Pioneering Sustainable Cathodes and Anodes for Next-Generation Electric Vehicles

KID: 20250415 | Ms Jyotirekha Dutta, Prof Surendra K Martha

Imagine powering your phone or car with a lightweight powerhouse that recharges hundreds of times without fading quickly; that's the lithium-ion battery (LIB) revolutionising our daily life. These batteries pack more energy into smaller spaces than ever before, fueling everything from laptops to EVs with minimal self-discharge. No memory effect means you can top them up at any time, making them ideal for our on-the-go world. However, there's a downside: extracting rare metals from the earth can devastate nature and risk supply disruptions. [1,2] However, game-changing recycling that reclaims nearly all those valuables, innovative material designs paired with greener technology, unlocks a circular, eco-friendly energy revolution.

The rapid proliferation of LIBs in electronics and electric vehicles has generated vast amounts of hazardous e-waste, with only 3% of spent batteries currently being recycled. This highlights the urgent need for robust closed-loop protocols to mitigate environmental impacts and promote resource sustainability through circular economy principles (Figure 1). [1] Enhancing pretreatment stages, such as cell discharge, mechanical dismantling, and black mass recovery, integrated with AI-driven automated segregation and policy-driven collection incentives, offers a pathway to profitable, eco-friendly mechanochemical separation of high-grade materials, dramatically boosting recycling efficiency and curbing future energy demands. [4]

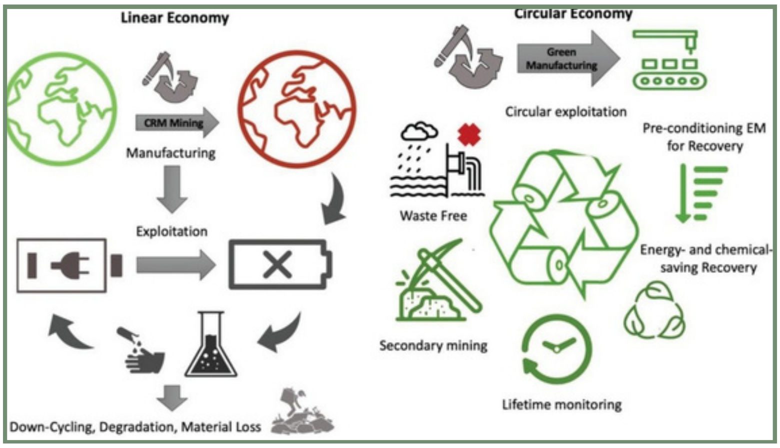

Figure 1: Comparison of recycling in the linear economy and the circular economy. [1]

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Sustainable battery research envisions electrochemical technologies that not only store energy but also protect the ecological and social systems on which they rely. It emphasises that the design, production, use, and disposal of batteries must respect environmental and social boundaries. The goal is to ensure long-term resource security and social equity throughout the battery lifecycle. [1] It demands innovation in cathode and anode materials to power electric vehicles while minimizing environmental impact and enabling circular economies. Efforts in developing low-cobalt Ni-rich layered oxides, high-entropy cathodes, and silicon-graphite anodes focus on enhancing energy density, cycle life, and recyclability to support scalable EV adoption without resource depletion. [3] In this view, sustainability becomes a unifying thread that weaves together environmental conservation (mitigating life-cycle emissions, toxicity, and resource depletion), social responsibility (safeguarding workers and communities), and economic resilience (delivering scalable, affordable technologies), all coordinated through circular strategies such as eco-design, enhanced durability, thoughtfully engineered second-life pathways, and efficient, high-recovery recycling.

In our laboratory, comprehensive efforts focus on reutilising all LIB components, from graphite anodes and $LiNi_xMn_yCo_yO_2$ (NMC xyz, x + y + z = 1) / $LiFePO_4$ / $LiCoO_2$ cathodes to separators and current collectors (Figure 2). Significant effort has been devoted to regenerating spent LIB graphite to restore electrochemical performance and upcycle carbon components, emphasising graphite recovery as a critical material due to its high environmental and economic production costs. [5] We are also working on freestanding alloy and conversion-type anodes to achieve high cycle life and power through simplified designs, minimising inactive mass and additives. [6] These integrated strategies link superior battery metrics with resource efficiency, curbing raw material demands and diverting waste. Our laboratory advances sustainable battery research by developing efficient extraction methods for valuable elements, such as Li, Ni, and Co, from spent LIB cathodes, prioritising closed-loop recovery. Concurrently, we target Co alternatives through Co-less and Co-zero cathodes, achieving key milestones in high-performance with resource-efficient elements such as Mn and Fe. [7,8]

We are developing a cobalt-free $LiNi_{0.5}Mn_{1.5}O_4$ cathode through a greener and more sustainable synthesis route and investigating its compatibility with silicon-based anodes. Pioneering among leaders, our extensive work on dual-carbon batteries eliminates the use of transition metals entirely, delivering the most sustainable and environmentally friendly energy storage solutions. [9]

Through our lab's closed-loop recycling of all LIB parts, from graphite anodes and key metals like Li, Ni, and Co to Co-free cathodes and dual-carbon batteries, we are on our way to deliver high-performance EV power while cutting waste and raw material needs. These efforts turn battery challenges into green solutions that protect the planet and ensure long-term resource security. In short, we are developing sustainable energy storage solutions for a greener future.

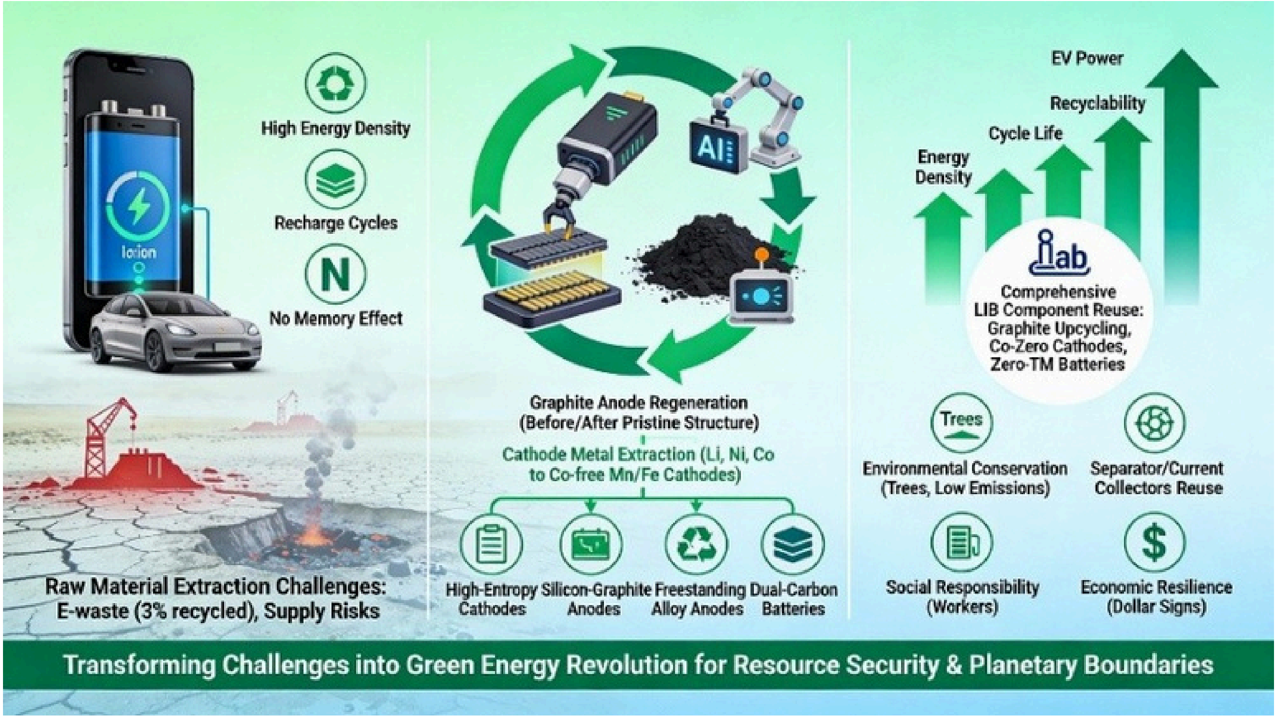

Figure 2: An overview of our ongoing research on sustainable battery chemistry.

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