Novel Approaches for Critical Raw Materials Recovery: Advances in Urban Mining and Lithium Battery Recycling

Montini D*[1,2,3], Galli E[1,2,3], Vassalini I[1,2,3], Alessandri I[1,2,3]

[1]University of Brescia, Dept. of Information Engineering, Brescia, Italy.
[2]INSTM, Florence, Italy
[3]CNR-INO, Brescia, Italy

*daniele.montini@unibs.it

The accelerating transition toward low-carbon energy systems has created an unprecedented demand for critical raw materials (CRMs), placing severe pressure on global supply chains and raising serious concerns about resource security. Lithium, cobalt, nickel, and manganese are at the core of technologies enabling the green transition, from electric vehicle (EV) batteries to permanent magnets in wind turbines and electric motors. The European Union has formally classified these materials as strategically critical under Regulation (EU) 2024/1252, the Critical Raw Materials Act (CRMA) [1], which entered into force in May 2024. The CRMA establishes binding benchmarks for 2030: at least 10% of the EU's annual consumption of strategic raw materials must be covered by domestic extraction, at least 40% by EU processing capacity, and at least 25% sourced from recycling. In addition, no single third country may supply more than 65% of the EU's annual consumption of any individual strategic material.

Despite this legislative momentum, Europe remains structurally dependent on imports across the entire value chain. Research and innovation are two central pillars on which the Union must concentrate investment and effort; however, gaps in regulatory harmonization and the absence of a fully unified internal market for secondary materials continue to pose significant structural barriers.

In this context, the development of robust and economically viable secondary recovery processes is no longer optional but essential. Urban mining, defined as the systematic recovery of valuable materials from end-of-life products and industrial waste streams, has emerged as a cornerstone of the circular economy strategy, capable of simultaneously reducing environmental burdens and securing domestic access to critical materials. However, the complexity and heterogeneity of modern waste streams pose formidable technical and logistical challenges that conventional hydrometallurgical and pyrometallurgical processes alone cannot fully address.

Spent lithium-ion batteries (LIBs) represent one of the fastest-growing and most chemically complex waste streams in the world. According to EU Urban Mobility Observatory, battery volumes from end-of-life electric vehicles in the EU are expected to exceed 110,000 tons by 2030, with further exponential growth in subsequent decades. Global EV battery demand is projected to reach approximately 3 TWh by 2030, with EVs accounting for over 90% of total battery use in the energy sector [2]. Traditional recycling routes, predominantly high-temperature smelting, are energy-intensive, result in significant lithium losses, and generate toxic emissions, making them poorly suited for a sustainable circular economy.

These limitations have catalyzed a new generation of research efforts aimed at developing innovative, low-impact, and selective recovery processes, combining advanced pre-treatment techniques with green leaching chemistries.

A particularly significant example of this approach is provided by the Tech4Lib project, a research initiative focused on the development of an innovative recycling process for spent lithium-ion batteries. The process integrates two core steps: (i) microwave-assisted pre-treatment of the battery black mass, enabling efficient carbothermal reduction and phase transformation of cathode active materials at significantly reduced processing times and temperatures compared to conventional furnace-based methods; and (ii) selective leaching using waste-derived organic acids as citric, ascorbic, and oxalic acids recovered from agro-industrial by-products as both lixiviants and reducing agents. This dual function eliminates the need for hazardous inorganic acids such as H_2SO_4 or HNO_3, dramatically reducing the environmental footprint of the leaching stage while achieving competitive extraction efficiencies for Li, Co, Ni, and Mn. The use of waste-sourced organic acids introduces an additional dimension of circularity into the process, effectively coupling two separate waste streams into a single integrated recovery chain.

Microwave-assisted carbothermic reduction of NMC battery black mass, followed by organic acid leaching with L-malic acid, has achieved recovery rates above 90% for lithium and above 80% for manganese and cobalt, representing promising proof-of-concept results and establish a credible technological foundation on which industrial integration can be built [3]. However, significant work remains to optimize operating parameters, extend the approach to other cathode chemistries, and demonstrate scalability at industrially relevant throughputs.

More broadly, securing Europe's access to the materials that underpin the energy transition will require the simultaneous advancement of multiple complementary strategies: legislative harmonization to create a genuine secondary materials market, public and private investment in pilot and demonstration infrastructure, and sustained research into processes that can handle the growing complexity and diversity of end-of-life material streams.

REFERENCES

[1] Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020

[2] IEA (2026), Global EV Outlook 2026, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2026, Licence: CC BY 4.0

[3] Cornelio A, Galli E, Scaglia M, Zanoletti A, Zacco A, Bonometti A, Maguglianic G, Mossini, Macerata E, Stefania Federici S, Bontempi E, (2024), "Recovery of NMC-lithium battery black mass by microwave heating processes, *Energy Storage Materials*, 72, 103703