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further summarized and extensively compared traditional battery manufacturing methods with the use of emerging waterborne binders, highlighting the benefits in terms of cost-effectiveness, environmental sustainability, and enhanced processing conditions. The integration of aqueous binders promises advancements and also shapes a strategic outlook for future research, contributing significantly to the sustainability of lithium-ion batteries manufacturing and recycling.

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Perovskites have drawn huge attention for their promise as solar materials, recently achieving efficiencies of 26.7% and 34.6% for single junction and silicon tandem devices, respectively. However, these devices are notoriously short-lived and the presence of lead fuels raises questions on toxicity. Ouyang and Li *et al.* (<https://doi.org/10.1039/D4SU00431K>) review the current state of the LCA and sustainability analysis of perovskite/Si tandem solar cells. Special attention is drawn to analyse aspects such as the global warming potential, economic costs, and toxicity effects. Valadez-Villalobos and Davies (<https://doi.org/10.1039/D4SU00100A>) focus on remanufacturing processes for perovskite devices, including capture and recycling of lead. Both papers highlight the importance of reducing dependence on toxic solvents in perovskite recovery and remanufacture as vital in improving the environmental impact of these materials. Bai *et al.* (<https://doi.org/10.1039/D3SU00348E>) also focus on lead-containing material recycling. Results show that perovskite composites can be used in piezoelectric ceramic recycling at greatly reduced energy cost during initial manufacturing, offering a potential route for dual recycling of ceramics and halide perovskites.

As a widely recognized methodology to evaluate the environmental impact of materials and products throughout their life cycle (Chen *et al.*³), this themed issue

also deals with the application of LCA to energy materials. Korre *et al.* (<https://doi.org/10.1039/D4SU00223G>) explored the upstream process for LIBs with particular emphasis on producing lithium carbonate from Chilean Atacama brines. The results highlight a large footprint from NaOH and sodium carbonate use, and the authors emphasize the need for increasing brine evaporation rates to reduce water resource stress in the region where raw battery materials are extracted.

Following the ongoing policy efforts to increase the circularity and reduce the environmental impact of the battery industry Rizos and Urban⁴, considered the end-of-life treatment of spent battery materials has received much attention in this themed issue. As one of the largest streams of secondary sources of raw and critical materials in LIBs, Titirici *et al.* (<https://doi.org/10.1039/D4SU00427B>) focused on the recovery of high purity (99.8%) spent graphite from industrially sourced black mass. When compared with graphite production from coal, the recycled graphite offered 75 and 81% savings in energy and water consumption, respectively. As another relevant component in LIBs, the fabrication of cathodes utilizing spent materials is also an area of intense research. In this sense, Younesi *et al.* (<https://doi.org/10.1039/D4SU00131A>) proposed a new method for the upcycling of lithium cobalt oxide (LCO) into $\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$ (NMC111) materials by

firstly leaching LCO with a citric acid followed by acetone antisolvent crystallization precipitation. This method avoids primary and hazardous extraction of cobalt, as the lithium cobalt citrate obtained acts as a precursor for NMC111 sol-gel synthesis.

Although it has not received a great deal of attention to date, the transport distance and cost of shipping electric vehicle batteries between end-use sector facilities and potential second-use locations is a matter that should not be overlooked when establishing a sustainable battery value chain. In this regard, Hatzell *et al.* (<https://doi.org/10.1039/D3SU00319A>) show the potential of machine learning approaches to identify the optimal locations for large LIBs recycling infrastructure using California as a case study.

References

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