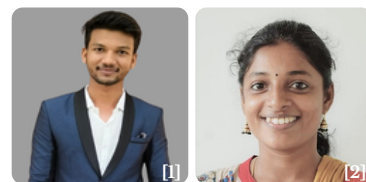


Turning Battery Waste into Resources: Innovative Membrane Technologies for Critical Mineral Recovery

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Introduction

The rapid expansion of the energy storage and electric vehicle markets has led to a significant rise in the generation of spent LIBs. But what happens when these batteries reach the end of their useful life? What appears to be waste may contain significant concentrations of critical minerals, including lithium (Li), cobalt (Co), nickel (Ni), and manganese (Mn).

Recovering these metals, however, is far more complicated than simply recycling a battery. During the recycling process, these valuable metals are transferred into complex aqueous solutions containing multiple ions and high concentrations of inorganic compounds. The challenge is not merely to recover metals but to do so selectively, efficiently, and sustainably.

At IIT Hyderabad, research is being directed towards these challenges through the development of advanced green solvent- and membrane-based technologies that aim to transform battery-recycling wastewater from a treatment problem into a source of valuable resources.

From waste to resource

Conventional hydrometallurgical recycling techniques, such as precipitation, solvent extraction, and ion-exchange, have notable limitations, including low selectivity, secondary waste generation, and high energy and solvent consumption. More importantly, selectively separating these metal ions from a complex mixture remains a major challenge. Their chemical behaviour can overlap, and the presence of competing ions can interfere with separation. Developing a selective recovery process, therefore, requires more than simply finding a reagent that reacts with a metal.

To address this question, our research focuses on two areas of innovation: designer solvents and selective membranes. Rather than treating all metals in the leachate the same way, the objective is to design a system that uses distinct chemical interactions to transport and recover specific metals selectively.

One of the key components of our research is the development of target-specific green solvents, particularly deep eutectic solvents (DESs) designed for the extraction of critical minerals.

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This creates an important research question:

Can the chemistry of the separation process itself be designed to capture individual critical metals selectively?

DESs are formed by combining suitable components of hydrogen-bond donors (HBDs) and hydrogen-bond acceptors (HBAs) to produce a liquid system with properties that differ from those of the individual components (Figure 1). Their composition can be tailored to provide specific chemical functionalities, making them attractive for selective extraction and separation. The importance of this approach lies in its tunability.

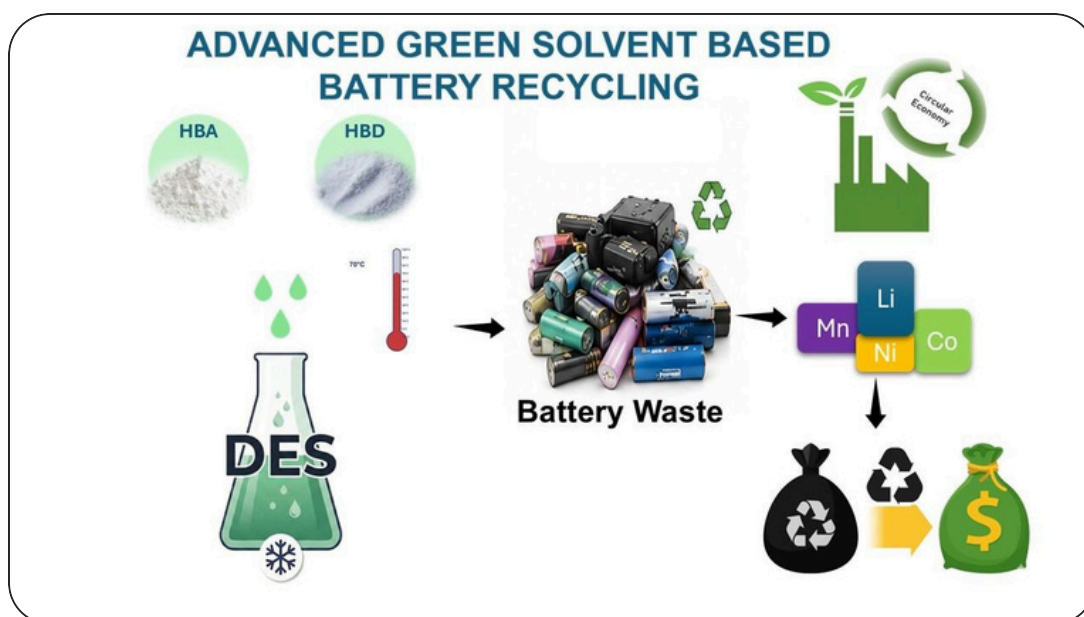


Figure 1. Metal extraction from LIBs

Instead of relying on a conventional solvent whose properties are largely fixed, a DES can be viewed as a designer separation medium whose composition and functionality can be modified according to the target metal and application. We have been working on the synthesis of DESs systems for the selective extraction of critical minerals, including lithium, cobalt, nickel, and manganese, from aqueous solutions.

Next phase of work:

The next step of our research is to move beyond conventional liquid-liquid extraction. In a conventional solvent extraction process, the aqueous metal solution must be contacted with an immiscible organic phase. After extraction, another operation is generally required to recover the metal from the organic phase. A new approach, which includes liquid membranes (LMs), is a platform in which a polymer matrix contains a carrier or extractant that transports the target metal across the membrane as shown in Figure 2. Unlike a conventional membrane that primarily separates species based on size or physical properties,

a LMs can perform a much more sophisticated task. It can use chemical interactions to selectively transport a target metal, thereby avoiding the need to mix large volumes of an organic solvent with the aqueous phase. We are exploring various selective green solvents that can be tuned to enable the development of membranes with distinct metal-selective transport characteristics. The transition from green solvents to LMs represents an important evolution in the research. At the green solvent level, the focus is on understanding and designing chemical interactions, whereas at the LMs level, those interactions are incorporated into a functional material that can physically separate species. By designing solvents that recognize valuable metals and membranes that selectively transport them, this research is taking steps towards making recovery more efficient—and turning battery-recycling wastewater from a disposal challenge into a potential source of critical resources.

“The future of battery recycling may depend not only on how efficiently we recover materials but also on how intelligently we separate and reuse them.”

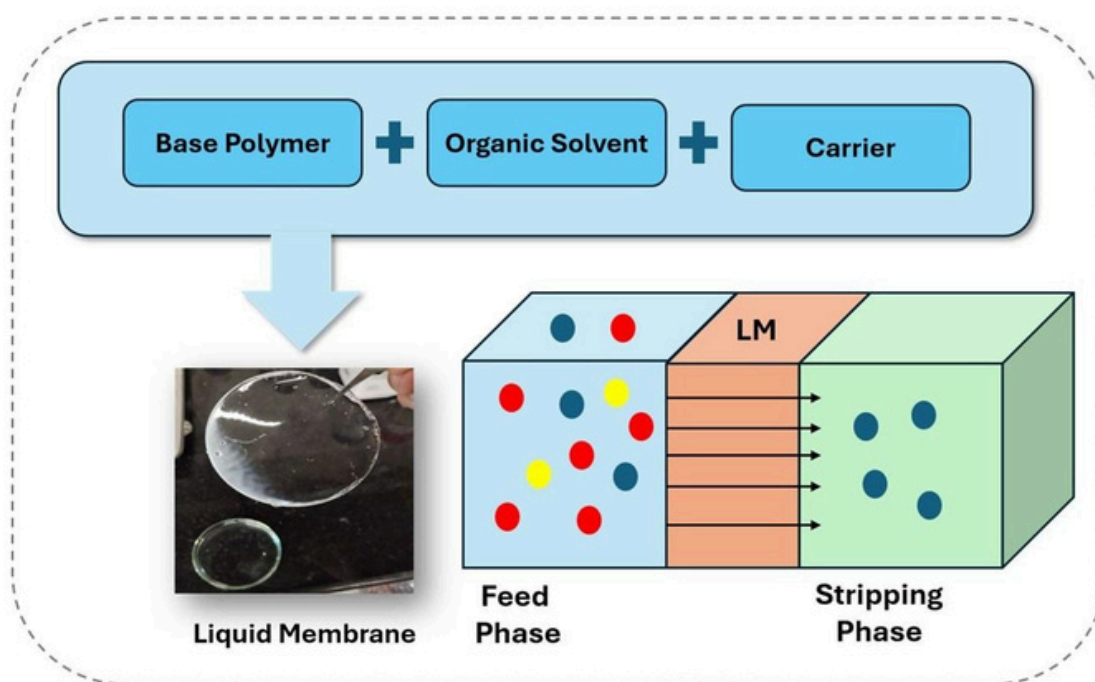


Figure 2. Liquid Membranes (LMs)

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