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Introduction to green and sustainable batteries

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Introduction

This themed collection on *Green and Sustainable Batteries* presents the latest breakthroughs, pressing challenges, and bold ideas driving the quest for the "*holy grail*" of energy storage: battery technologies that combine high performance, low cost, safety, and sustainability.

The race to net zero is on—and the clock is ticking. As governments, industries, and research institutions mobilise to cut greenhouse gas emissions, green and sustainable energy storage has become a cornerstone in the clean energy transition. Batteries are central to this mission, enabling solar, wind, and other renewables to deliver power reliably despite their natural intermittency.

Today, lithium-ion batteries (LIBs) dominate—from grid storage to electric vehicles to the devices in our pockets. Yet, their high costs, dependence on scarce and sometimes toxic materials, and lingering environmental and safety issues are fuelling an urgent search for better options.

This themed collection on *Green and Sustainable Batteries* spotlights the cutting-edge advances, critical challenges, and radical ideas shaping the future of energy storage.

Advances in LIB sustainability

From a materials perspective, the scientific community is devoting increasing attention to the development of more sustainable electrodes for LIBs. This collection highlights notable advances, including new electrode designs to reduce reliance on critical materials such as Co, Ni, Mn, and Li: **https://doi.org/10.1039/D4TA04976D**. A common strategy involves lowering cobalt content by adopting Ni-rich cathodes; however, their high surface reactivity accelerates solvent decomposition, cathode–electrolyte interphase (CEI) growth, and rapid capacity fade. Recent approaches—such as surface modifications to inhibit carbonate deprotonation—are being explored to improve the stability of Ni-rich layered cathodes.

Graphite, the primary anode material in most LIB chemistries, has been designated as a critical raw material by the EU due to potential supply shortages. While synthetic graphite offers an alternative, its production—especially graphitization—requires significant energy. Regeneration of graphite from spent LIBs offers a promising solution, with studies demonstrating strong electrochemical performance and efficiency over multiple cycles: **https://doi.org/10.1039/D4TA07618D**.

Sustainability efforts in battery research also extend to waste-based and biomass-derived electrodes, not only for LIBs but also for post-lithium technologies. Examples featured in this collection include hard carbons derived from barley husk: **https://doi.org/10.1039/D5SU00254K**, holm-oak waste: **https://doi.org/10.1039/D5SE00645G**, and vine-shoots: **https://doi.org/10.1039/D4TA07393B** for Sodium ion batteries (SIB) and LIB anodes, as well as biogenic silicon anodes for LIBs.

The collection also highlights the replacement of inorganic electrodes with versatile organic alternatives that are abundant, more sustainable, and exhibit tunable properties applicable across various battery technologies. Notable examples include the development of tetrathiafulvalene-based COFs and vanillin bio-based redox polymers as LIB cathodes; PTMA-based copolymers and derived polyimides (PNTCDI) serving as cathode and anode, respectively, in dual-ion all-polymer batteries; and covalent triazine-based frameworks (CTFs) for the design of rocking-chair all-organic systems.

Lithium metal and polymer electrolytes

Lithium metal batteries (LMBs) offer high energy density but face severe interfacial instability, dendrite growth leading to inefficient lithium use and poor cycle life. Strategies to address these include artificial SEI layers: **https://doi.org/10.1039/D5GC01282A**, three-dimensional (3D) electrode archi-

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tecture for uniform Li plating/stripping: https://doi.org/10.1039/D5GC02081F, and the development of more stable and sustainable electrolytes, such as bio-based solvents: https://doi.org/10.1039/D4GC05476H and single-ion polymer electrolytes: https://doi.org/10.1039/D5GC00252D. Research into these new electrolytes should also address hazard and toxicity assessments, establishing a benchmark for future studies.

Beyond lithium: alternative chemistries

Since no single battery technology can meet the entire global energy demand, this collection also examines advances in alternative chemistries, including sodium-ion (SIBs), potassium-ion (KIBs), zinc-ion (ZIBs), zinc–air: https://doi.org/10.1039/D4GC04687K, and more emerging technologies, such as Zn–CO_2 (https://doi.org/10.1039/D4TA06665K), and polymer–air batteries (https://doi.org/10.1039/D5SE00825E).

Sodium-ion batteries (SIBs) benefit from sodium's abundance and low cost, with hard carbon as the most common anode. Research focuses on improving performance and sustainability using biomass-derived carbons and biowaste sources: https://doi.org/10.1039/D5SE00645G, https://doi.org/10.1039/D4TA07393B. Sn-based anodes, offering higher capacity, face challenges from large volume changes during cycling, which can be mitigated through engineered morphologies: https://doi.org/10.1039/D5TA03000E and heterostructures (*e.g.* core–shell and coral-like structures: https://doi.org/10.1039/D4TA08119F). The use of 2D-layered transition metal carbides and nitrides (MXenes) as anodes, along with their functionalized or surface-modified composites, represents a promising approach for advancing SIB performance (https://doi.org/10.1039/D4TA05669H). By mitigating volume expansion during charge–discharge, enhancing mass transport, and improving conductivity, these materials can significantly boost specific capacity, rate capability, and cycling stability.

Potassium-ion batteries (KIBs) are attractive for their abundance and favorable redox potential. While materials from LIB and SIB research—such as PEO-based polymer electrolytes: https://doi.org/10.1039/D5TA02762D and carbon-based anodes: https://doi.org/10.1039/D5GC01554E—are under exploration, the large K^+ ion requires tailored material designs to overcome current performance limitations.

Zinc-ion batteries (ZIBs) have emerged as a promising post-lithium-ion technology, offering high theoretical energy density, reduced manufacturing costs, and enhanced safety. While ZIBs generally operate with neutral or mildly acidic aqueous electrolytes, their practical application is constrained by challenges such as hydrogen evolution, electrode passivation, and undesirable dendrite formation at the zinc anode. Additionally, the development of suitable cathode chemistries compatible with ZIB electrochemistry remains limited. In this themed collection, advances involving macromolecular electrolyte engineering: https://doi.org/10.1039/D4GC05107F and deep eutectic solvent electrolytes (https://doi.org/10.1039/D5TA00395D offer insight into the dynamic role of water in the electrolyte, while composite strategies for vanadium- and manganese-based cathodes (https://doi.org/10.1039/D5GC01694K) provide an understanding of zinc storage mechanisms.

Recycling, waste valorization, and circularity

The current linear economy model is not aligned to meet the net-zero commitments, given the ecological impact of primary metal extraction and growing waste generation. Waste valorization and direct recycling are critical strategies to reduce waste and resource depletion. This approach has been reinforced by the EU Battery Regulation that has set ambitious recovery targets—90% for cobalt and nickel and 50% for lithium by 2027, rising to 95% and 80%, respectively, by 2031. Some innovative approaches have been included in this themed collection. This themed collection features innovative recycling approaches for LIBs (https://doi.org/10.1039/D4TA04976D), such as https://pubs.rsc.org/en/content/articlelanding/2025/ta/d4ta07618d the recycling of common cathodes (*e.g.* NMC: https://doi.org/10.1039/D5GC00054H and LMNO-type) cathodes: https://doi.org/10.1039/D4TA07642G, offering new perspectives on recovering the main components of LIBs.

Final remarks

Additional contributions in this collection push the boundaries of sustainable battery innovation, from Zn–CO_2: https://doi.org/10.1039/D4TA06665K and Zn–air: https://doi.org/10.1039/D4GC04687K systems to photo-rechargeable designs: https://doi.org/10.1039/D5TA00517E and all-solid-state polymer–air batteries: https://doi.org/10.1039/D5SE00825E, complemented by techno-economic analyses of next-generation technologies. Together, these works chart a compelling route toward batteries that power our future without compromising the planet. While this collection cannot cover every critical facet of sustainable battery research, we recognise and celebrate the breadth of pioneering work taking place across the field.

As guest editors of this themed collection on Green and Sustainable Batteries, we extend our sincere thanks to all contributing authors for the exceptional quality, creativity, and depth of their work. We are equally indebted to the editorial teams of *Green Chemistry*, *Journal of Materials Chemistry A*, *Sustainable Energy & Fuels*, and *RSC Sustainability* for their expertise and steadfast support in bringing this collection to life.

We hope this collection will inspire and energise researchers across chemistry, materials science, engineering, and environmental science to drive forward the next generation of sustainable batteries—technologies that unite high performance, affordability, and environmental responsibility to truly transform our energy future.