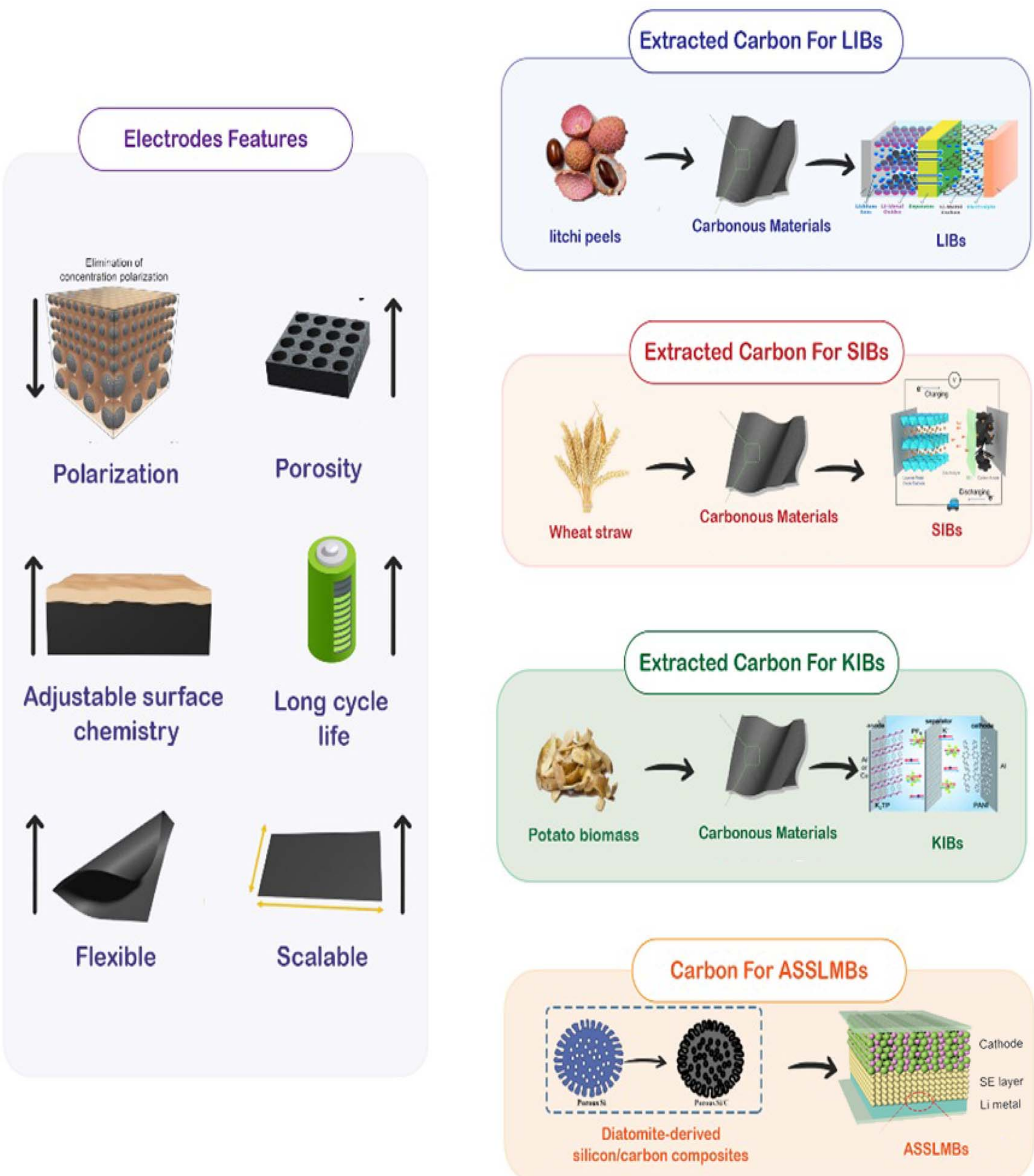

Fig. 11 Illustrating the carbon types used for secondary batteries, showing their advantages as an electrode.

a feedstock.[153] According to Acevedo *et al.*,[26] banana peels, rice husks, mango and tangerine peels, maize stalks, avocado seeds, cotton stalks, and coconut shells are among the various crop wastes that are currently being used to create carbon-rich materials that are used as anodes in LIBs and SIBs. These materials not only enhance battery performance but are also inexpensive, renewable, and eco-friendly. As per Khandaker *et al.*,[3] carbon-based anodes for LIBs are created by carbonizing agricultural waste at high temperatures, usually 600 °C to 1000 °C, occasionally with the use of KOH or $CaCl_2$ for chemical activation. Conversely, $CaCl_2$ has been used as an activator to carbonize buckwheat hulls. Lithium storage and ion transport have been enhanced using the method, and it has been shown to eliminate volatile components and afford a structure with mesopores and micropores, displaying a high capacity of 715 mAh g^{-1} at 0.2C in the final material. In contrast, green tea waste formed mesoporous carbon nanoparticles (~30 nm) following treatment with KOH and HCl. In this case, the structure maintained 86% of its capacity after 100 cycles and provided a wide surface area (1241 m^2 g^{-1}), which helped to achieve a capacity of 543 mAh g^{-1}.[153] Additionally, tubular porous carbon anodes were produced from agricultural cotton stalk waste *via* pyrolysis, generating micro- and mesoporous structures through the decomposition of cellulose, hemicellulose, and lignin. The particle size (<200 μm) significantly influenced pore distribution, particularly pore sizes less than 4 nm, while preserving the inherent tubular architecture. After 100 cycles, the optimized carbon exhibited a high Li^+ diffusion coefficient (1.47×10^{-11} cm^2 s^{-1}), demonstrating its potential as a sustainable LIB anode. Cotton stalk-derived materials have also been recently modified by incorporating both nitrogen and MoS_2, resulting in improved performance of lithium–sulfur batteries.[154] Fig. 12 describes the use of cotton stalk by the pyrolysis method to produce tubular carbon. According to Zhang *et al.*,[83] biomass-derived non-doped carbons are usually produced at high temperatures (600–1200 °C) in inert atmospheres (N_2 or Ar), where pore formation and structure ordering are controlled by thermal breakdown. To customize micro- and meso-porosity, which increases surface area and improves lithium-ion storage sites, chemical activation agents, like H_3PO_4, KOH, or $ZnCl_2$, are essential. For example, KOH-activated peanut shell carbon produced at 600 °C showed a high specific surface area of 706 m^2 g^{-1} and provided 474 mAh g^{-1} at 1 A g^{-1} after 400 cycles, indicating a substantial relationship between sustained electrochemical performance and activation-induced porosity. Similarly, after 100 cycles, green tea waste-derived spherical carbon (~30 nm) reached a capacity of 498 mAh g^{-1}. This was probably made possible by the shorter Li^+ diffusion paths and better charge-transfer kinetics due to the decreased particle size and homogeneous shape.

These results demonstrate how structural engineering and activation chemistry play a crucial role in the electrochemical behavior of carbon anodes generated from biomass. Similarly, rice husk activated with $ZnCl_2$ generated a highly porous carbon with a surface area of 1191 m^2 g^{-1} and delivered a capacity of 1105 mAh g^{-1} after 360 cycles at 0.1 A g^{-1}. With a carbonization temperature of 700 °C and a KOH mass ratio of 3 : 1, nitrogen-rich carbon derived from wheat straw produced a high capacity of 1470 mAh g^{-1} at 0.1 °C and maintained 344 mAh g^{-1} at 50 °C. These dopants increase conductivity, increase the number of active sites for lithium-ion storage, and widen the interlayer gap.[155] According to Molaiyan *et al.*,[156] it has been highlighted that using techniques like carbonization, pyrolysis, and chemical activation, biomass materials (like sisal fibers,

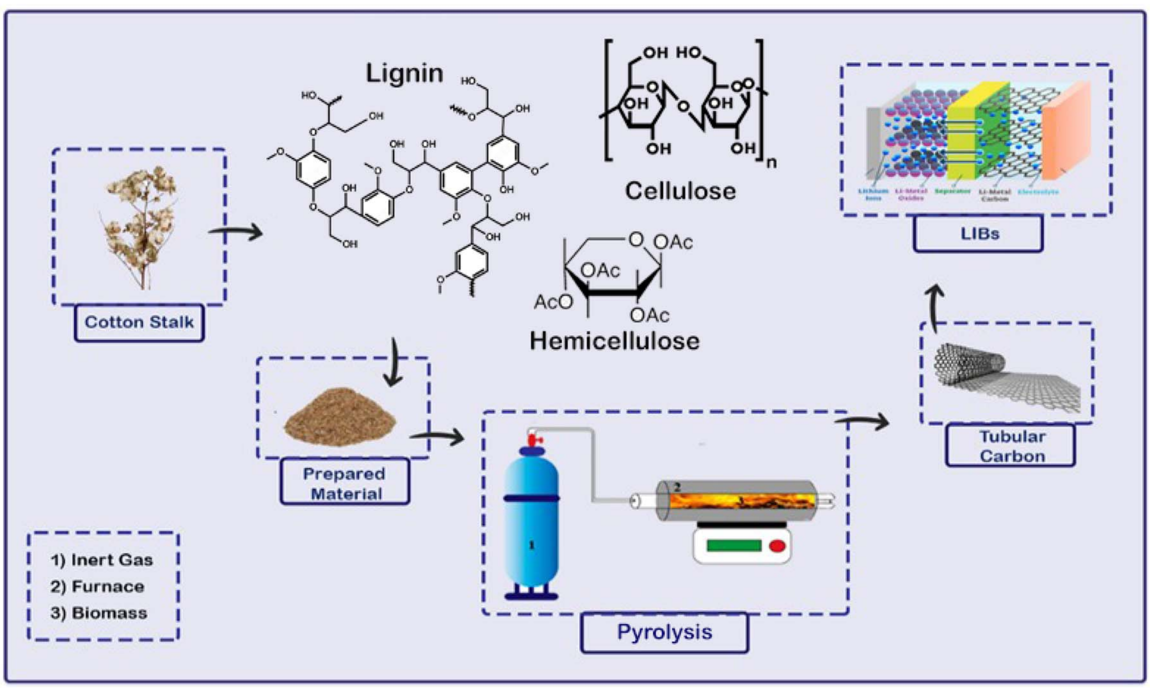

Fig. 12 Pyrolysis for cotton stalk to get tubular carbon used in LIBs.

Table 6 Conversion routes of agricultural biomass and performance advantages of derived activated carbon[152,153,156]

Waste used	Conversion process	Application	Advantages
Banana peels Rice husks Mango peels Tangerine peels Maize stalks Avocado seeds Cotton stalks Coconut shells	Carbonizing at (600 °C to1000 °C) with KOH/$CaCl_2$ as the active agent	Anodes for LIBs	Enhancement for lithium storage and ion transport Mesopores and micropore structure High capacity of 715 mAh g^{-1} at 0.2C
Peanut shells Green tea trash Rice husk Wheat straw	Carbonizing at (600 °C to 1200 °C) and at inert atmosphere (nitrogen or argon) with (H_3PO_4), (KOH), ($ZnCl_2$)	Anodes for LIBs	More active sites for lithium-ion storage Enhance conductivity Widen the interlayer gap Improvement in the surface area
Sisal fibers Cherry pits Jute fibers Bagasse Banana peels Coffee grounds Tamarind seeds Rice straws Mustard seeds	Carbonizing at (600 °C to 1100 °C) with KOH, $ZnCl_2$, H_3PO_4, $CuCl_2$, or $MgCl_2$	Anodes for LIBs	Banana peel-derived carbon produced a capacity of 800 mAh g^{-1} after 300 cycles Bagasse carbon co-doped material demonstrated a capacity of 800 mAh g^{-1} after 200 cycles
Biomass-derived carbon materials (BCMs)	Carbonization, followed by activation for porosity and conductivity	Anodes and cathodes for LIBs	High conductivity Good volume expansion Good cycling stability

cherry pits, jute fibers, bagasse and others) have been transformed into anode materials. Different activating agents, such as KOH, $ZnCl_2$, H_3PO_4, $CuCl_2$, and $MgCl_2$, are used to increase pore structure and surface area during pyrolysis, which normally takes place at temperatures between 600 °C to 1100 °C. On the other hand, another approach involving biomass-derived carbon materials (BCMs) has been investigated and deemed highly promising because of its abundance, structural diversity, and environmental compatibility.[23] The majority of BCMs offer capacities greater than 500 mAh g^{-1}, and in composite forms made of silicon and other materials, they can even surpass 1000 mAh g^{-1}. Through thermal methods like carbonization, biomass materials, such as plant matter, cellulose, silk, chitin, and algae, are converted into carbon. Activation or doping is frequently applied to improve porosity and conductivity. As per Zhang *et al.*,[2] BCMs assist anodes in overcoming problems like low conductivity, volume expansion, and cycling instability that are frequently observed with high-capacity materials, like silicon or metal oxides. Carbon-coated SnO_2 nanoplates for enhanced stability and TiO_2 integrated into 3D graphene for ultra-fast charge transfer and 10 000-cycle stability are two examples. The "pomegranate structure" encases silicon nanoparticles in several carbon layers and achieves a high volumetric capacity of 1270 mAh cm^{-3} and exceptional cycling stability. According to Zhao *et al.*,[157] over hundreds of cycles, coated cathodes like RGO-NCM and CNT-$LiMnO_4$ demonstrated enhanced rate capability and capacity retention. Table 6 highlights the conversion methods of different lignocellulosic materials and their advantages when used as activated carbon.

Agricultural leftovers constitute a plentiful and renewable lignocellulosic resource that has promising results for the creation of sustainable carbon compounds, which can be used for energy storage. The structural properties and electrochemical behavior of carbons generated from biomass are largely determined by the intrinsic composition of biomass, namely the relative amounts of cellulose, hemicellulose, and lignin. Lithium-ion storage performance is ultimately impacted by the pore structure, heteroatom functionality, and carbon yield,[83,153] all of which are directly impacted by variations in feedstock composition, geographic dispersion, and processing conditions. Agricultural waste can be efficiently converted into porous carbon materials with adjustable physicochemical characteristics and promising electrochemical capabilities using thermochemical conversion processes like pyrolysis, hydrothermal carbonization, and chemical activation.[156] Strategies, including controlled preprocessing, feedstock blending, and improved activation processes, provide workable routes toward scaling production despite the difficulties related to feedstock variability and repeatability.[137] Therefore, the valorization of agricultural biomass offers a sustainable and economical foundation for the development of cutting-edge electrode materials for next-generation rechargeable batteries, in addition to reducing environmental problems related to the disposal of agricultural waste.

3.2 Development of electrodes for sodium and lithium-ion batteries

SIBs are gaining traction as a less costly alternative to LIBs.[158] Because sodium ions are larger than lithium ions, they need different carbon structures, especially hard carbon with large holes and disordered layers.[156] Because of their high energy density and extended cycle life, LIBs are widely employed in portable devices; nevertheless, their usage is restricted by the high cost and scarcity of lithium supplies. On the other hand, because sodium is abundant and has a comparable electrochemical behaviour, SIBs have become a possible substitute. The slower reaction kinetics and worse performance are caused by the greater ionic radius of Na^+ (1.02 Å) compared to Li^+ (0.76 Å).[159] Rice husks, maize stalks, and soybean roots were carbonized at temperatures between 700 and 1300 °C; hydrothermal treatment or chemical doping with nitrogen and phosphorus have also been used on occasion. In contrast to the carbon produced from mango peel, which was also N,P-doped and heated to 1000 °C, which achieved 398 mAh g^{-1} and retained more than 50% of its capacity after 2500 cycles, hard carbon from soybean roots, which are rich in N and P, produced 369 mAh g^{-1} with an exceptional cycling capacity of 288 mAh g^{-1} after 1000 cycles at 1 A g^{-1}. Tangerine peel was carbonized at 800 °C, activated, and doped in a similar manner, resulting in 266 mAh g^{-1} and 94% retention over 2000 cycles, and even hard carbon was created from natural fluff from parasol trees, coconut shells, and walnut shells, with capacities close to 300 mAh g^{-1}. Both the porous N/S dual-doped carbon from broad beans and the nitrogen-doped carbon from egg yolk demonstrated outstanding cycling stability and exceptional sodium storage, with the latter achieving 466 mAh g^{-1} at 0.2 A g^{-1}.[152] While SIBs share conceptual similarities with LIBs and serve as promising alternatives for large-scale grid or low-cost applications, the market emphasizes LIB systems due to their prevailing market share, maturity in commercial deployment, and the central role of graphite carbon anodes in existing LIB architectures. As described by Pham *et al.*,[147] biomass-derived carbon electrodes have shown promising potential for both LIB and SIB systems. However, the differing electrochemical requirements, interlayer spacing constraints, and ionic radius effects of lithium and sodium require distinct material design strategies. Table 7 highlights various agricultural waste sources and their battery applications, alongside their life cycles. Pham *et al.*[147] evaluated biomass wastes, including spent coffee grounds, sunflower seed shells, and rose stems, with and without HTC pretreatment. After 1000 cycles, the HTC-derived SEED electrodes exhibited excellent capacity retention, high specific discharge capacity, and significantly improved initial coulombic efficiency (ICE). The enhanced ICE and rate performance were attributed to the HTC and direct carbonization promoting C=O/COOH functional groups, higher carbon yield, improved O and N incorporation, and expanded graphitic interlayer spacing. Additionally, carbonized HTC supernatant waste delivered 302 mAh g^{-1} with 91% ICE, outperforming conventional hard carbon (178 mAh g^{-1}, 75% ICE), demonstrating HTC's effectiveness in converting wet biomass waste into high-performance anode materials for sustainable SIBs.[147] Ghodadara[160] demonstrated the synthesis of porous carbon materials from wood-based biomass, including bamboo, oak, and pine, where the intrinsic hierarchical structures are largely preserved during carbonization. Pine-derived carbon exhibits a high degree of graphitization, leading to excellent electrical conductivity and sodium-ion storage capacity, while oak-derived carbon forms mechanically robust structures with high capacity and stable cycling performance.[158] Bamboo-derived carbon features a unique microstructure that enhances sodium-ion diffusion and storage. Directly carbonized wood produces mesoporous carbon anodes, delivering specific capacities of up to 270 mAh g^{-1} with long-term cycling stability, with many biomass-derived anodes retaining over 80% of their initial capacity after 500 cycles. The rate capability of these anodes is strongly governed by surface area and pore architecture.[160]

3.3 Carbon materials in modern energy-storage systems

The foundation of contemporary electrochemical energy-storage systems is carbon materials because of their superior electrical conductivity, chemical stability, adjustable surface chemistry, and structural adaptability.[161] In LIBs, SIBs, supercapacitors, and other storage technologies, a variety of carbon designs, including graphite, activated carbon, carbon nanotubes, graphene, and porous carbon frameworks, are crucial, according to recent thorough evaluations.[156] These materials serve as conductive skeletons that support effective electron transport and structural integrity inside composite electrodes, in addition to being active charge-storage media.[162] Advanced carbon materials enable enhanced electrochemical performance through hierarchical porosity, defect engineering, and heteroatom doping, which collectively improve ion diffusion, charge-transfer kinetics, and interfacial stability.[162] In particular, carbon frameworks used as carbon matrices have been shown to significantly mitigate volume expansion and mechanical degradation in high-capacity electrode materials, thereby improving cycling stability and rate performance.[163] Despite its efficacy, high manufacturing costs, energy-intensive synthesis processes, and ecological effects continue to limit the widespread use of synthetic carbons like graphene and carbon nanotubes. Carbon materials made from agricultural waste have become viable substitutes that support the ideas of the circular economy.[164] Biomass-derived carbons provide low-cost, scalable manufacture utilizing sustainable feedstocks while providing structurally varied and hierarchically porous structures. Bio-based carbons have great potential to supplement or replace traditional carbon materials in next-generation energy-storage devices when compared to the larger landscape of carbon electrode materials, especially when analysed *via* life cycle and techno-economic perspectives.[165]

3.4 Agricultural waste utilization in energy storage

To address the energy problem and waste management issues, turning agricultural waste into energy materials is a perfect alternative for creating sustainable energy-storage systems, like LIBs, SIBs, supercapacitors, and even green hydrogen systems, since they are affordable, plentiful, biodegradable, and environmentally supportive. Because of their large specific surface areas, high electrical conductivities, and changeable porosities, activated carbons derived from biomass have a lot of potential for

Table 7 Sources of agricultural waste and their applications in batteries alongside life cycle perspective[155,156,158]

Agricultural waste source	Processing temperature (°C)	Activating/doping agent	Battery type	Electrochemical performance
Buckwheat hulls	600–1000	$CaCl_2$	LIBs	715 mAh g^{-1} after 150 cycles
Cotton stalks	—	—	LIBs	271.7 mAh g^{-1} after 100 cycles
Green tea	600–1000	KOH + HCl	LIBs	543 mAh g^{-1} after 100 cycles
Soybean roots	700–1300	—	NIBs	288 mAh g^{-1} after 1000 cycles (0.1C)
Mango peel	—	—	NIBs	398 mAh g^{-1} after 2500 cycles
Tangerine peel	800	—	NIBs	266 mAh g^{-1} over 2000 cycles
Corn stalk	1000	—	NIBs	268 mAh g^{-1} after 100 cycles
Peanut shells	600	KOH	LIBs	474 mAh g^{-1} after 400 cycles
Green tea	—	—	LIBs	498 mAh g^{-1} after 100 cycles
Rice husk	—	$ZnCl_2$	LIBs	1105 mAh g^{-1} after 360 cycles
Wheat straw	700	KOH	LIBs	1470 mAh g^{-1} at 0.1C; 344 mAh g^{-1} at 50C
Banana peels	600–1100	KOH	LIBs	800 mAh g^{-1} after 300 cycles
Bagasse	—	—	LIBs	800 mAh g^{-1} after 200 cycles
Jute fiber	—	$CuCl_2$	LIBs	580.4 mAh g^{-1} at 0.2C
Cocklebur fruit	1100	N/O-doped	NIBs	366 mAh g^{-1} over 800 cycles
Seaweed	—	KOH	NIBs	200 mAh g^{-1} after 500 cycles
Onion and garlic peels	1100	Sulfur-doped	NIBs	145–178 mAh g^{-1} after 200 cycles
Pistachio shells	1000	—	NIBs	225 mAh g^{-1}
Broad beans	—	N/S dual-doped	NIBs	466 mAh g^{-1} at 0.2 A g^{-1}

usage in supercapacitors.[156] Furthermore, they promote waste reduction, increase energy efficiency, and offer a cheap, sustainable substitute for synthetic products. High-performance electrodes for batteries and capacitors can be designed with nanotechnological interventions through straightforward and scalable procedures. These developments move us closer to a circular, green economy in which waste is recycled to sustainably power our infrastructure and gadgets rather than being thrown away. Biomass feedstocks do not require energy-intensive or chemically demanding pretreatment processes to be immediately transformed into products with added value. However, because most raw and waste biomass materials have a high moisture content, many thermochemical conversion methods are inappropriate for processing them, making drying to acceptable levels an often required step, which is expensive and energy-intensive. This restriction is successfully addressed by hydrothermal carbonization (HTC) and associated hydrothermal techniques, which allow wet biomass to be processed directly. Because biomass qualities and reaction parameters have a significant impact on the physicochemical and structural properties of biomass-derived carbon materials (BMCS), determining the ideal processing conditions is difficult and requires a great deal of trial-and-error testing.[78] These approaches are often time-consuming, costly, and labour-intensive, limiting the accurate prediction of BMCS yield and properties. Recently, machine learning has emerged as a promising solution by enabling simulation-based optimization of processing parameters prior to laboratory-scale experimentation.[166] Fig. 13 highlights the agricultural biomass-derived carbon types and their applications.

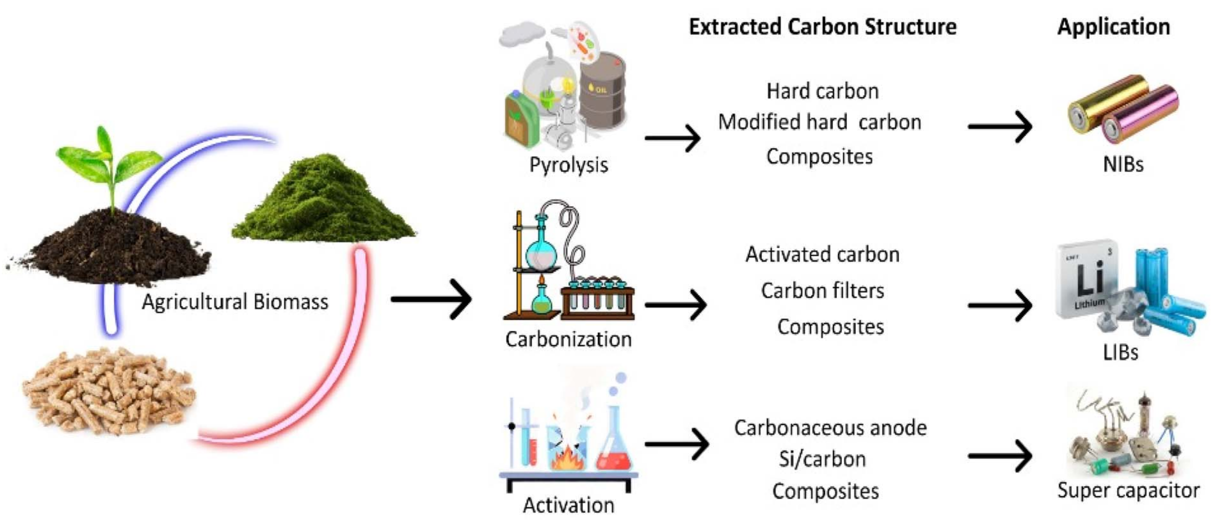

Fig. 13 Illustrating agriculture biomass-derived carbon types and their applications.

Rice husk has been widely available as an agricultural residue, which has been successfully converted into a high-performance electrode material for lithium-ion capacitors (LICs) through a scalable and environmentally friendly process. Rice husk ash (RHA), which is a by-product generated during the combustion of rice husks for energy production, serves as the primary precursor material. Typically, RHA consists of approximately 80–90% silica (SiO_2) and 10–20% carbon, and it exhibits a relatively low surface area of around 80 $m^2 g^{-1}$. To enhance its suitability for electrochemical applications, different researchers have employed a silica extraction process using hexylene glycol and potassium hydroxide (KOH) at 200 °C. This treatment removes the silica component and produces silica-depleted rice husk ash (SDRHA), a carbon-rich material with improved structural properties suitable for energy-storage applications.[167] There are multiple technological and environmental benefits to using bio-based materials in lithium-ion battery systems, especially those made from debris of agriculture. These materials are perfect for sustainable energy-storage applications since they are inexpensive, plentiful, renewable, and carbon-neutral. The dual extraction of silicon and carbon from biomass sources, like rice husks, is one of the most promising developments since it offers a scalable and environmentally friendly method of creating Si/C composites. Compared to traditional graphite anodes, these composites offer a substantially higher capacity, improve electrical conductivity, and efficiently buffer volume variations during charge–discharge cycles.[168] As per Temeche *et al.*,[169] silica-depleted rice husk ash (SDRHA) can maintain capacity and rate performance without requiring severe chemical activation. Its environmentally friendly production method, which eliminates the need for intricate chemical treatments, is consistent with the circular economy and greatly lessens the environmental impact of electrode fabrication.[170] Fig. 14 highlights the advantages of agricultural wastes as bio-based materials.

3.5 Biomass-derived carbon in redox flow batteries

Biomass-derived carbon compounds have drawn interest in redox flow battery (RFB) systems, especially vanadium redox flow batteries (VRFBs), in addition to lithium-ion batteries.[171] Porous carbon electrodes, which offer large surface area, electrical conductivity, and chemical stability in acidic and oxidative environments, are essential for promoting redox reactions in RFBs. Current developments emphasize the creation of lignin-based carbon fibres as environmentally friendly

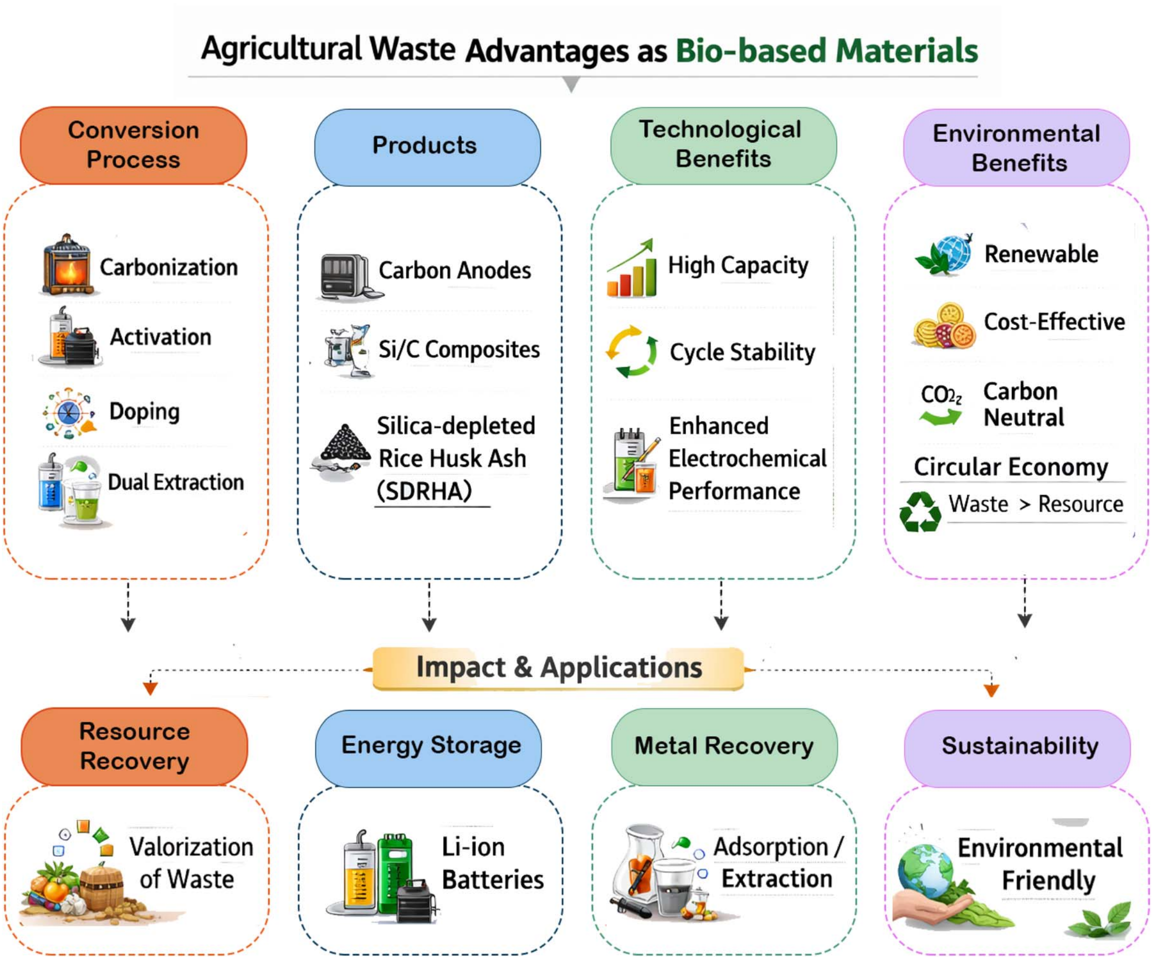

Fig. 14 Illustrating the advantages of agricultural wastes as bio-based materials.

substitutes for traditional carbon felts made from polyacrylonitrile (PAN).[172] These biomass-derived carbon fibres exhibit enhanced electrochemical activity, tuneable porosity, and improved wettability, contributing to increased energy efficiency and reaction kinetics in VRFB systems.[173] Additionally, hydrothermal carbon spheres and other biomass-derived nanostructures have demonstrated promising catalytic activity and surface functionalization properties suitable for redox flow applications.[174] These materials enable improved electrode–electrolyte interaction, enhanced mass transport, and reduced polarization losses. Crucially, using lignin and other renewable biomass precursors reduces the carbon footprint associated with electrode production and lessens dependency on polymers generated from fossil fuels. RFBs are essential technology for large-scale stationary energy storage, especially for renewable grid integration, whereas LIBs predominate in portable and mobility applications.[175] The use of carbon materials sourced from biomass in VRFB electrodes demonstrates how agricultural waste valorisation techniques may be used more broadly in the development of a variety of energy-storage systems. The literature shows that carbon compounds obtained from biomass are not only useful for lithium-ion systems but also greatly improve electrode performance in redox flow batteries, especially VRFBs.[176] These results support the adaptability of carbons produced from agricultural waste as multipurpose electrode materials for both stationary and mobile energy-storage systems.[177] These findings reinforce the versatility of agricultural waste-derived carbons as multifunctional electrode materials across both mobile and stationary energy-storage technologies.[177] In this regard, carbons generated from biomass and agricultural waste have shown great promise as sustainable anode materials for both SIBs and LIBs, providing advantageous electrochemical performance, customizable pore architectures, and heteroatom doping possibilities. Beyond battery systems, these bio-derived carbons exhibit promising uses in redox flow batteries and supercapacitors, demonstrating their versatile significance in contemporary energy-storage technologies.[149]

4 Environmental assessment of lithium-ion batteries

4.1 Carbon footprint and environmental impact of lithium mining

Concerns over the potential environmental impacts of lithium mining, which includes both the extraction and processing of lithium, have grown significantly because of the increasing demand for lithium-based products, such as effective electric batteries, on a global scale.[178] The sharp surge in demand for more efficient, reasonably priced, and high-performing electric batteries throughout the world has led to an increase in lithium mining and exploitation.[179] Electrical grids, computers, cell phones, and electric vehicles all use lithium-ion batteries.[4] After more than quadrupling between 2015 and 2020, the demand for lithium-ion batteries is expected to rise by more than 500% to 2.2 million tons by 2030.[180] As per Liang *et al.*,[181] China is expected to produce 1.34 billion lithium-ion batteries to meet this growing need on a worldwide scale. By 2025, the demand for lithium was expected to reach over 1.3 million metric tons of lithium carbonate equivalent (LCE), an even greater increase.[178] Johnson *et al.*[182] state that since the prices of lithium carbonate and lithium hydroxide doubled in 2017, the "lithium triangle" of Argentina, Bolivia, and Chile, which together hold nearly 70% of the world's lithium reserves, has drawn substantial international investment, with Chile producing about 38% of the world's lithium. The elemental form of lithium metal is not found in nature due to its strong chemical reactivity. Rather, lithium is usually found in tiny amounts in rocks, soils, geothermal brines, and natural water sources.[183] Large amounts

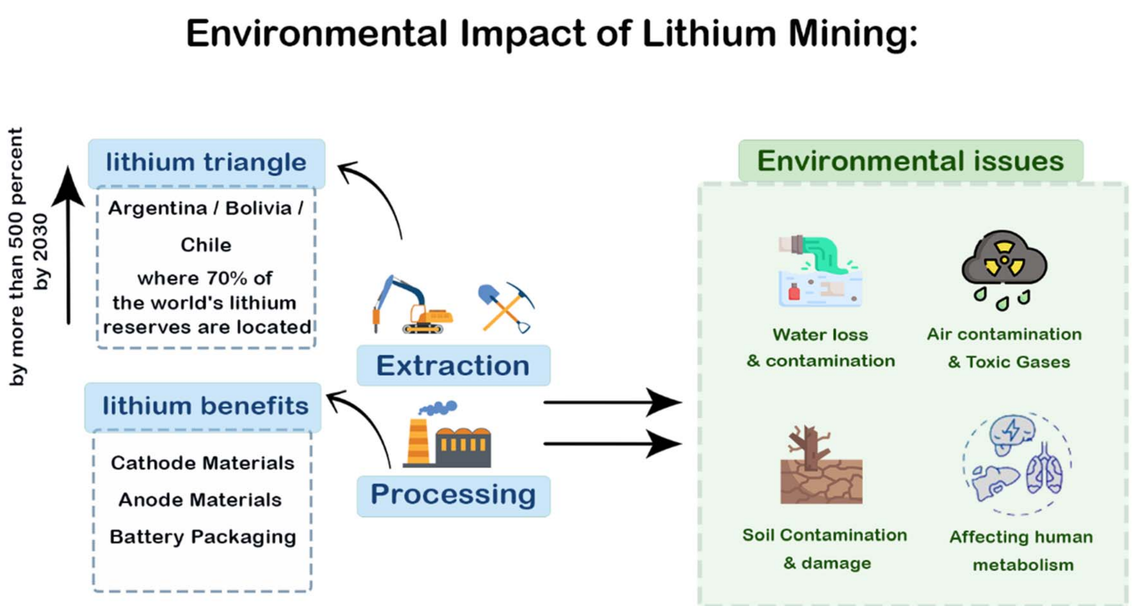

Fig. 15 Lithium extraction and processing and the corresponding environmental impact.

of lithium are seldom discovered on Earth, but when they are, they can be found in pegmatite, a granitic rock that typically contains minerals like spodumene, lepidolite, petalite, and zinnwaldite.[184] The environmental problems in these lithium mining sites are especially linked to soil, water, and air pollution, as well as the loss of vital human water supplies.[179] Fig. 15 illustrates how mining affects the ecosystem.

Different studies and meta-analyses show that the results of life-cycle assessments for LIBs are strongly affected by different methodological parameters. These parameters includes the functional unit, system boundaries (such as cradle-to-gate or cradle-to-grave approaches), end-of-life stages, and electricity grid mix, which are considered during battery manufacturing.[185–188] Meta-analysis studies indicate that the battery production stage, which includes active material preparation, electrode manufacturing, and cell assembly, usually dominates environmental impacts in cradle-to-gate assessments. However, the usage phase and the related energy mix are crucial in determining the total climatic effect of batteries used in electric cars and grid storage systems across their entire life cycle. To better assess emerging technologies, pLCA is often integrated with techno-economic analysis, and this combined framework enables different studies to evaluate the future developments in energy systems and battery technologies, which may influence both environmental performance and economic viability.[161,186] Comparative studies on LIB recycling technologies have revealed various advantages and limitations with regard to different recycling approaches. Traditional techniques, such as pyrometallurgical processes, are widely implemented at the industrial scale because of their operational robustness and handling capability (in terms of mixing battery waste); however, they are limited by high energy consumption and elevated processing temperatures. Conversely, hydrometallurgical methods operate under relatively milder conditions and enable more selective metal recovery, although their overall environmental performance depends on the type of chemical reagents used and the management of the resulting wastewater streams. More recently, alternative recycling strategies, such as solvometallurgical and bio-based methods, have gained increasing attention. In particular, deep eutectic solvent (DES)-based leaching has emerged as a promising approach, as it offers the potential to reduce environmental impacts when solvent recovery and process integration are effectively implemented.[189] Additionally, many comparative life cycle assessments show that the environmental advantages of battery recycling are mostly dependent on elements like the effectiveness of metal recovery, the purity of recovered materials, and the degree to which recycled materials may take the place of original material production.[164] Recent reviews have also highlighted several best practices for conducting environmental assessments, particularly for biomass-derived carbon electrodes. These include clearly defining the functional unit, specifying system boundaries and recycling credits, incorporating future-oriented scenarios, performing sensitivity analyses for key parameters, and integrating environmental assessments with techno-economic analysis. Incorporating these methodological considerations can significantly improve the robustness and reliability of environmental evaluations.[165–181,183–188,190,191] In addition, many studies have reported that primary lithium extraction causes significant greenhouse gas emissions, high water consumption, and environmental damage, especially in brine and hard-rock mining regions. These impacts highlight the need to reduce dependence on primary lithium sources and encourage alternative strategies, such as recycling, material substitution, and the development of bio-based electrode materials.

4.2 Role of carbon materials in sustainable energy-storage systems

A variety of carbon structures, including graphite, activated carbon, graphene, porous carbon frameworks, and carbon composites, are crucial to contemporary electrochemical energy-storage systems, according to recent studies on carbon electrode materials.[192] These materials act as the main structural and conductive components in batteries and supercapacitors. Carbon materials are widely used because they have high electrical conductivity, good chemical stability, and adjustable surface properties, which help improve electron transport and strengthen electrode structures.[193] In addition, carbon frameworks often act as conductive supports that help reduce the effects of volume expansion and improve the mechanical stability of electrodes, especially when combined with high-capacity active materials.[194] However, from an environmental perspective, producing advanced carbon materials, such as graphene and carbon nanotubes, at a large scale usually requires high energy input, strong chemical treatments, and complex purification steps.[155] Life-cycle assessment studies indicate that although these advanced materials provide excellent electrochemical performance, their environmental impacts during manufacturing can reduce the overall sustainability benefits if energy use and chemical consumption are not properly controlled.[156] Because of these concerns, recent studies suggest a growing interest in using more sustainable carbon sources and scalable production methods that reduce environmental impacts while maintaining good electrochemical performance.[195,196] In this context, biomass-derived carbon materials are considered promising alternatives. These materials can provide similar conductive and structural functions while using renewable raw materials and potentially lower-impact processing methods.

4.3 Life cycle assessment (LCA) of bio-based lithium-ion batteries

In smaller electrical and electronic equipment, LIBs typically last up to three years, while in bigger applications, such as electric vehicles (EVs), they can last for five to 10 years. Lead-acid batteries (LABs) have a lifespan of five to 10 years, whereas nickel–cadmium (NiCd) batteries can last up to twenty years.[197] End-of-life (EoL) LIBs have significantly increased due to the growing global demand for LIBs in EVs and renewable energy-storage systems. This presents significant waste management challenges because the batteries are made up of essential components like anodes, cathodes, and electrolytes, as well as reactive salts, volatile organics, and various additives.[198] They are necessary for consumer electronics, electric vehicles, and grid storage because they include polymers, electrolytes, and key metals (including lithium, cobalt, nickel, and manganese). However, insufficient treatment or incorrect disposal of LIBs can unleash dangerous compounds into the land, water, and air, posing major health concerns to people.[199,200] Fig. 16 illustrates the various health and safety hazards linked to metal compositions in an open setting.

Existing recycling methods, including pyrometallurgy and hydrometallurgy, are not only energy-intensive and inefficient but also environmentally unsustainable.[193] Additionally, processing mixed-chemistry LIBs presents a significant challenge, further complicated by inefficiencies in collection systems. Advanced, environmentally friendly recycling technologies like bio-hydrometallurgy and solvometallurgy, which provide a more sustainable method of recovering vital raw minerals like lithium, cobalt, and nickel, are desperately needed to enable the

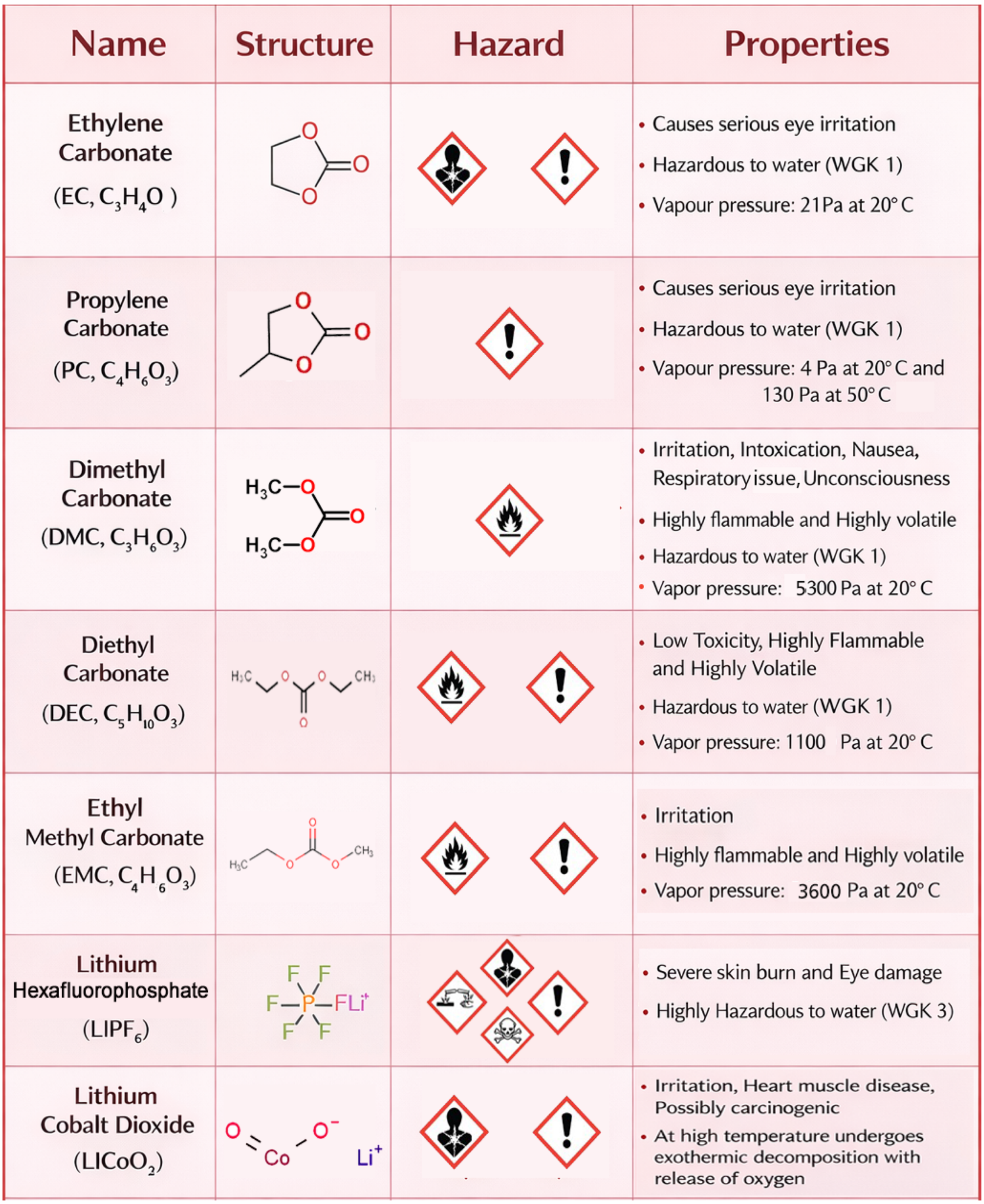

Fig. 16 Health and safety risk associated with metal compositions.

Table 8 Different challenges associated with the LIB life cycle and recycling

Challenge	Key issues/causes	Implications/risks	Mitigation strategies	References
Diverse and hazardous composition	• Complex and diverse battery chemistries require distinct recycling routes	• No universal recycling method applicable	• Develop standardized recycling protocols for multiple chemistries	197 and 202
	• Presence of flammable electrolytes and toxic materials increases safety risks	• Risk of electrical shock, burns, and thermal runaway leading to explosion	• Employ inert atmosphere dismantling and thermal management systems	
	• Solid electrolyte interface (SEI) decomposition and interfacial reactions accelerate temperature rise, triggering oxygen release	• Safety challenges in dismantling and processing	• Introduce automated discharging and safety monitoring	
Collection and sorting difficulties	• Labor- and time-intensive discharging and dismantling processes	• Inefficient material recovery and environmental contamination	• Implement extended producer responsibility (EPR) policies	203
	• Inefficient collection infrastructure leading to disposal in landfills or incineration	• Increased sorting errors and operational delays	• Establish national collection networks and battery take-back programs	
	• Lack of uniform labeling or identification of battery types	• Hindered progress toward a circular economy	• Introduce digital labeling and traceability systems (QR/RFID tags)	
Economic viability	• High reagent cost in hydrometallurgy and high energy demand in pyrometallurgy	• Limited profitability and scalability	• Develop hybrid recycling methods combining mechanical and hydrometallurgical steps	204
	• Low purity and recovery efficiency from mechanical pre-treatment	• Recycling cost exceeds the value of recovered materials	• Improve automation and energy recovery systems	
	• Volatile metal prices and expensive lithium extraction	• Unstable investment environment for recyclers	• Introduce economic incentives and subsidies for recyclers	
Safety risks	• Electrical, chemical, and thermal hazards during handling, storage, and processing	• Threat to worker safety and facility integrity	• Use automated dismantling systems and controlled discharge stations	205
	• Fire or explosion risk from damaged or improperly stored cells	• Potential large-scale fire hazards in recycling plants	• Enforce strict safety training and protective standards • Install early fire detection and suppression systems	

shift to a circular economy.[201] Table 8 explains the many difficulties related to the life cycle and recycling of LIBs.

4.4 Future perspectives for biomass-derived carbon anodes in LIBs

As described by Jia *et al.*,[206] despite significant progress in the development of biomass-derived carbon materials, their synthesis and evaluation remain largely confined to laboratory-scale studies, typically involving batch sizes below 1 g, with limited integration into existing LIB manufacturing infrastructure. The assistance of several pilot-scale initiatives and related developments in sodium-ion battery (SIB) systems can provide promising pathways toward industrial translation.[207] According to Lin *et al.*,[208] industrial demonstrations, such as hydrometallurgical battery recycling and commercial silicon–carbon composite production, highlight the feasibility of integrating sustainable carbon materials into battery value chains. In the study by Sun *et al.*,[209] pilot-scale SIB programs successfully produced kilogram-scale hard carbon anodes from biomass precursors, demonstrating compatibility with conventional electrode fabrication processes used in LIB manufacturing lines. Despite these encouraging developments, several technical and economic challenges remain for the large-scale deployment of biomass-derived carbon materials.[24] Variability in agricultural feedstocks can lead to fluctuations in carbon composition and structural properties, necessitating pre-processing steps, such as sorting, blending, and real-time characterization, to ensure consistent material quality.[150] At the same time, scaling thermochemical conversion processes remains a major challenge, since laboratory-scale batch furnaces must transition to continuous systems, such as rotary kilns or fluidized-bed reactors, to enable industrial production.[78] In addition, material purity and compositional consistency are critical, as residual ash and inorganic impurities can trigger gas evolution, unstable solid-electrolyte interphase (SEI) formation and reduced initial coulombic efficiency.[71] Biomass-derived carbons are largely compatible with conventional slurry mixing and coating processes, although adjustments in calendaring and electrode densification may be required to account for their higher intrinsic porosity.[78] These considerations also highlight opportunities for improving the practical integration of biomass-derived carbon materials in battery technologies.[97] The layered or fibrous microstructures of biomass-derived carbons often resemble graphite-like structures, enabling partial compatibility with existing lithium-ion battery manufacturing infrastructure.[93] Furthermore, the widespread availability of agricultural residues offers economic benefits and localized supply chains, which may reduce anode material costs while enhancing resource sustainability.[45] Approaches, such as blending biomass-derived carbons with graphite or silicon-based materials, optimizing carbonization conditions through data-driven methods, and implementing supportive policy frameworks, could further promote their integration into next-generation battery technologies.[78]

4.5 Environmental policies and regulations for sustainable batteries

Governments all over the world have recently developed environmental policies and regulations with the goal of promoting sustainable battery management and addressing the major environmental issues brought on by the battery industry's explosive growth, like waste management and resource depletion.[210] Under the Bipartisan Infrastructure Law, the U.S. Environmental Protection Agency (EPA) is creating regulations to encourage the safe, profitable, and ecologically responsible collecting and recycling of batteries, including lithium-ion models.[211] These guidelines emphasize practical implementation, worker safety, and the prevention of fires and air pollution from improper disposal. The initiative outlines best practices for communication, collection, transport, and tracking, along with voluntary labelling to aid proper battery identification and handling. It also promotes critical mineral recovery from recycled batteries to strengthen the domestic supply chain and support sustainable technologies. As per Melin *et al.*,[212] the European Union's Sustainable Batteries Regulation, enacted in August 2023, governs the entire lifecycle of batteries sold within the EU, ensuring stricter environmental and safety standards from production to disposal, which include mandatory carbon footprint declarations for electric vehicle batteries by 2025, followed by phased requirements for other battery types. A major innovation is the introduction of a 'battery passport' for industrial and EV batteries, enabling transparency and traceability within the supply chain.[213] The regulation enforces ambitious targets for recycled content in key materials, such as cobalt, lead, lithium, and nickel, alongside stringent recovery rate goals of up to 95% by 2031.[214] By integrating sustainability into battery production and reducing reliance on raw material extraction, the EU aims to minimize the ecological impact of the industry (Regulation – 2023/1542 – EN – EUR-Lex, 2023). Beyond environmental considerations, the regulation also emphasizes consumer rights and ethical sourcing. By 2027, portable batteries in consumer appliances must be designed for easy removal and replacement, aligning with the 'right to repair' movement and reducing electronic waste (current atate of EU right to repair – right to repair Europe, 2024). This regulation provides a structured timeline for compliance, allowing industries to gradually adapt while maintaining progress toward sustainability.

4.6 Environmental implications of graphite and its derivatives

Beyond conventional natural and synthetic graphite, advanced carbon derivatives, such as graphene aerogels, transition metal dichalcogenides (TMDs), and black phosphorus, have been widely explored as next-generation electrode materials due to their superior electrochemical properties.[215] From an environmental perspective, recent literature highlights that many of these materials are associated with substantial energy and material footprints during synthesis. Despite their ultra-high surface area and interconnected conductive networks, graphene aerogels usually require multi-step processes, such as chemical vapor deposition, freeze-drying, or supercritical drying, all of which increase greenhouse gas emissions and energy consumption.[216] Similarly, transition metal dichalcogenides, such as MoS_2 and WS_2, rely on metal-intensive precursors and high-temperature or solvent-intensive synthesis routes. Life-cycle considerations discussed in recent studies and reviews indicate that while TMDs provide excellent pseudocapacitive performance, their environmental sustainability is constrained by transition-metal mining impacts, precursor toxicity, and challenges in end-of-life recovery.[217] Black phosphorus has also emerged as a multifunctional electrode material with high theoretical capacity and favourable ion-transport characteristics; however, its production is energy-intensive, and its poor ambient stability necessitates protective processing steps that further increase environmental burdens. Collectively, these studies demonstrate that although advanced graphite derivatives and two-dimensional materials deliver exceptional electrochemical performance, their large-scale deployment is limited by environmental and economic constraints.[218] In comparison, biomass-derived carbon materials offer a lower-impact alternative by utilizing renewable feedstocks, reducing reliance on energy-intensive synthesis routes, and enabling integration within circular economy frameworks. This contrast highlights the environmental rationale for exploring agricultural waste-derived carbons as sustainable substitutes for conventional graphite and its advanced derivatives in lithium-ion battery applications. The literature clearly indicates that while graphene aerogels, TMDs, and black phosphorus represent high-performance graphite derivatives, their environmental footprints remain significant due to energy-intensive synthesis and resource-critical precursors.[219] These limitations strengthen the case for low-impact, biomass-derived carbon materials as environmentally preferable electrode alternatives within sustainable LIB life-cycle frameworks.[220]

5 Economic assessment of bio-based lithium-ion batteries

Economic assessment holds a key importance in the production factors of LIBs, and with the constant technological advancements and resource scarcity, it has become essential to assess the economics of products.[221] So, assessing the economics of bio-based LIBs, especially in comparison to conventional materials, is both relevant and compelling. Materials derived from agricultural waste are emerging as promising alternatives, valued for their sustainability and lower costs.[69] Because of the complexity of extraction, refining, and geopolitical dynamics, conventional LIBs depend on extracted minerals like nickel, cobalt, and lithium, which come at a high cost.[222] By reducing reliance on expensive mining methods, bio-based products obtained from agricultural waste, such as carbon extracted from biomass or lignin-based electrolytes, offer a financially feasible substitute.[223] Traditional battery manufacturing often requires the use of high-purity materials and energy-intensive processes, which increases costs. Using agricultural waste can simplify production procedures and lower overall costs.[224] From a supply chain perspective, conventional battery materials are prone to price fluctuations owing to resource scarcity and geopolitical uncertainties.[225] In contrast, agricultural waste, characterized by its abundance and renewability, offers a more consistent and potentially more economical supply alternative. However, despite the economic advantages of bio-based materials, it is imperative that they meet the performance benchmarks established by conventional batteries concerning energy density, cycle longevity, and operational efficiency. Table 9 shows the material and manufacturing cost analysis of conventional *vs.* agricultural waste-derived materials.

Agricultural waste-derived materials offer a sustainable and cost-effective alternative to conventional materials used in energy-storage technologies.[114] In contrast, agricultural waste-derived materials utilize abundant and renewable resources like biomass-based carbon and lignin, significantly reducing raw material cost. The manufacturing of conventional materials typically involves energy-intensive processes and strict purity requirements, which intensify production expenses, whereas agricultural waste-derived materials can often be processed using simpler, less resource-demanding techniques, leading to lower manufacturing costs.[14] Moreover, the supply chain for conventional materials is susceptible to disruptions due to scarcity and geopolitical tensions, making them less reliable.[113] Agricultural waste materials, however, are widely available across the globe as by-products of farming activities, offering a more stable, renewable, and locally accessible supply chain with reduced risk of price volatility. The utilization of agricultural waste serves to diminish greenhouse gas emissions, alleviate environmental pollution, and lessen dependence on fossil fuel sources.[144] This practice facilitates the transition towards a circular economy by transforming waste materials into valuable resources.[226] The implementation of agricultural waste management strategies has the potential to generate employment opportunities in rural regions, enhance farm income diversification, and stimulate local economic development. With appropriate governmental support and strategic investment in infrastructure, efficient supply chains for the collection, preprocessing, and distribution of agricultural waste can be successfully established.[227]

5.1 Market potential and investment, challenges and opportunities in the sustainable battery sector

The electrification of transportation, the integration of renewable energy sources, and the strong legislative push for net-zero emissions are driving the rapid growth of the worldwide market for sustainable batteries, particularly lithium-ion (Li-ion) varieties.[228] McKinsey projects that the value chain for Li-ion batteries will climb from $85 billion in 2022 to over $400 billion by 2030, with demand exceeding 4.7 TWh, nearly a seven-fold increase, mainly due to the adoption of electric vehicles (EVs).[26] The value chain offers investment possibilities in cell production, active materials, raw material refinement, and recycling in particular, which is expected to generate $6 billion in profits by 2040.[113] Advances in battery technology, such as solid-state and dry electrode coating, favourable government regulations, and the rise of circular economy models that lessen dependency on raw materials are important motivators. All things considered, the sustainable battery industry has enormous economic potential and is essential to a robust, low-carbon future. The worldwide trend toward electrification, particularly in the EV industry, which is expected to dominate battery consumption, is a major driver of this increase. According to Islam *et al.*,[229] energy-storage systems (ESS), which store surplus energy produced from renewable sources and provide it during times of peak demand, are essential in resolving these issues. ESS provides several benefits, such as reducing peak demand and related tariffs, lowering carbon emissions,[230] delaying investments in transmission and

Table 9 Material and manufacturing cost analysis of conventional *vs.* agricultural waste-derived materials[224,225]

Aspect	Conventional materials	Agricultural waste-derived materials
Material costs	Depends on costly mined resources, such as Li, Co, and Ni, whose prices are affected by extraction challenges and geopolitical factors	Incorporates sustainable, low-cost alternatives, including biomass-derived carbon and lignin
Manufacturing expenses	Demands the use of highly purified materials and intricate manufacturing procedures, which significantly increase production costs	Simplified techniques have the potential to lower manufacturing expenditures
Supply chain and availability	Prone to price fluctuations due to scarcity and geopolitical tension	Widely available, renewable, and less susceptible to price instability

Fig. 17 Illustrating the scalability and commercial viability of bio-based batteries.

distribution infrastructure, facilitating energy arbitrage, improving grid stability, enabling energy and peak-load shifting, offering ancillary grid services, supporting higher levels of renewable energy integration, and mitigating fluctuations in renewable energy generation.[231] At the same time, the necessity of creating efficient battery recycling laws has been brought to light by growing international worries about the growing number of batteries that are nearing the end of their useful lives.[228] These regulatory frameworks can lessen reliance on primary resources, encourage the circular economy, limit environmental concerns, and aid in the accomplishment of climate mitigation objectives.[219,221] The utilization of agricultural waste-derived materials in LIBs requires further investigation to ensure that these materials can effectively replace conventional components without compromising electrochemical performance.[232] While utilizing waste materials can reduce dependence on mined resources, their processing may still result in environmental impacts, such as energy consumption and emissions.[233] For widespread adoption, the cost of converting agricultural waste into battery-grade materials must be competitive with existing supply chains.[234] Additionally, the recycling and disposal of LIBs remain complex, and the integration of waste-derived materials into current recycling systems requires significant improvements in infrastructure and technology.[235] By reducing their overall carbon footprint, advances in battery chemistry and recycling technologies offer the potential to greatly increase the sustainability of lithium-ion batteries. Because they rely on renewable and biodegradable resources that can lessen the environmental effects of battery manufacture and end-of-life management, bio-based battery materials are becoming more and more popular as sustainable substitutes for traditional LIB components.[236] As per Liu *et al.*,[223] while agricultural waste is abundant, ensuring a consistent and reliable supply of bio-derived raw materials on an industrial scale remains a significant hurdle. These materials often require specialized treatment processes, such as carbonization, chemical activation, or structural modification, to enhance their electrochemical properties, which can significantly increase production costs and complicate scalability.[207] Fig. 17 describes the scalability and commercial viability of bio-based batteries.

5.2 Standardization and regulatory framework for sustainable batteries

By guaranteeing the safe handling, recovery, and disposal of hazardous batteries, effective battery recycling standards are crucial for lowering environmental pollution. Along with heavy metals, like nickel, cobalt, manganese, and lithium, used batteries frequently include flammable and poisonous electrolytes like $LiClO_4$, $LiBF_4$, and $LiPF_4$.[225] When these materials are disposed of improperly, they may leak into the soil and water, endangering human health as well as ecosystems. By enforcing the proper collection, transportation, and processing of battery trash, regulatory frameworks can stop the discharge of air pollutants and hazardous leachates from cremation.[14] Recycling laws also contribute to the preservation of natural resources by reducing the need for primary mining, which is frequently associated with significant greenhouse gas emissions, deforestation, disruption of ecosystems, and excessive water consumption.[16] Lithium-ion battery recycling into battery-grade materials offers substantial environmental benefits, with possible reductions in greenhouse gas emissions ranging from 58% to 81%, according to recent life cycle studies. Reducing the battery industry's carbon footprint helps to mitigate climate change. Additionally, battery recycling utilizes 72% to 88% less water and 77% to 89% less energy than conventional ways of extracting and processing raw materials.[236] All applications of biofuel cells currently encounter challenges related to suboptimal power, current, output voltage, open-circuit potential, and various other aspects of electrical performance.[237] By efficiently utilizing agricultural waste, the sector can move toward a more sustainable energy future, minimize waste-disposal

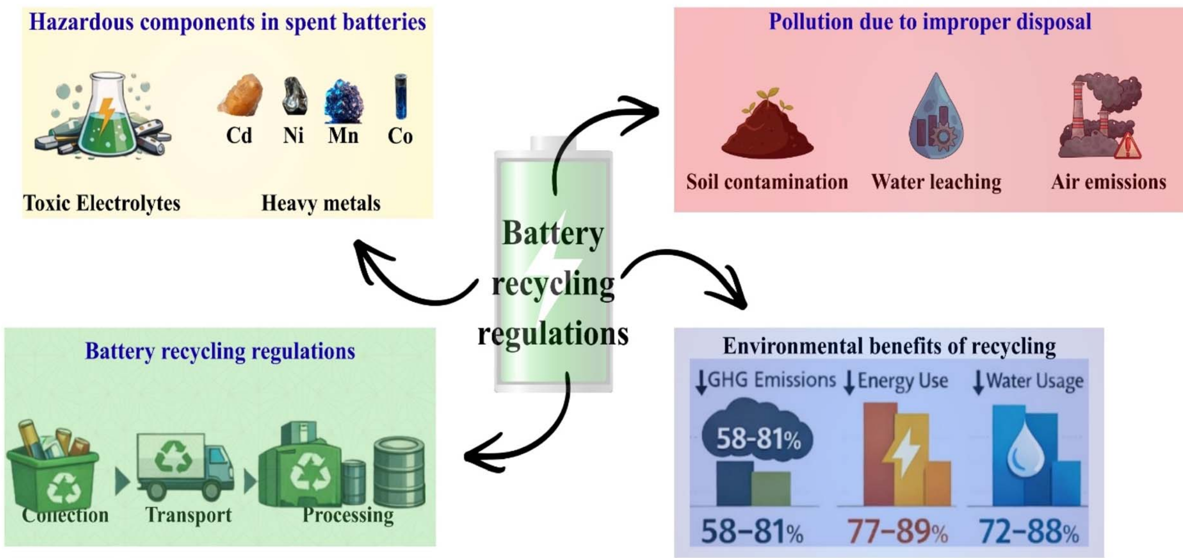

Fig. 18 Illustrating the technical challenges associated with using agricultural waste for energy storage.

issues, and open new income opportunities for the agricultural industry.[238] Fig. 18 presents the technical challenges associated with using agricultural waste for energy storage.

Beyond laboratory-scale performance, systematic benchmarking of biomass-derived carbons against commercial graphite under practically relevant conditions is crucial for assessing their real-world applicability. Although many agricultural waste-derived carbons show promising electrochemical performance, most studies remain limited to half-cell configurations, and systematic benchmarking against commercial graphite is scarce. Commercial graphite exhibits high initial coulombic efficiency, stable long-term cycling, and established full-cell performance,[239] whereas biomass-derived carbons are often tested against lithium metal, making direct comparison difficult.[240] Moreover, their integration into existing lithium-ion battery manufacturing infrastructure remains limited. Challenges, such as variability in biomass precursors, scalability of synthesis, relatively low initial coulombic efficiency, and lower tap density, hinder large-scale adoption. Future research should focus on standardized benchmarking under industrially relevant conditions, scalable synthesis, and pilot-scale validation to enable practical applications.

6 Future challenges, prospects and recommendations

Future studies should focus on optimizing conversion processes, like pyrolysis, hydrothermal carbonization, and activation of chemicals, to improve structural control, porosity, and conductivity to fully utilize the potential of carbon materials derived from agricultural waste in lithium-ion batteries.[241] When compared to traditional graphite, these enhancements are crucial for providing greater capacity, longer cycle stability, and faster ion-transport. Furthermore, to quantitatively demonstrate the financial and environmental advantages of biomass-derived electrodes and support their status as a reliable substitute for carbon sources derived from fossil fuels, thorough LCA and TEA should be made.[239] In addition to taking care of durability and safety in practical applications, particular emphasis should also be paid to addressing the failure mechanisms of these materials, such as structural degradation. Economic viability and environmental sustainability must be balanced to support large-scale adoption. Despite progress, challenges persist in scaling efficient and clean recycling processes to match the increasing LIB consumption, necessitating continued research and development and policy support. Besides that, investments should be made at the industrial and policy levels to scale up laboratory results into pilot projects and commercial manufacturing, backed by dependable supply chains and uniform material quality standards. The introduction of bio-based batteries into the general market can be greatly accelerated by global policies, especially by those that are trying to find a way to accelerate a green future.[242] Furthermore, a guiding principle to optimize sustainability should be the implementation of circular economy frameworks, which upcycle agricultural leftovers into high-value energy materials before being recycled for further use. To further improve electrochemical performance and sustainability, future studies should investigate the incorporation of next-generation functional materials. High electrical conductivity, hydrophilic surfaces, and adjustable interlayer spacing are features of two-dimensional materials, like MXenes, which enable better charge storage and quicker ion movement. Similarly, because of their open framework structure, affordability, and environmental compatibility, Prussian blue frameworks have become viable, sustainable cathode materials. Covalent organic frameworks (COFs), metal–organic frameworks (MOFs), and hydrogen-bonded organic frameworks (HOFs) are examples of porous crystalline materials that offer precisely specified and adjustable topologies that facilitate effective ion transport and structural stability.[243] High-performance and sustainable energy-storage devices can be developed by hybrid systems that combine MXenes with MOFs or COFs. However, before actual adoption, issues with large-scale production, long-term stability, recyclability, and economic viability must be resolved. The majority of synthesis techniques are still restricted to laboratory-scale experiments, despite the promising electrochemical performance of carbon compounds generated from biomass. Due to difficulties with precursor heterogeneity, process scalability, and material repeatability, large-scale integration into the current infrastructure for producing lithium-ion batteries has not yet been fully achieved. Batch-to-batch variations in carbon structure, surface chemistry, and electrochemical behavior might result from the composition of biomass feedstocks, which frequently varies based on source, season, and processing history.[244]

Furthermore, industrial deployment requires continuous and energy-efficient carbonization and activation processes, precise control over pore architecture, and uniform particle morphology to ensure compatibility with existing slurry coating, calendaring, and electrode fabrication lines. In addition, biomass-derived carbons must meet stringent industrial requirements, including consistent physicochemical properties, high purity, stable long-term cycling performance, and compatibility with commercial binders and electrolytes.[245] Current limitations also include scale-up cost, process energy demand, and the need for standardized precursor pre-treatment protocols.[246] The industrial translation of biomass-derived carbons presents significant opportunities for advancing sustainable energy-storage technologies. These materials offer several advantages over conventional graphite, including renewable sourcing, lower cost, tunable porosity, and a reduced environmental footprint. Emerging scalable strategies, such as continuous pyrolysis, template-free activation, and integration with biorefinery and waste-valorization systems, demonstrate promising pathways for bridging the gap between laboratory research and industrial production. With continued progress in precursor standardization, process intensification, and electrode engineering, biomass-derived carbon materials could serve as sustainable alternatives or partial substitutes for commercial carbon materials in next-generation energy-storage technologies. In addition to the economic considerations, the intrinsic variability of agricultural biomass presents further challenges. Agricultural biomass inherently exhibits regional, seasonal, and species-dependent variability in lignocellulosic composition, mineral content, and moisture levels. Such heterogeneity can significantly influence carbonization yield, pore-structure evolution, heteroatom-doping characteristics, and ultimately electrochemical performance.[247] Variations in lignin and cellulose content, for example, directly affect carbon yield and structural ordering, while inorganic impurities may alter activation efficiency and conductivity.[248] Importantly, the biomass composition critically governs the microstructure evolution and lithium storage performance of the derived carbons. Variations in lignin, cellulose, and hemicellulose content influence carbon yield, the degree of structural ordering, defect density, and pore development during carbonization. Lignin-rich precursors generally promote higher carbon yield and the formation of aromatic domains, whereas cellulose and hemicellulose-rich fractions facilitate micropore generation through enhanced volatile release.

Inherent heteroatoms (*e.g.*, N, S, and O) introduce defects and additional active sites, thereby improving electronic conductivity and contributing to pseudocapacitive lithium storage. Meanwhile, inorganic species and ash content can modulate graphitization behaviour, activation efficiency, and overall defect distribution.[249] These interconnected compositional factors ultimately determine the dominant lithium-storage mechanisms, including intercalation within graphitic layers, surface adsorption at defect sites, and capacitive contributions from porous structures. To mitigate these challenges, systematic feedstock characterization, blending of biomass sources to reduce compositional fluctuations, controlled pre-treatment protocols, and process parameter optimization are essential.[250–255] Standardization strategies and strong quality control frameworks will be critical to ensure batch-to-batch reproducibility and to facilitate reliable industrial-scale integration of biomass-derived carbon materials.

7 Conclusion

This review establishes the environmental and economic potential of utilizing agricultural waste-derived materials in lithium-ion battery production. The analysis demonstrates that biomass residues, when properly processed, can yield carbon-based electrode materials with electrochemical performance comparable to that of traditional graphite. From an environmental perspective, adopting agricultural waste significantly reduces greenhouse gas emissions, energy input, and the ecological degradation associated with raw material extraction. Economically, it offers a low-cost and locally available resource that supports waste valorisation and contributes to a circular economy framework. However, certain challenges remain, such as variability in biomass composition, limited scalability of conversion processes, and the need for consistent material quality at an industrial scale. Addressing these limitations through process optimization and material standardization can enhance the commercial viability of bio-based lithium-ion batteries. In conclusion, integrating agricultural waste into LIB manufacturing not only mitigates environmental burdens but also provides a sustainable and economically attractive route for the next generation of energy-storage technologies. This approach represents a critical step toward cleaner, more resilient, and resource-efficient energy systems aligned with global sustainability goals.

Author contributions

Pranav Prashant Dagwar: conceptualization and writing – original draft. Nada Ramadan: conceptualization and writing – original draft. Syed Suffia Iqbal: conceptualization and writing – original draft. Jasneet Singh: writing – original draft. Lakshmikanth Moganti: writing – original draft. Dina Magdy Abdo:

conceptualization, supervision; and writing – reviewing and editing. Deblina Dutta: conceptualization, supervision; and writing – reviewing and editing.

Conflicts of interest

Authors declare that they have no known competing financial interests or personal relationships that could have influenced the work presented in this manuscript.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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