



**Japan Society of Material Cycles  
and Waste Management**

# **Transforming Waste into Power: Next-Generation High-Energy Batteries via Recycling and Upcycling**

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**Michael J. Lee, Ph.D.**  
(Seunghoon Lee)

Assistant Professor  
Department of Mechanical Engineering  
Kyung Hee University



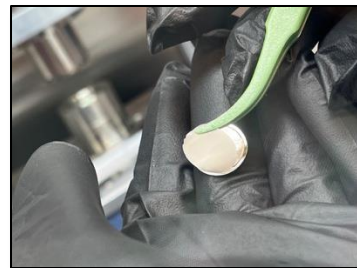
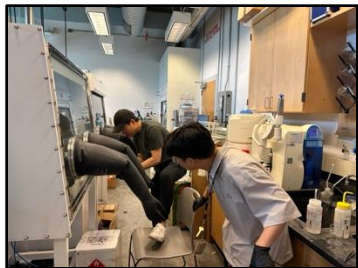
# INTRODUCTION

## EDUCATION AND EXPERIENCE

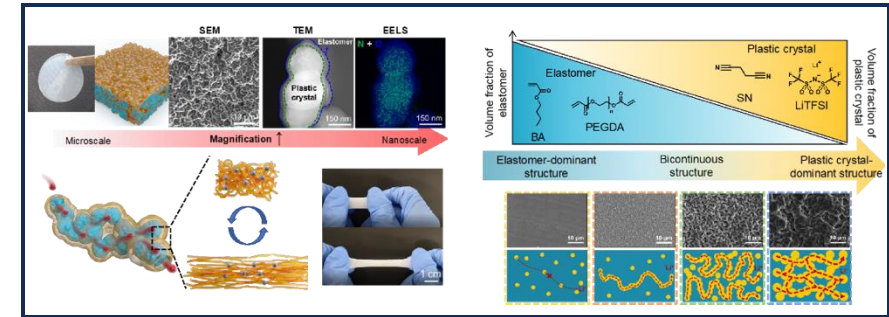
- **2023 – Present: Assistant Professor, Mechanical engineering, Kyung Hee University**
- **2022 – 2023: Postdoc, Mechanical engineering, Georgia Institute of Technology**
- **2017 – 2022: Ph.D., Mechanical engineering, Georgia Institute of Technology**
  - Dissertation: Designing 3D Structured Electrodes and Electrolytes for High-Performance Rechargeable Batteries
- **2011 – 2017: B.S., Mechanical engineering, Georgia Institute of Technology**
  - 2013 – 2015: Serving in the Republic of Korea Army

## RESEARCH AREA

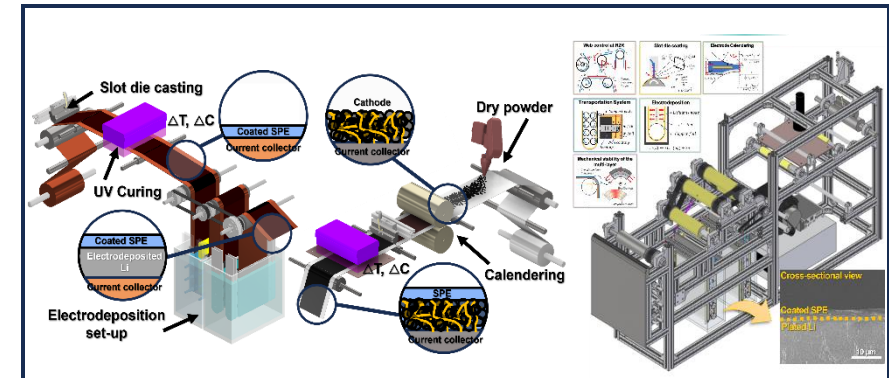
- **Solid-state electrolytes:** polymer electrolytes, oxide/sulfide/halide electrolytes, and composite (polymer-inorganic) electrolytes
- **Low-temperature batteries:** Low-temperature test protocol, electrolyte formulation, and design of carbon (graphene)-based anodes
- **Post-metal batteries:** sodium, potassium, zinc, magnesium, and aluminum batteries
- **Lithium-sulfur batteries:** electrolyte formulation, separator design, and sulfur cathode design



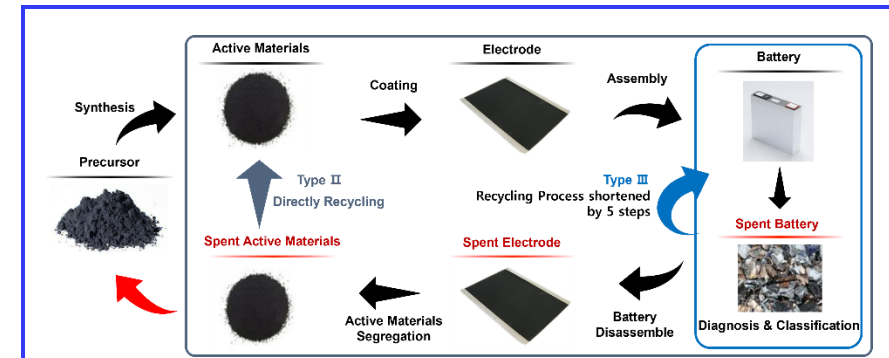
## Solid-state batteries



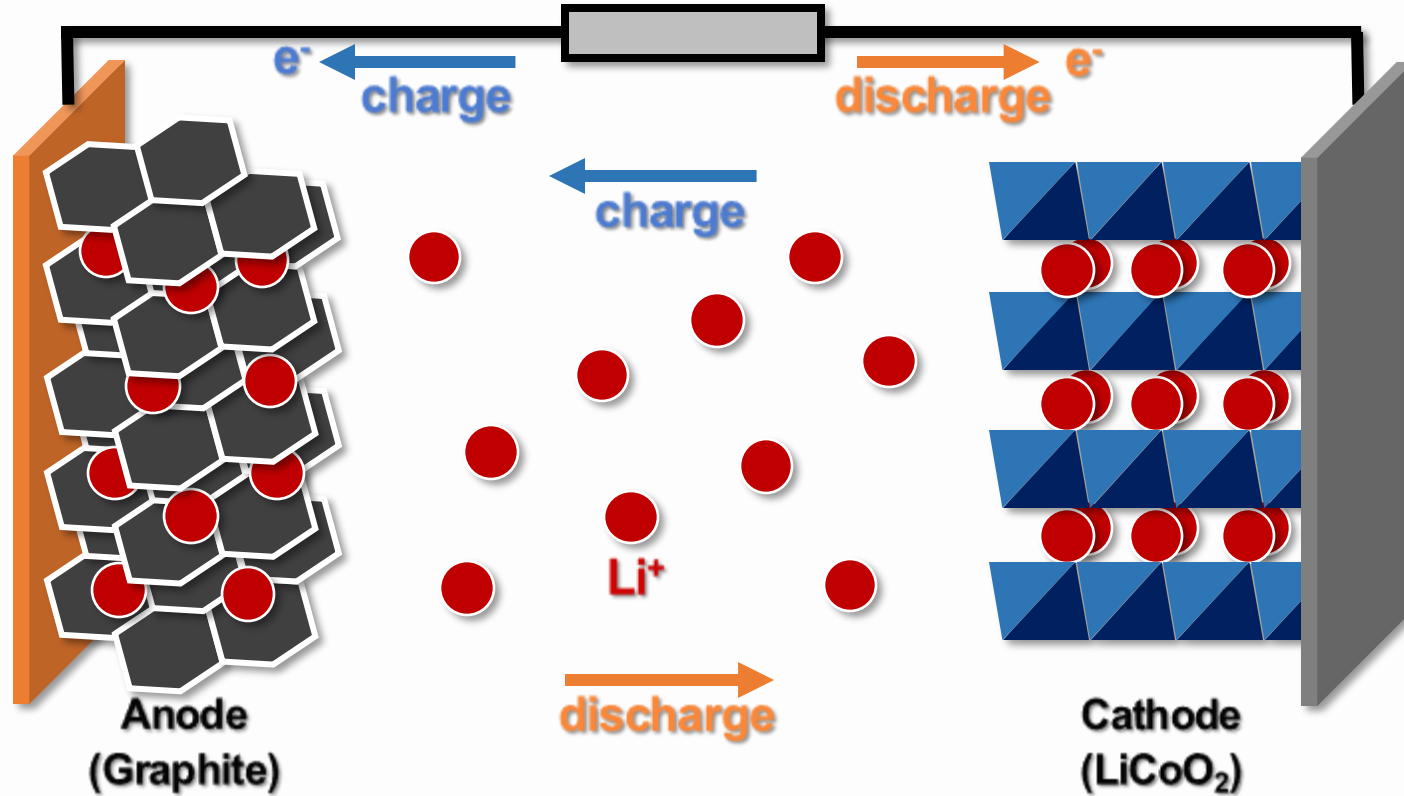
## Manufacturing design



## Recycling & Upcycling



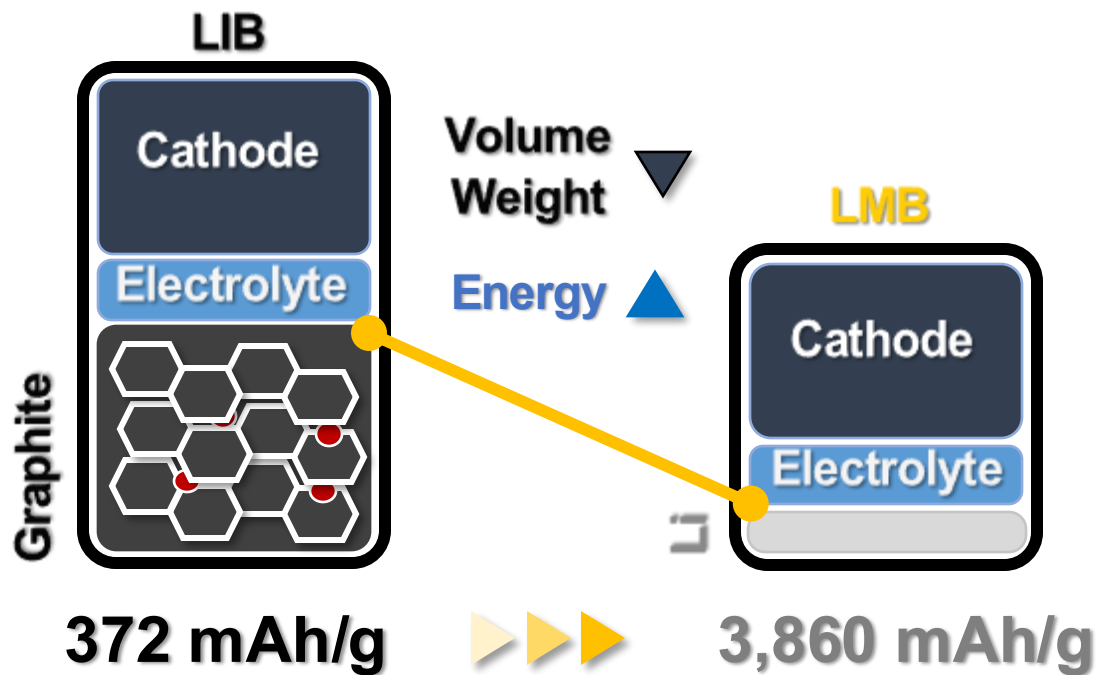
# LITHIUM-ION BATTERIES (LIBs)



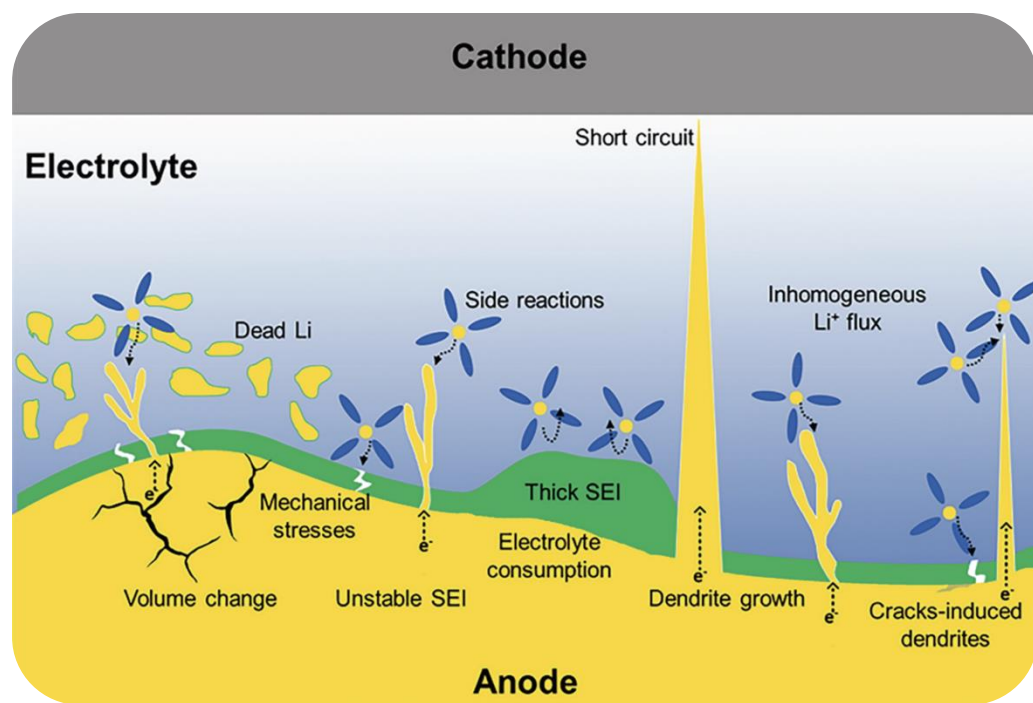
Charge stored in bulk of electrode via **intercalation**  
(Faradaic reactions)

# LITHIUM-METAL BATTERIES (LMBs)

## Li metal anode



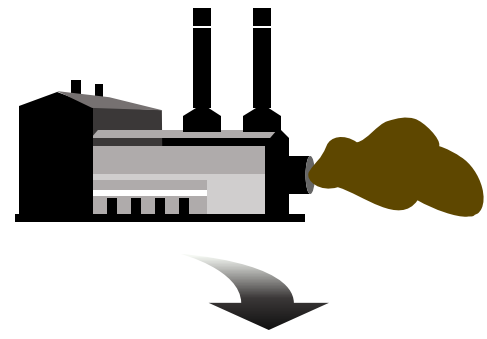
## Challenges of Li metal anode



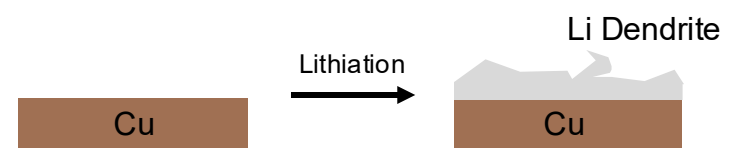
# BATTERIES & SUSTAINABILITY

## Part 1. Host material

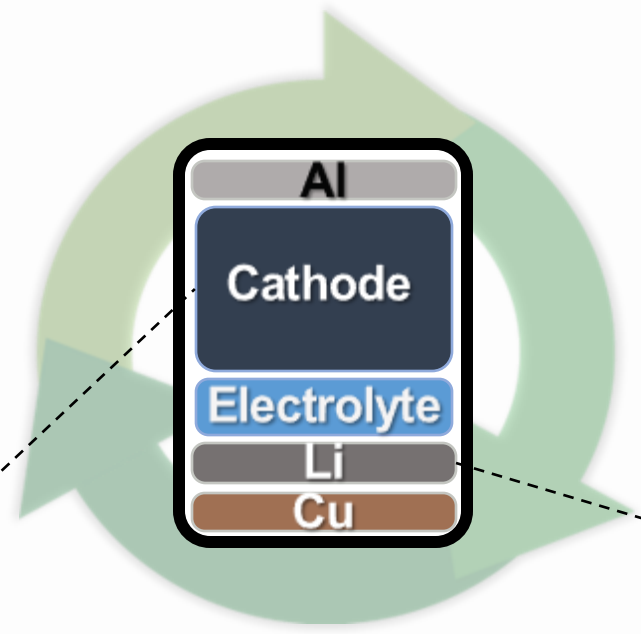
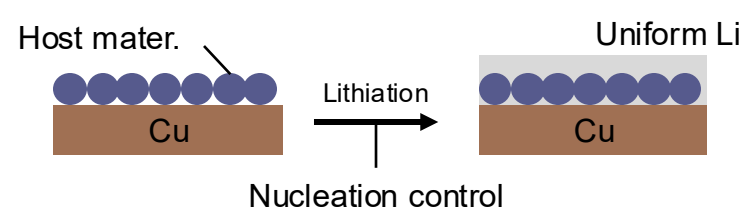
Wastewater



Without host material



With host material

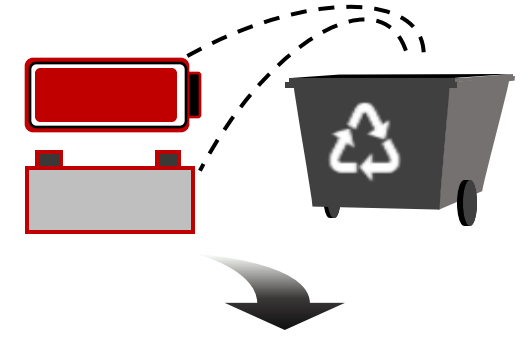


## Sustainability Issues

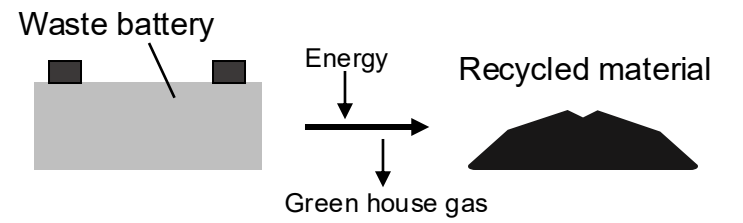
- Sustainable battery design
- Managing waste battery

## Part 2. Battery regeneration

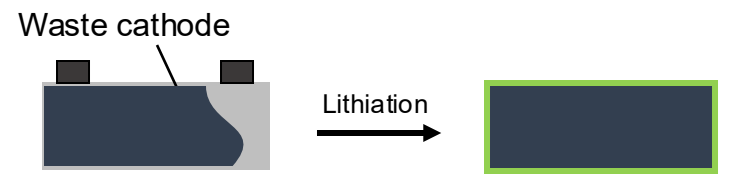
Waste batteries



Recycling materials



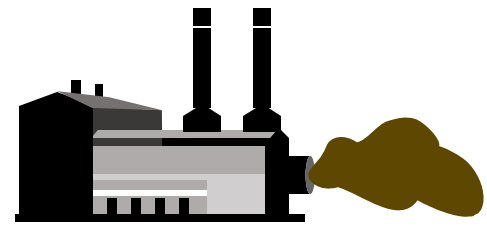
Regeneration



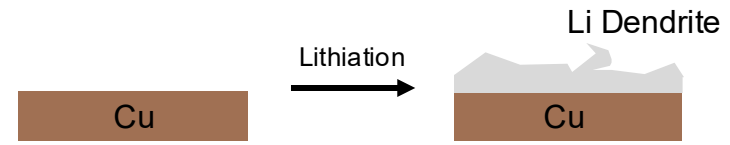
# BATTERIES & SUSTAINABILITY

## Part 1. Host material

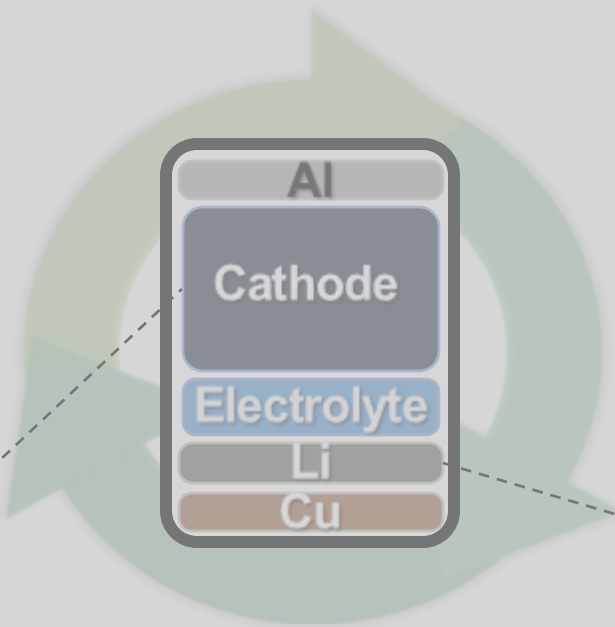
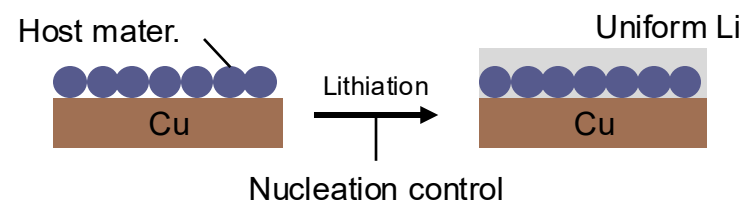
Wastewater



Without host material



With host material

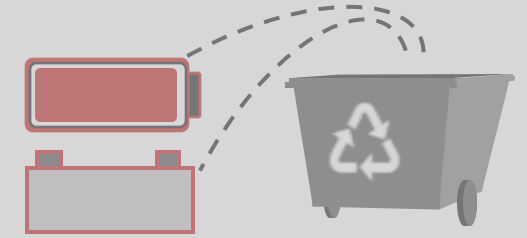


## Sustainability Issues

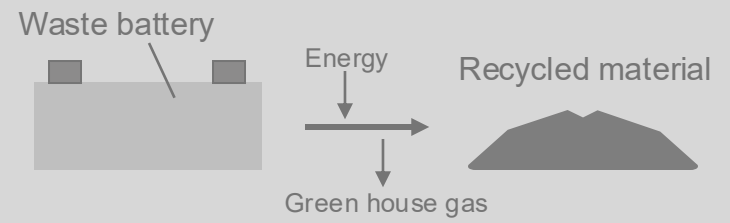
- Sustainable battery design
- Managing waste battery

## Part 2. Battery regeneration

Waste batteries



Recycling materials



Regeneration



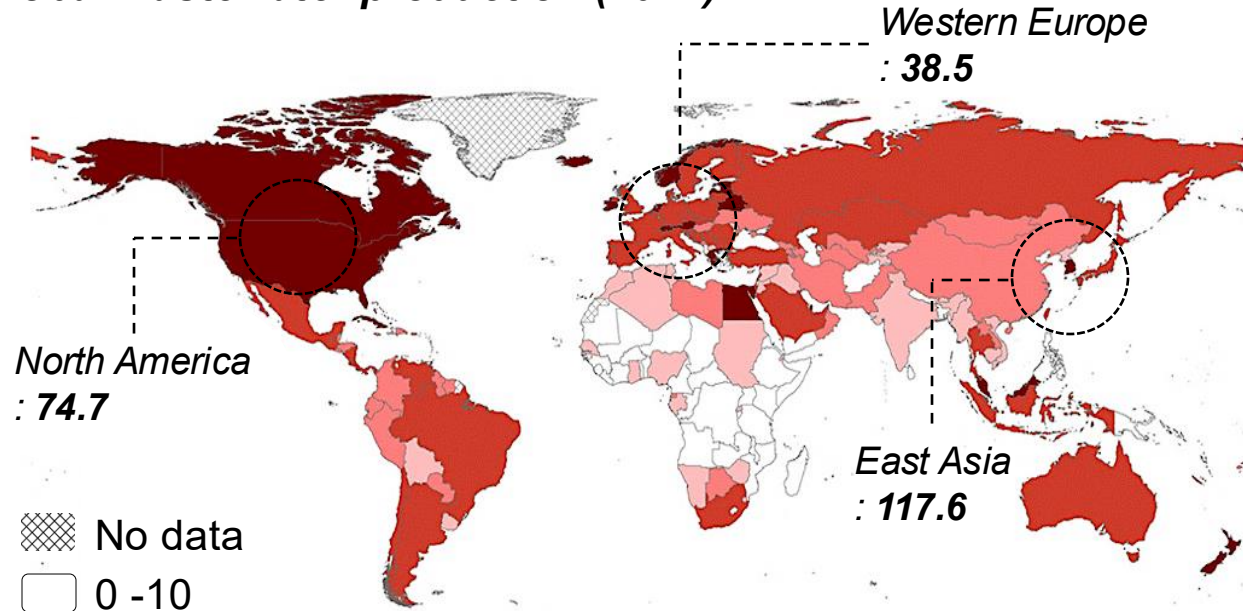
## GLOBAL CHALLENGE: SLUDGE DISPOSAL

- **Historical reliance on ocean dumping**
- **Persistent marine pollution impacts**
- **Ongoing concerns over seafood contamination**

# HANDLING WASTEWATER

## Backgrounds

Global wastewater production (2021)



- Oceanic dumping **prohibition**
- International treaty **enforcement**
- Disposal methods **discussion**

[Hatched Box] No data  
 [White Box] 0 - 10  
 [Light Red Box] 10 - 25  
 [Red Box] 25 - 50  
 [Dark Red Box] 50 - 100  
 [Darkest Red Box] > 100  
 ( Unit: 10<sup>9</sup> m<sup>3</sup> yr<sup>-1</sup> )

## London Protocol (2012)

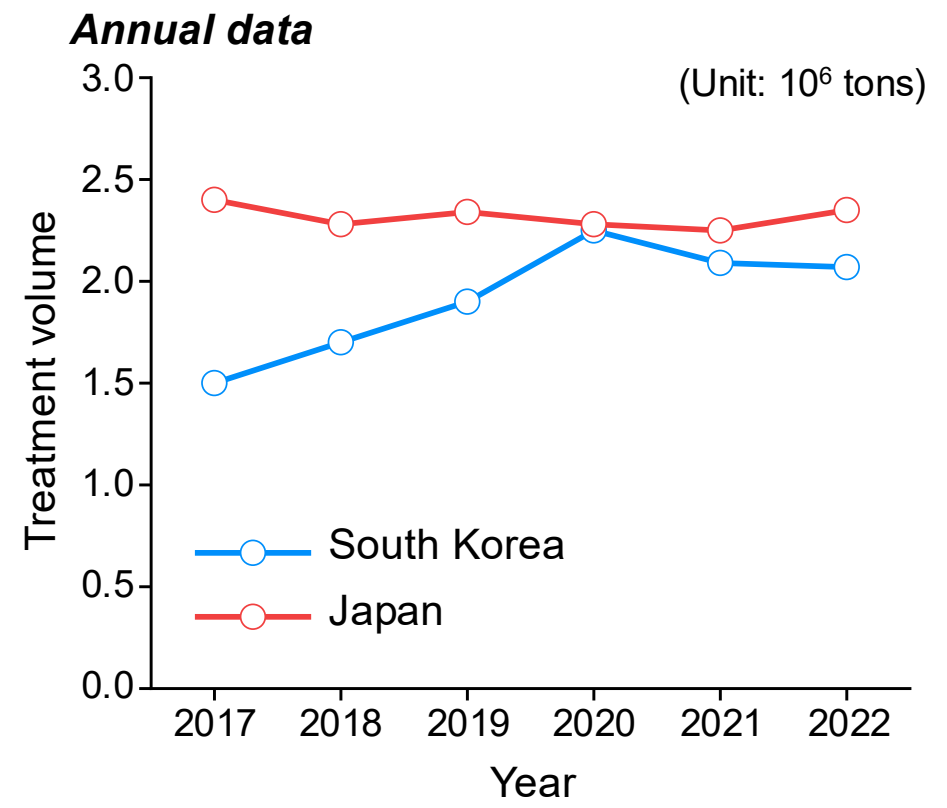


**Land-based treatment required**  
 → **Sludge drying**

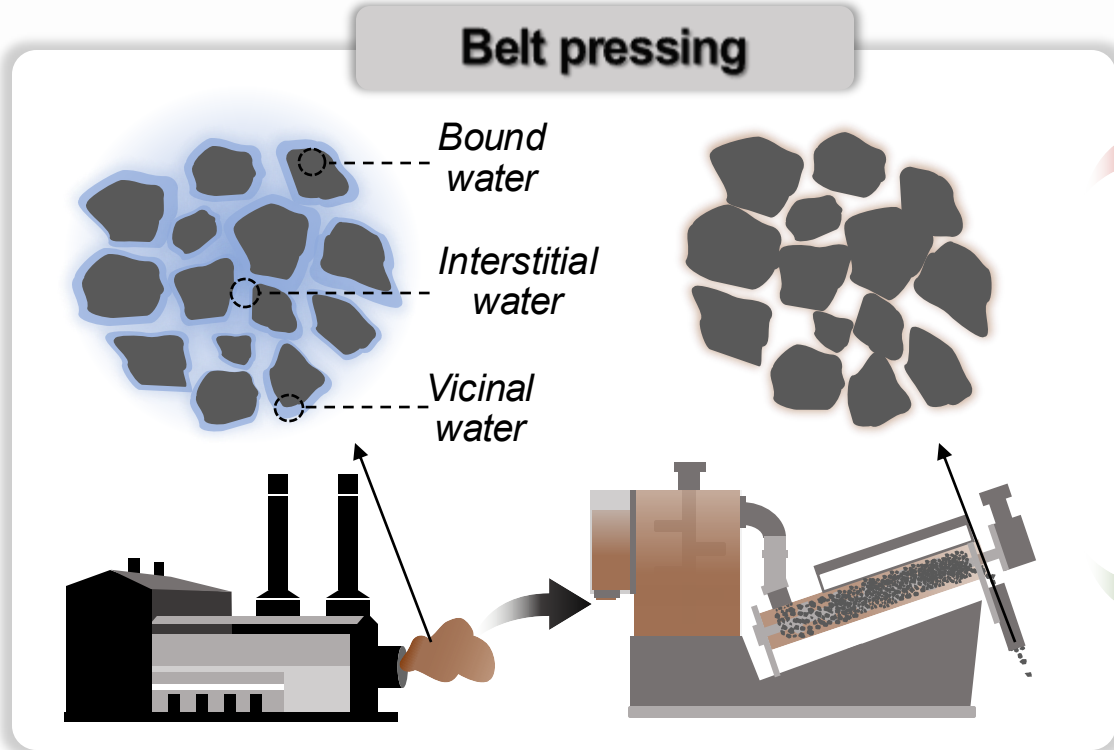
# INCREASING SLUDGE TREATMENT



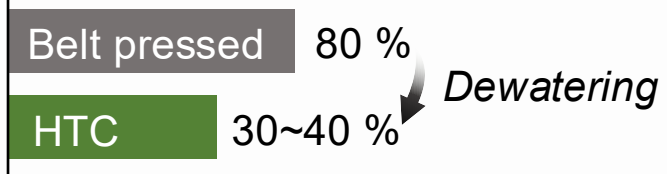
Sewage sludge treatment volume



# RECYCLING SLUDGE



### Water content



### Conventional sludge disposal

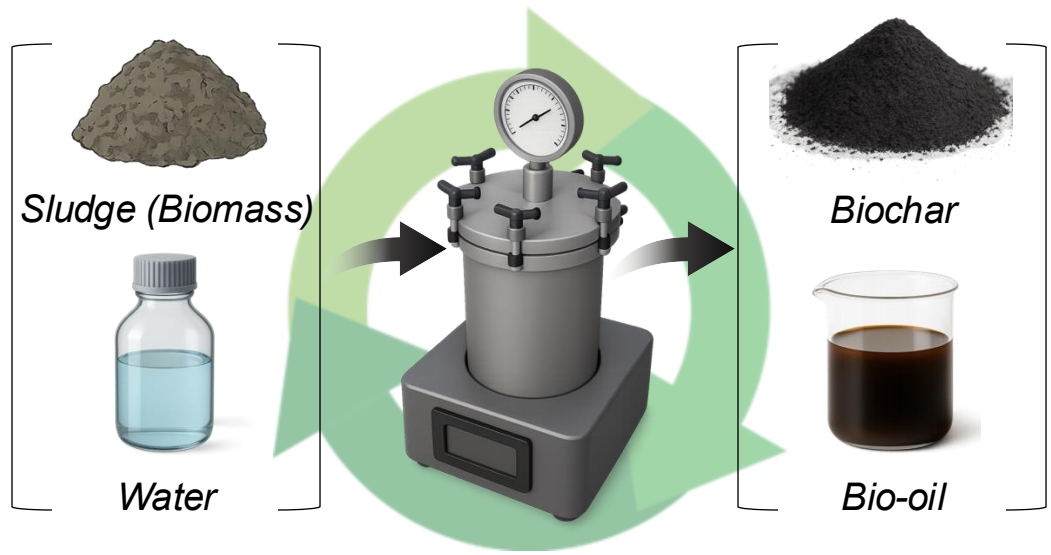
#### Incineration



#### Landfill

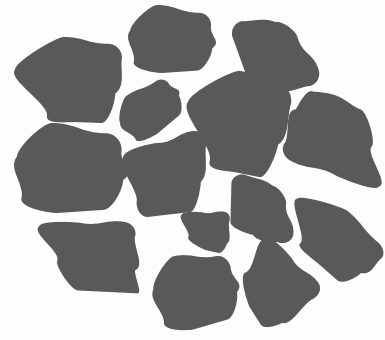


### Hydrothermal carbonization (HTC)

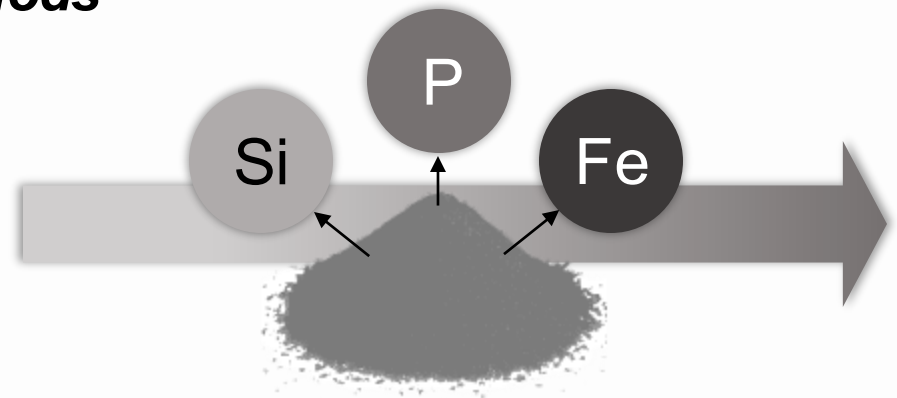


# SLUDGES IN BATTERY FIELD

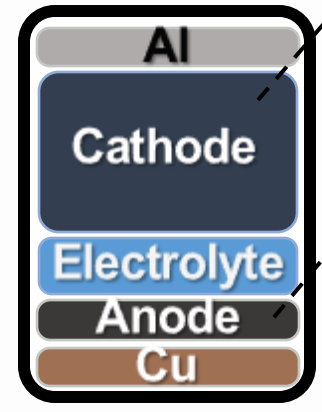
## Conventional methods



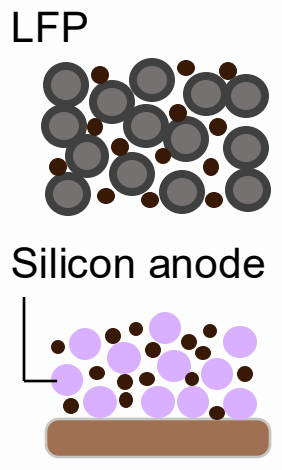
Sludge



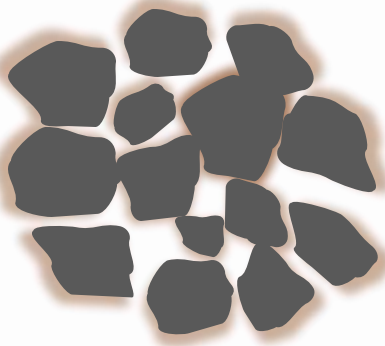
Extraction



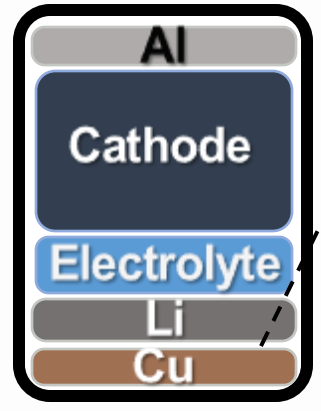
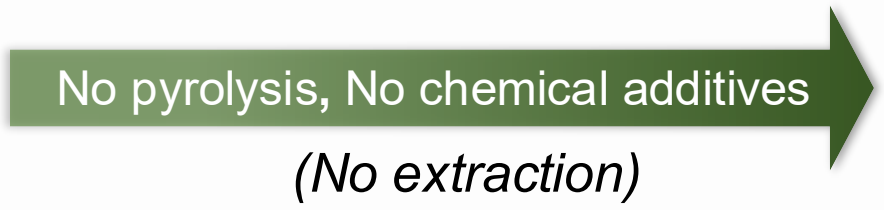
Li-ion batteries



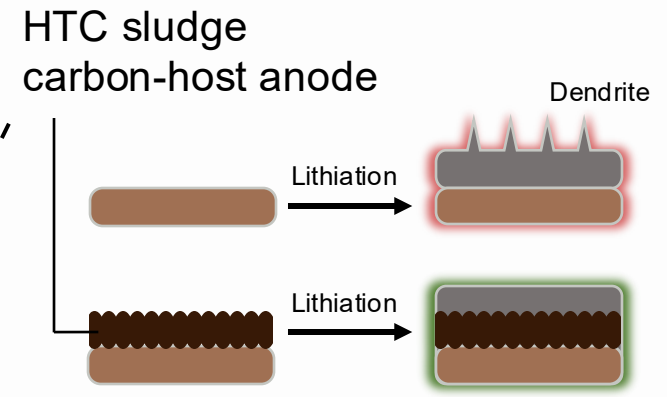
## Our work



Biochar  
(after HTC)

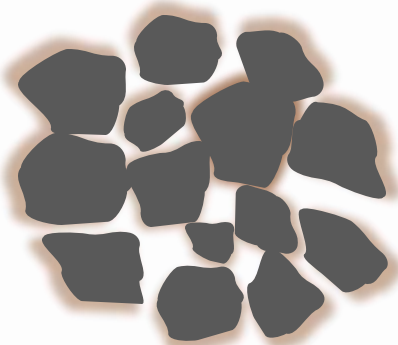


Advanced Li-metal batteries



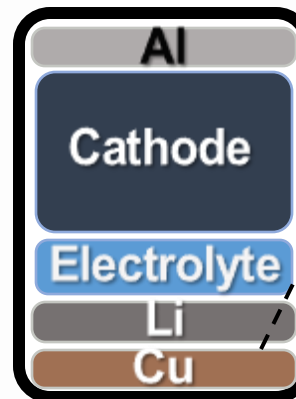
# SLUDGES IN BATTERY FIELD

## Our work



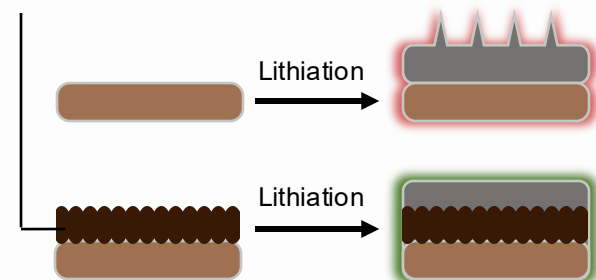
Biochar  
(after HTC)

No pyrolysis, No chemical additives  
(No extraction)



Advanced Li-metal batteries

HTC sludge  
carbon-host anode



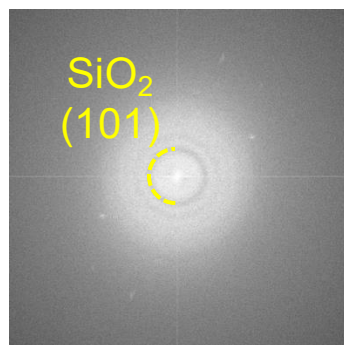
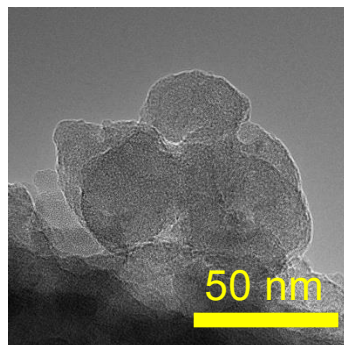
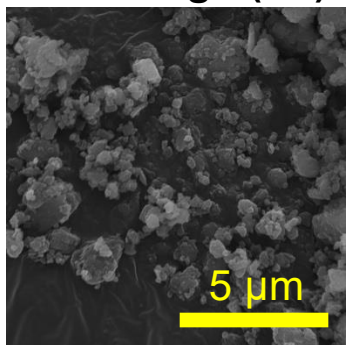
Collaboration with **Prof. Jai-young Lee**  
The University of Seoul (UOS), South Korea

Expertise in waste management

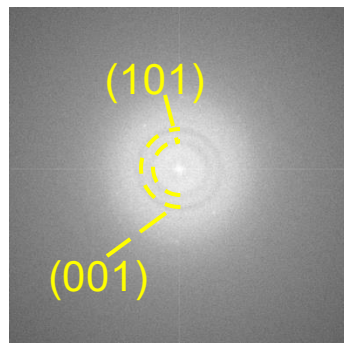
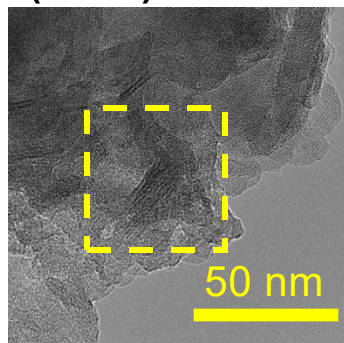
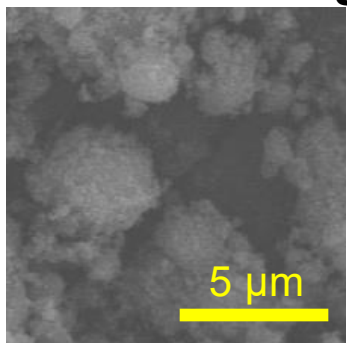
# MORPHOLOGY OF SLUDGES

## Purified waterworks sludge

### Raw sludge (P0)



### HTC 300°C sludge (P300)



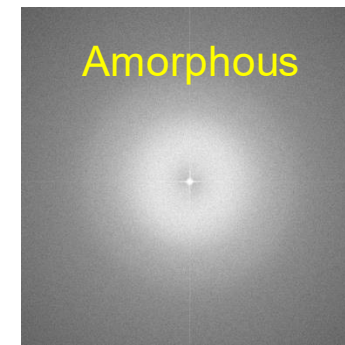
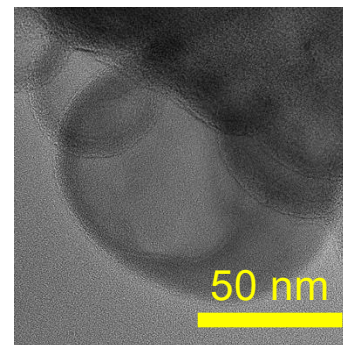
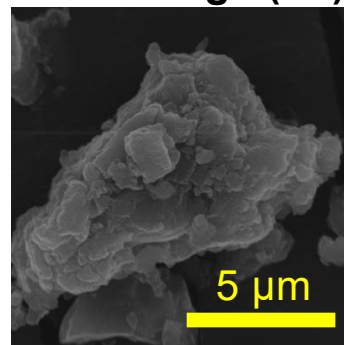
SEM

HR-TEM

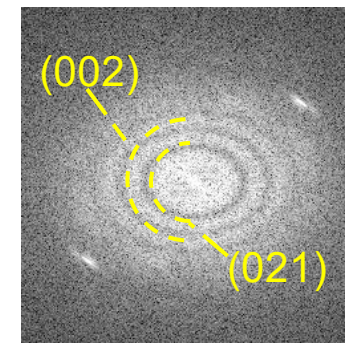
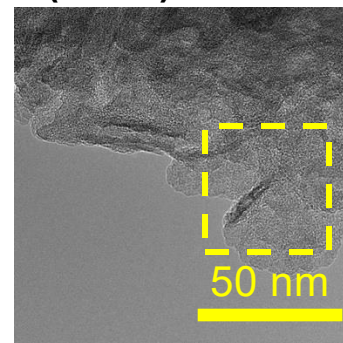
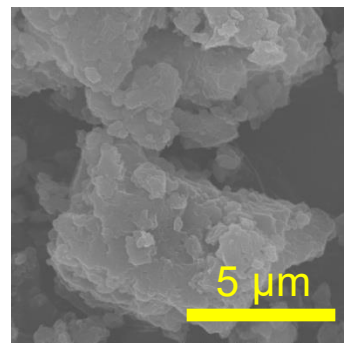
SAED

## Electronic wastewater sludge

### Raw sludge (E0)



### HTC 300°C sludge (E300)

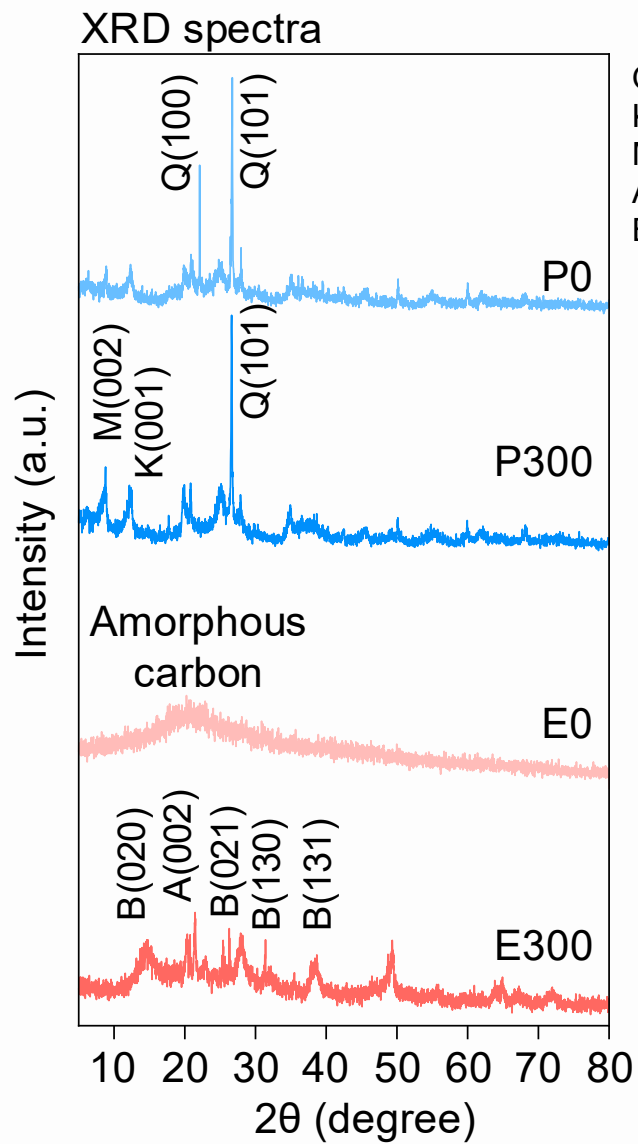


SEM

HR-TEM

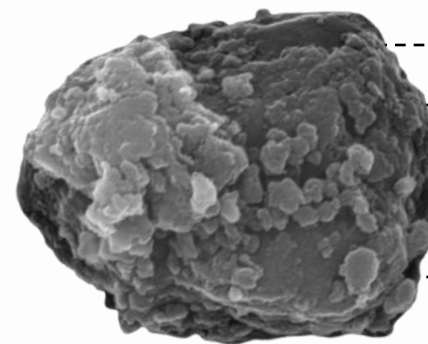
SAED

# CHARACTERIZATION

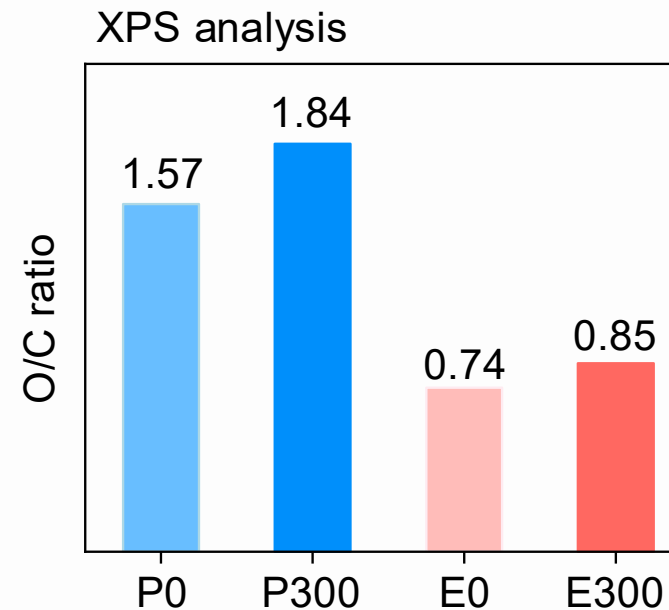
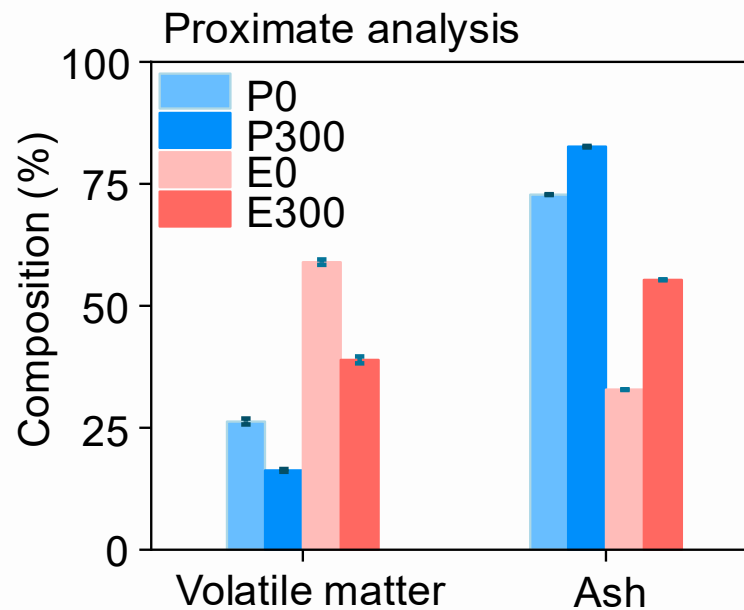


Q : Quartz  
 K : Kaolinite  
 M : Muscovite  
 A : Anhydrite  
 B : Boehmite

Sludge

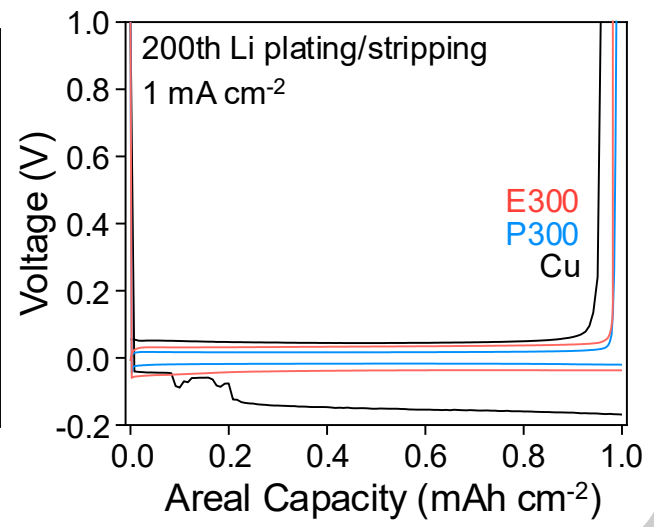
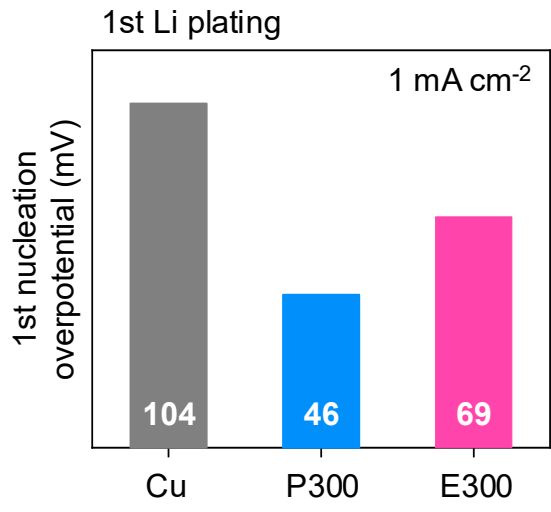
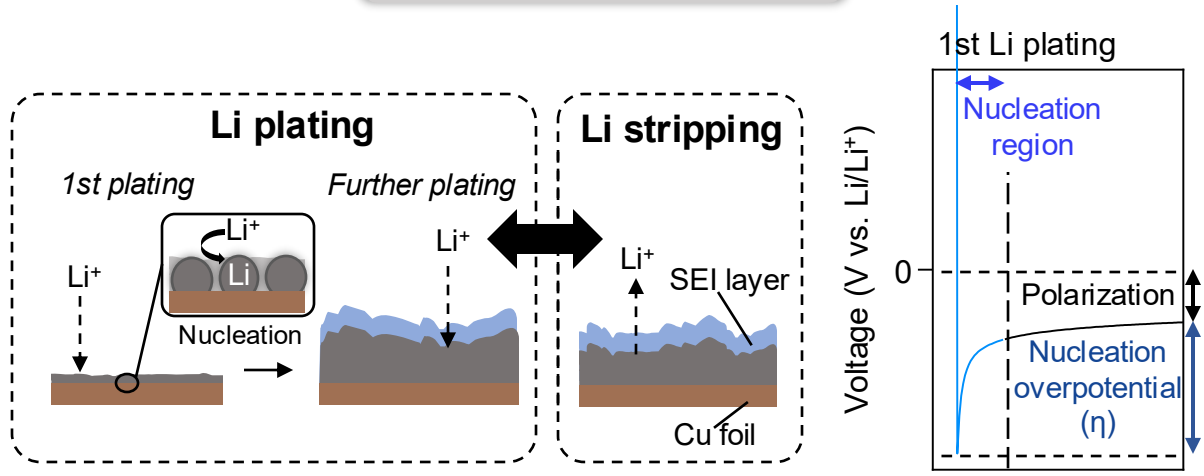


Ash  
 Mineral  
 Moisture  
 Heavy metals  
 Volatile matter

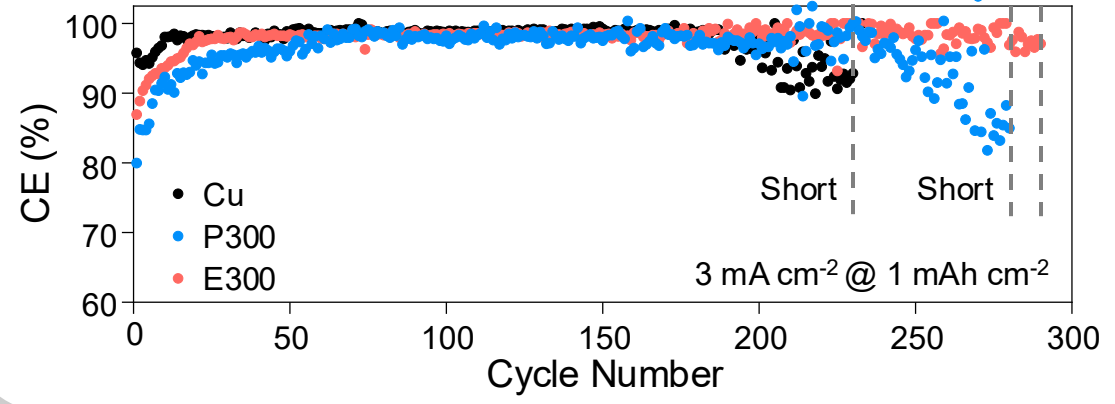
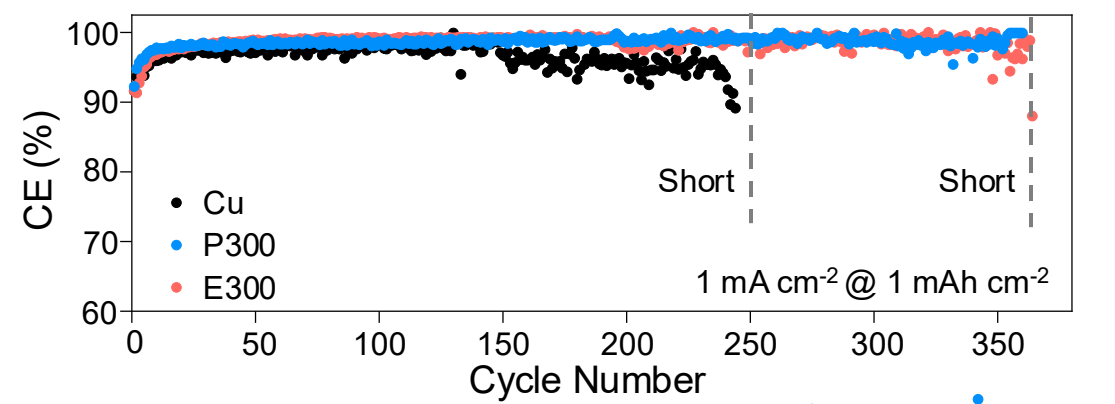
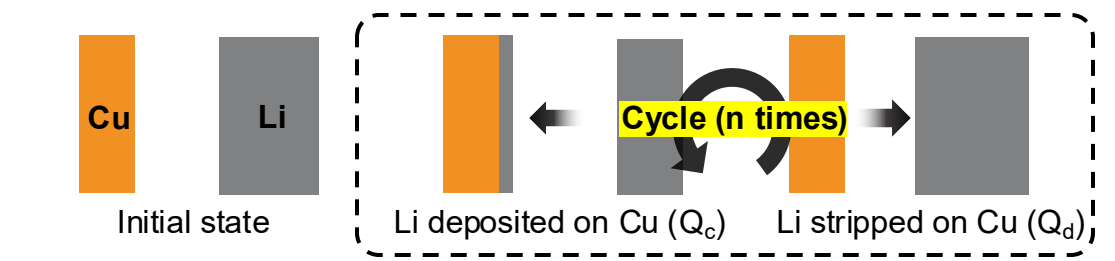


# SLUDGE-DERIVED HOST

## Li nucleation

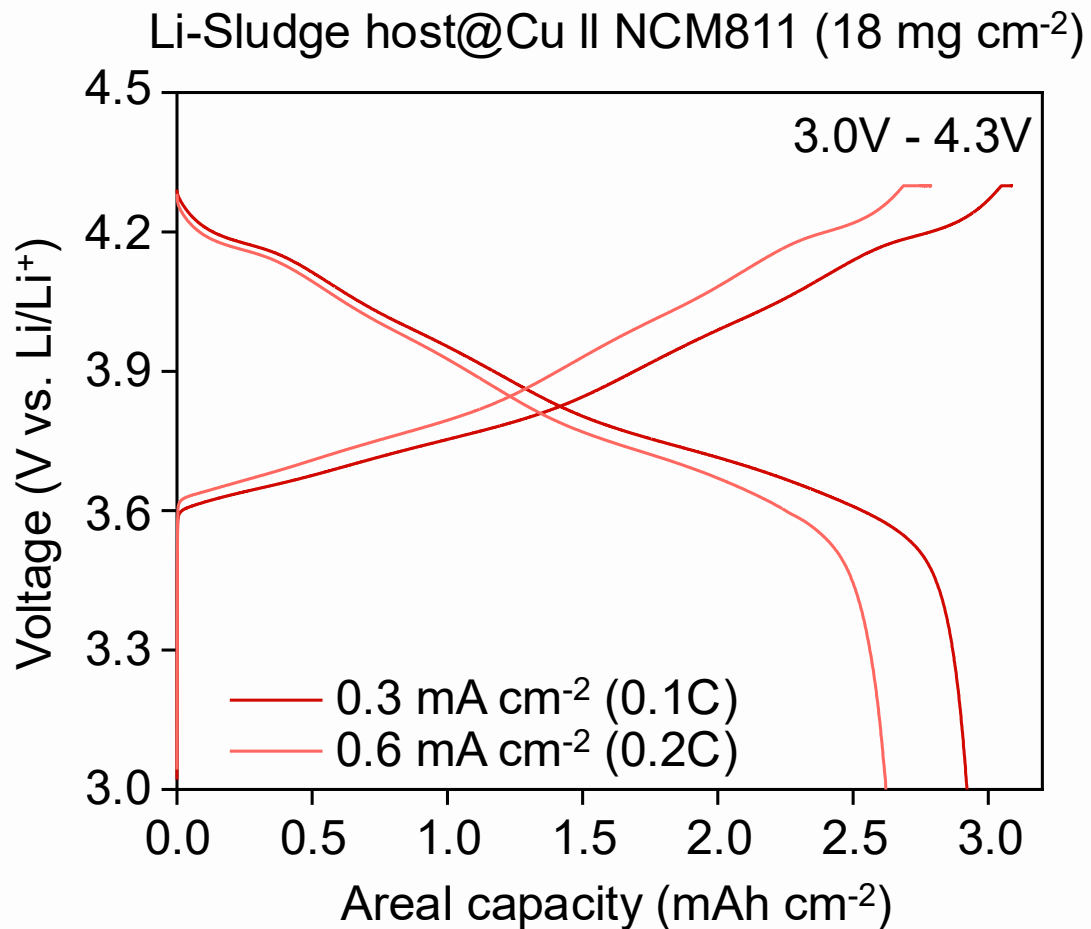


## Li || Cu



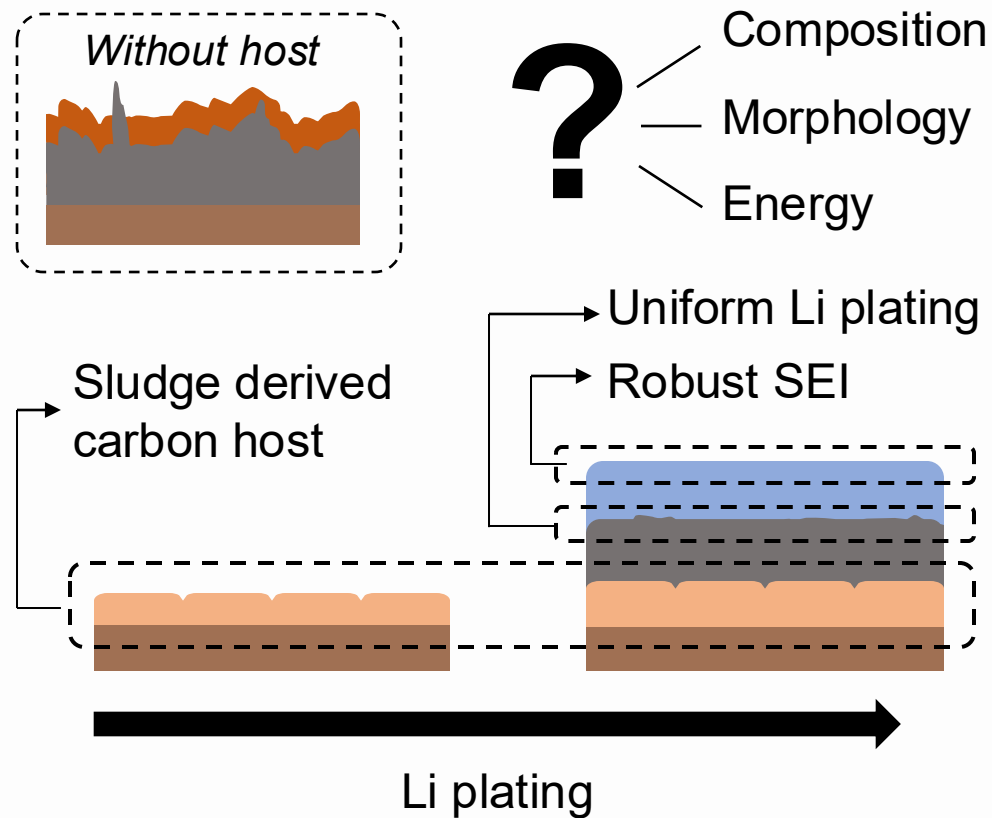
Coulombic efficiency (CE, %) = Charge capacity (Q<sub>c</sub>) / Discharge capacity (Q<sub>d</sub>)

# FULL-CELL



\*Cathode capacity : 3 mAh cm<sup>-2</sup>

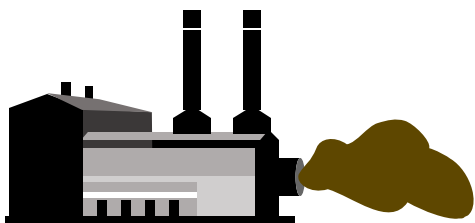
## Applying carbon host



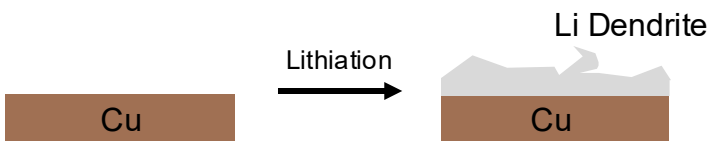
# BATTERIES & SUSTAINABILITY

## Part 1. Host material

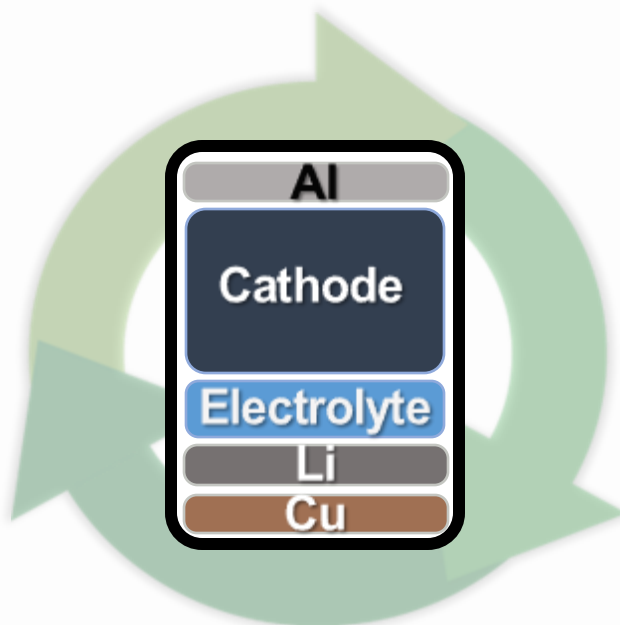
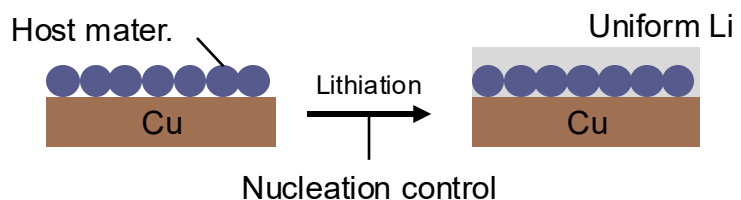
Wastewater



Without host material



With host material

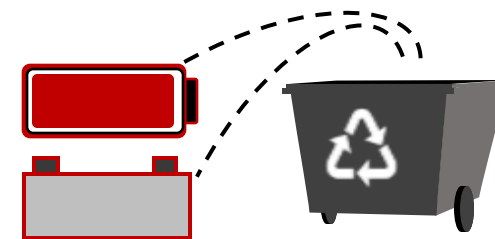


## Sustainability Issues

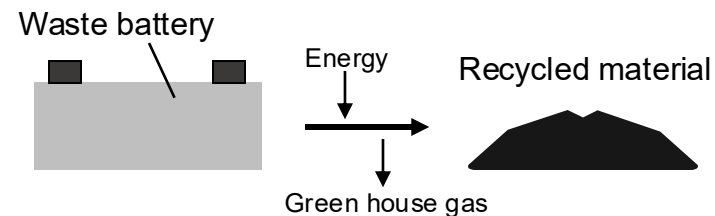
- Sustainable battery design
- Managing waste battery

## Part 2. Battery regeneration

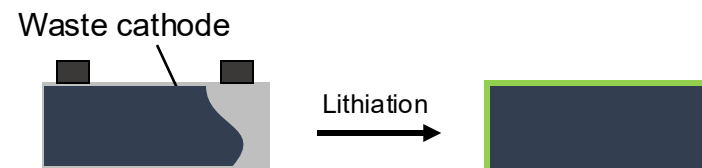
Waste batteries



Recycling materials



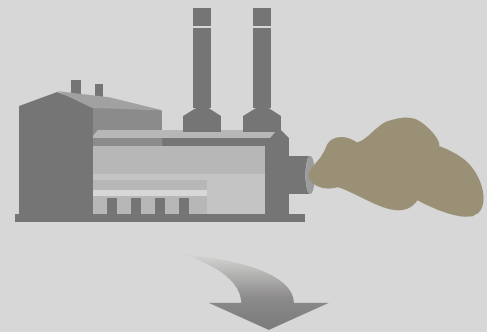
Regeneration



# BATTERIES & SUSTAINABILITY

## Part 1. Host material

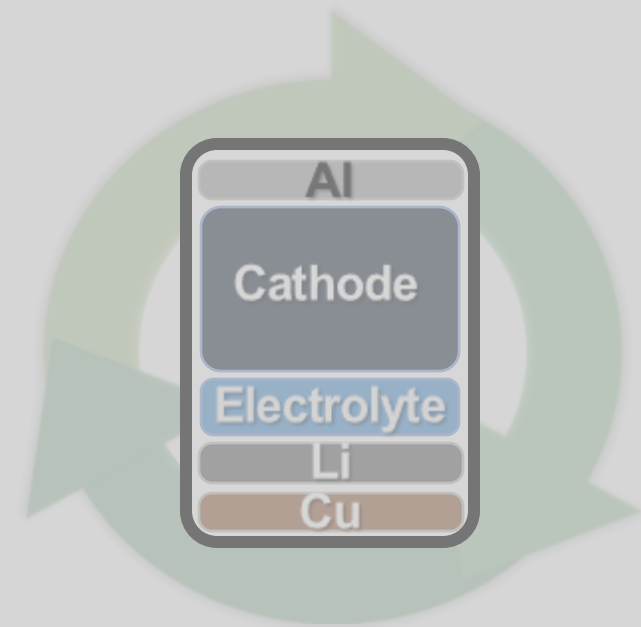
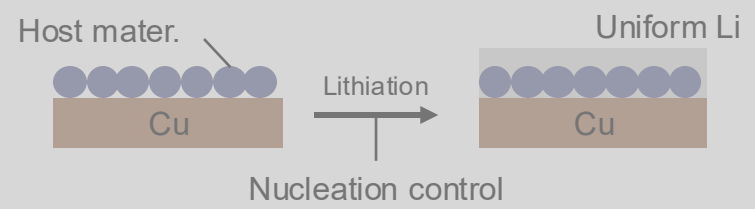
Wastewater



Without host material



With host material

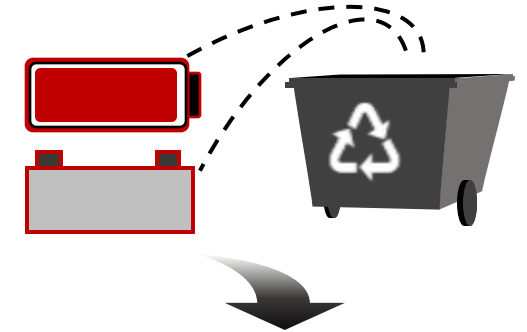


## Sustainability Issues

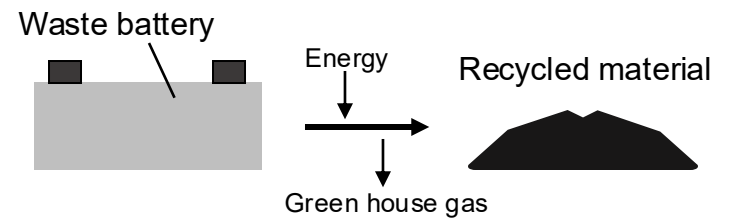
- Sustainable battery design
- Managing waste battery

## Part 2. Battery regeneration

Waste batteries



Recycling materials



Regeneration



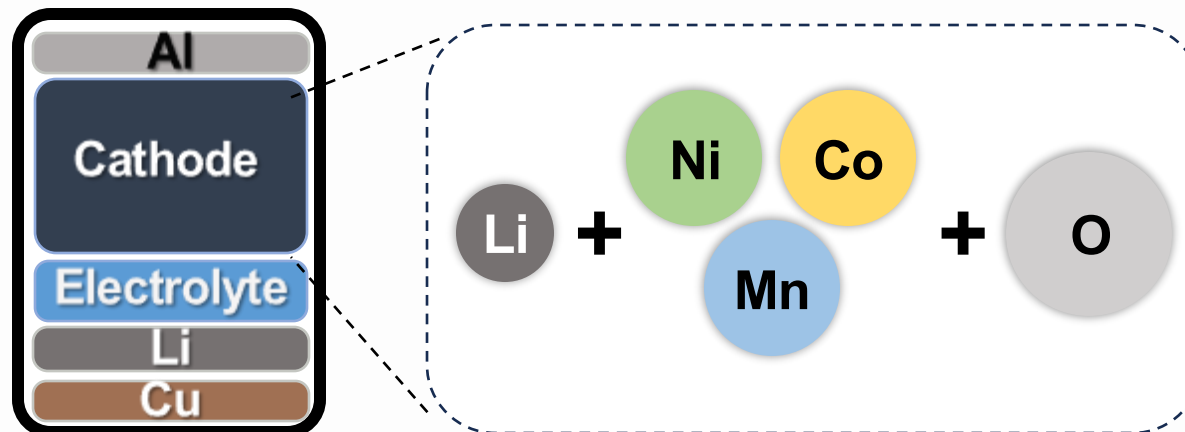


## **GLOBAL CHALLENGE: WASTE BATTERIES**

- **Critical resource depletion (Li, Ni, Co scarcity)**
- **Environmental risks from hazardous waste**
- **Inefficient or costly recycling technologies**

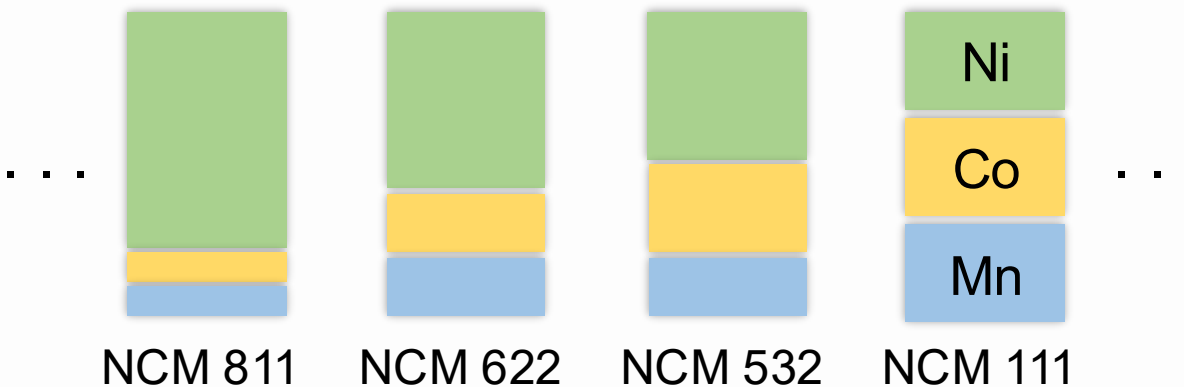
# TERNARY CATHODES (NCM)

Li-ion batteries



High nickel

- Energy density ↑
- Structural stability ↓
- Material cost ↑



Mid/low nickel

- Material cost ↓
- Structural stability ↑
- Energy density ↓

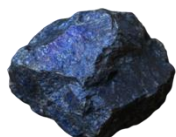
**Limited availability** of Lithium, Nickel, Cobalt

# ECONOMICAL NEEDS

## Rare metal price



**Li**



**Co**



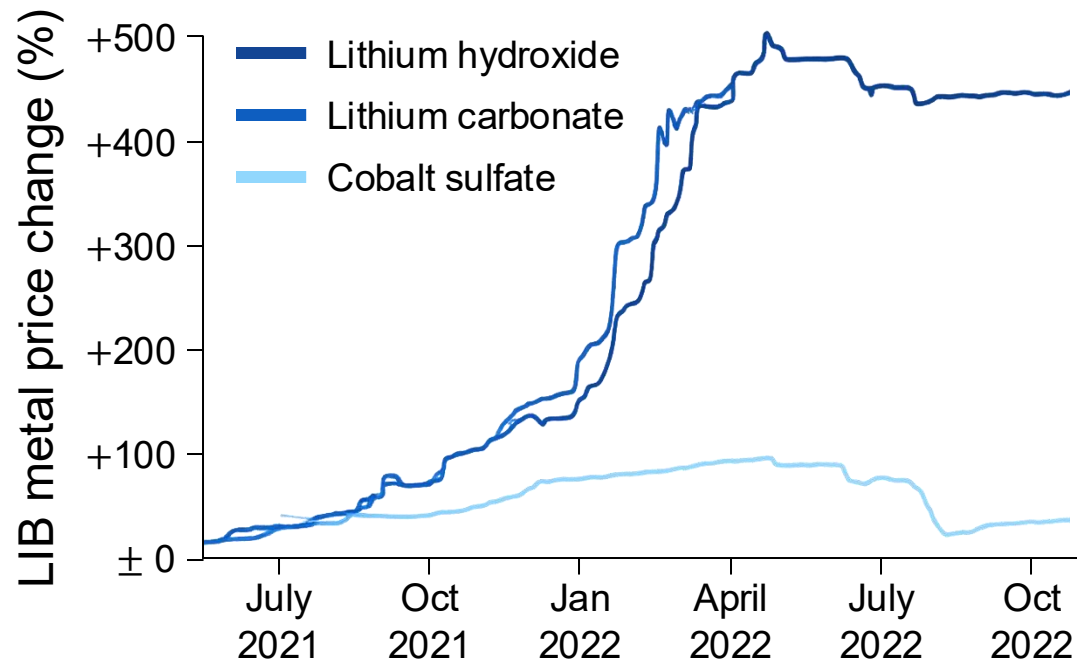
**Ni**

<b>Price (2025)</b>	9,615 \$/t	34,042 \$/t	16,089 \$/t
<b>Resource</b>	0.0006 %	0.0025 %	1.83 %
<b>Depletion</b>	<u>41 yrs</u>	<u>11 yrs</u>	<u>*10 ~ 44 yrs</u>

\*High purity : 10 yrs, Low degree : 44 yrs  
(Iron ore : 98.19 \$/t)

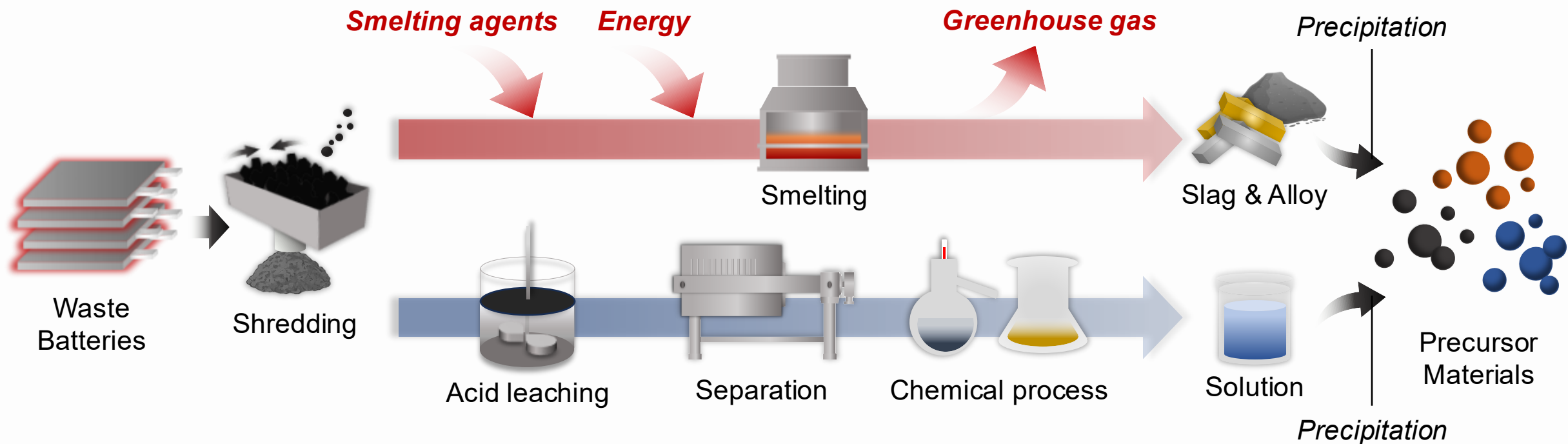
- **Critical supply constraints**
- **Risk of resource depletion**

## Price fluctuation



**Increasing demand for Li, Co, Ni**

# CONVENTIONAL RECYCLING METHODS



## Pyrometallurgy

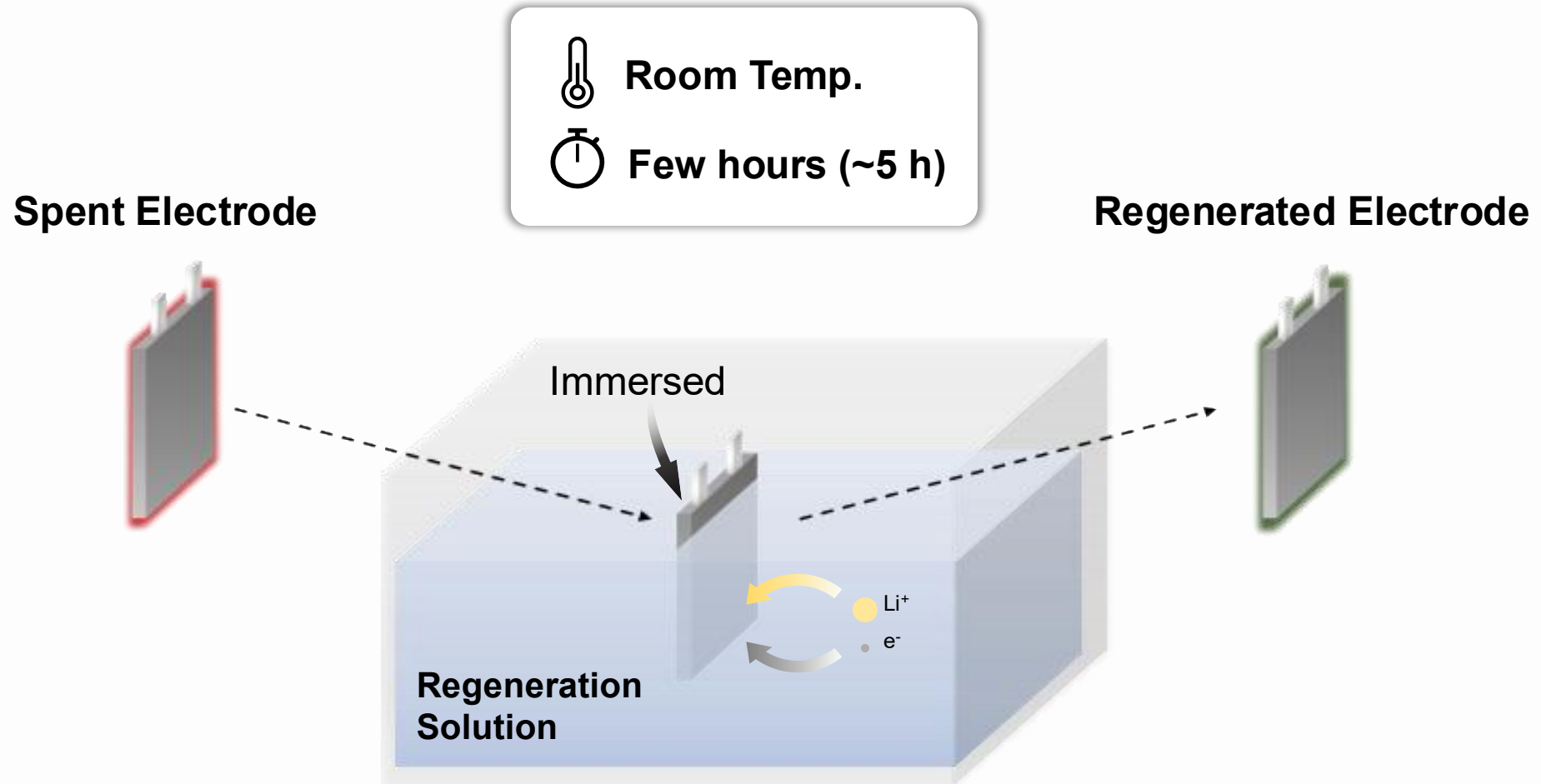
- High energy consumption
- Environmental pollution
- Material loss

## Hydrometallurgy

- Chemical waste
- Slow processing rate

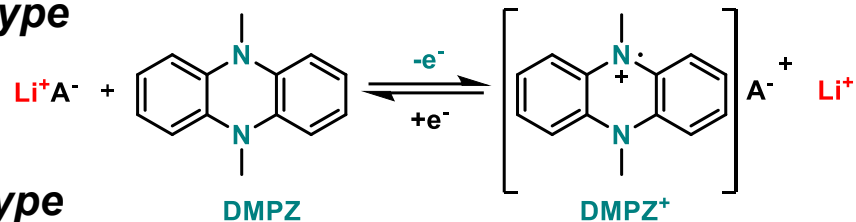
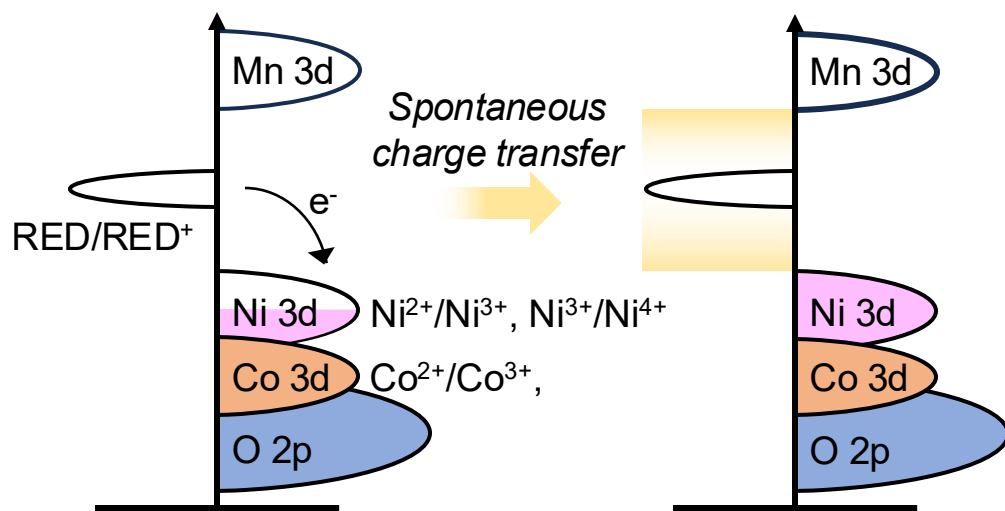
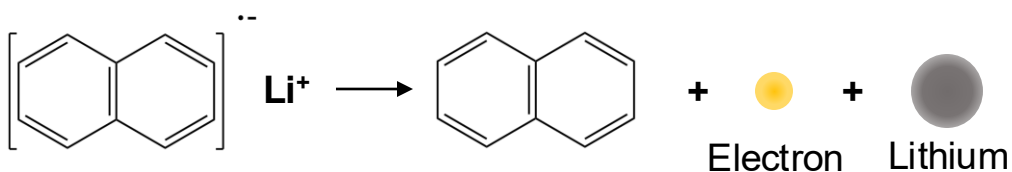
How to design **eco-friendly, closed-loop** recycling?

# REGENERATION

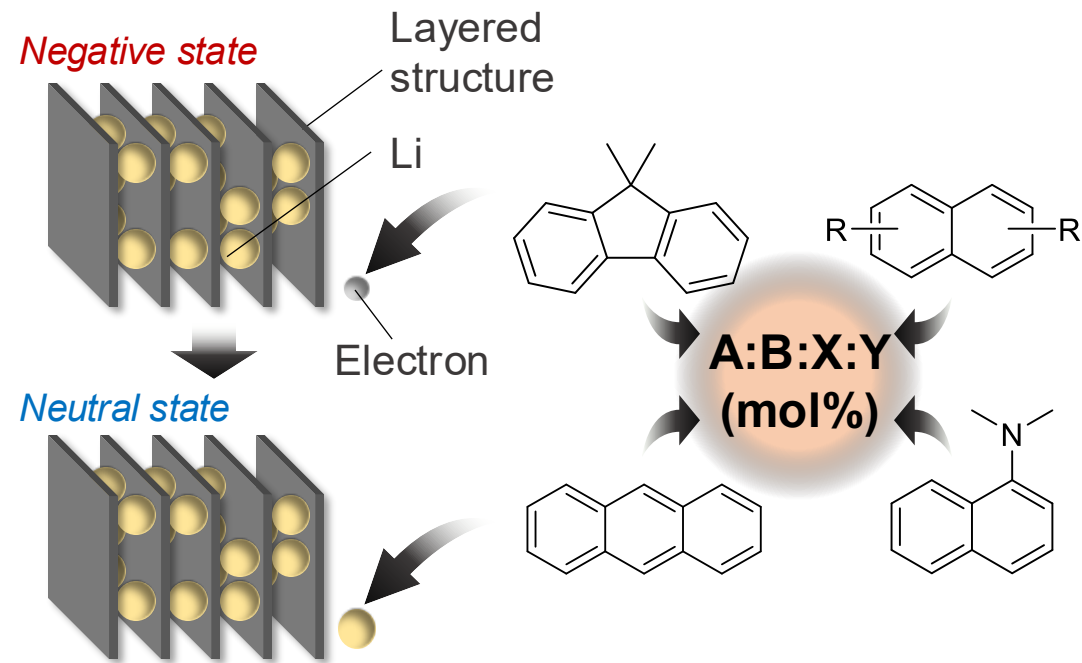


## MECHANISM

## Redox active compounds

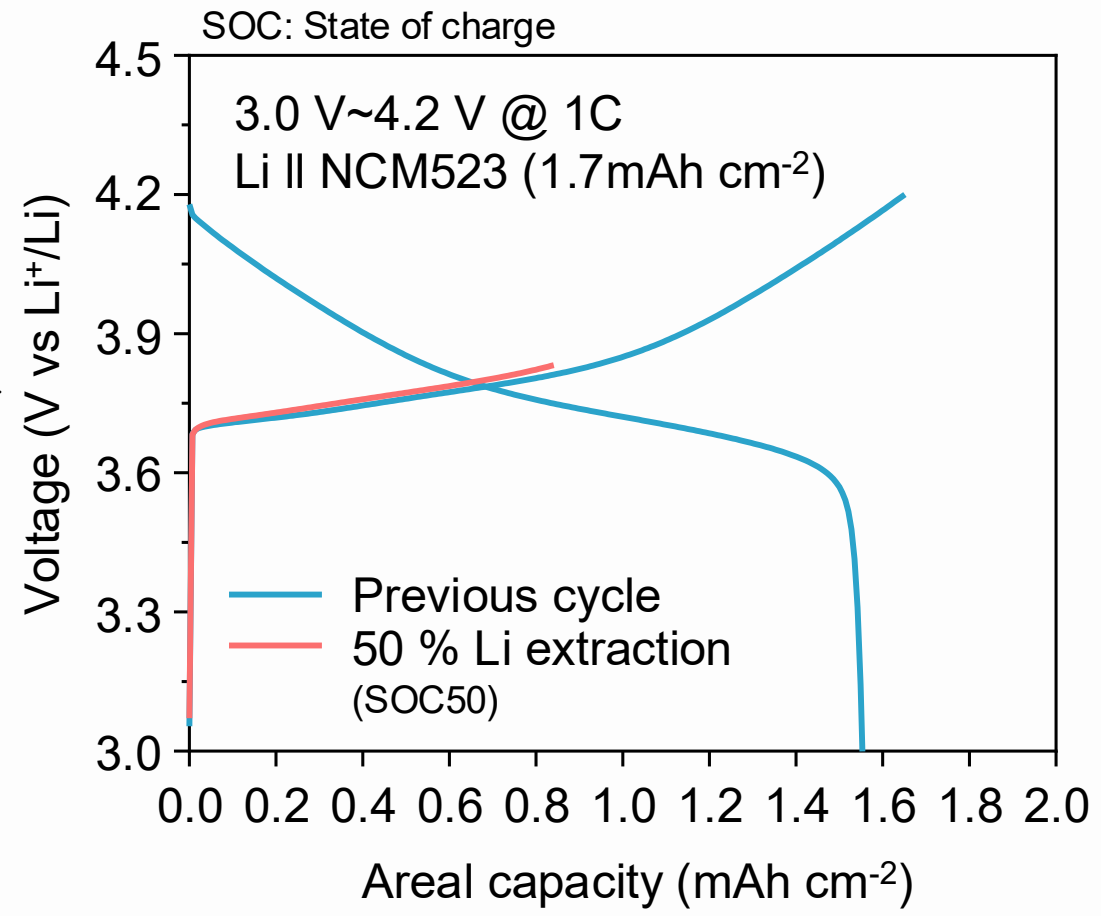
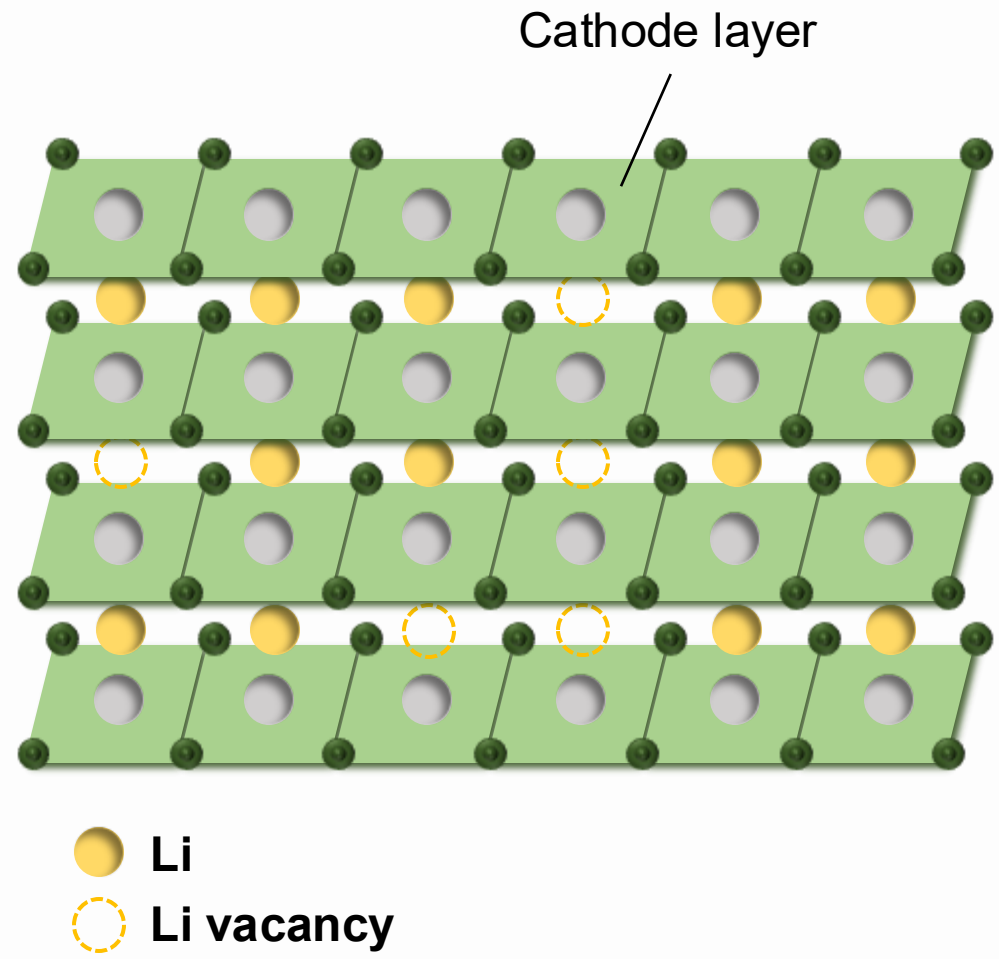
*p-type**n-type*Density of states,  $N(E)$ 

## Optimizing redox mixtures



- Spontaneous lithiation
- Designing optimal formulation

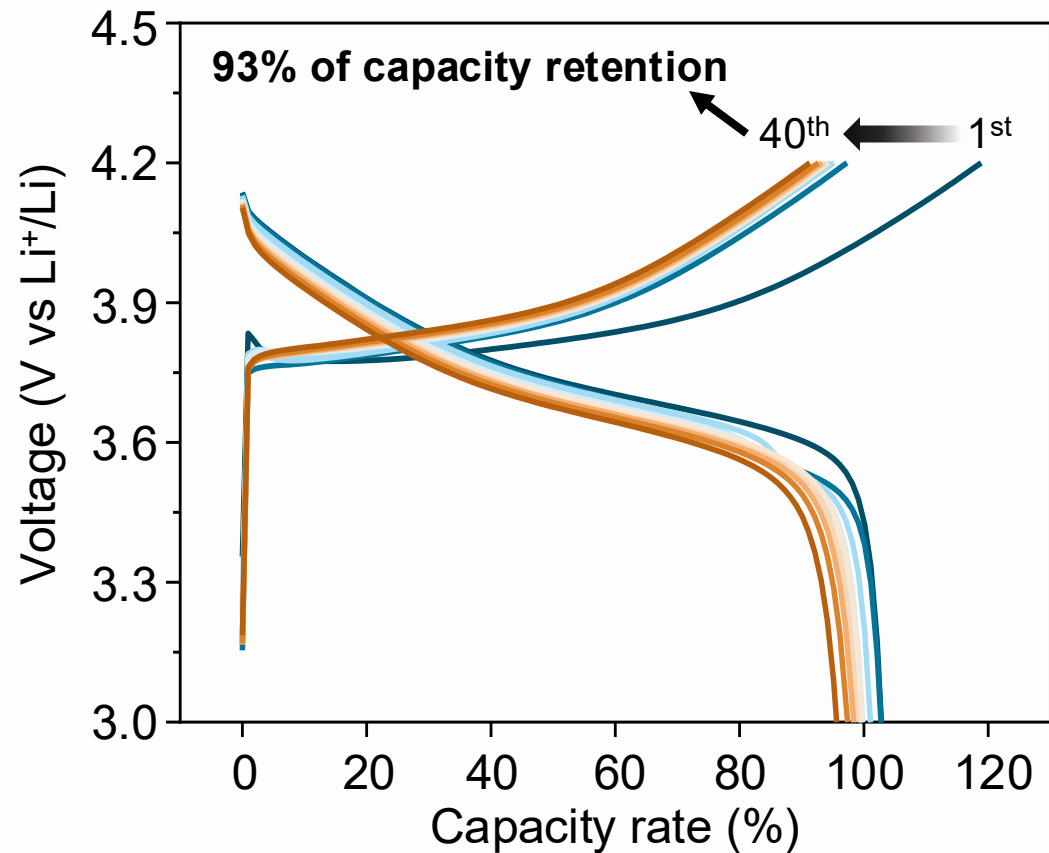
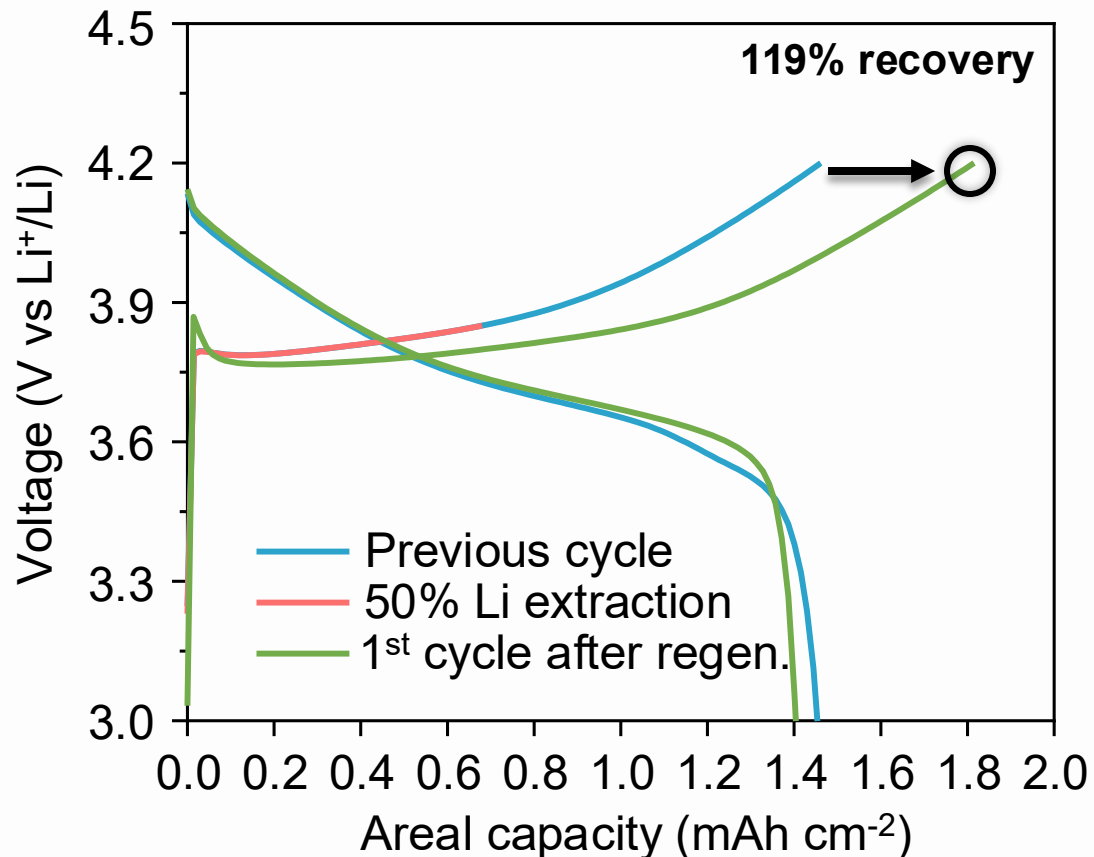
# EXTRACTING LI (SIMULATION)



# REGENERATION

3.0 V~4.2 V @ 1C

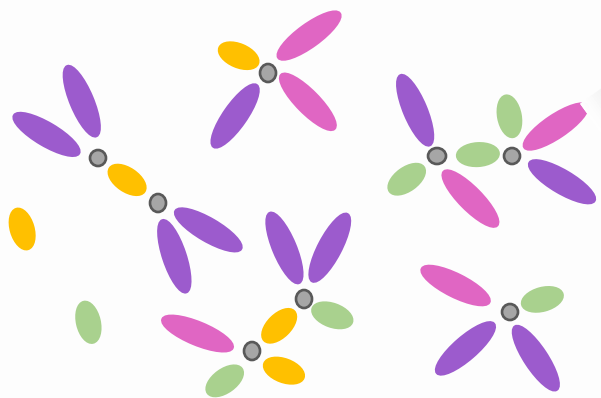
Li II NCM523 (1.7mAh cm<sup>-2</sup>)



**Successful recovery** with stable cycling after 50% Li loss

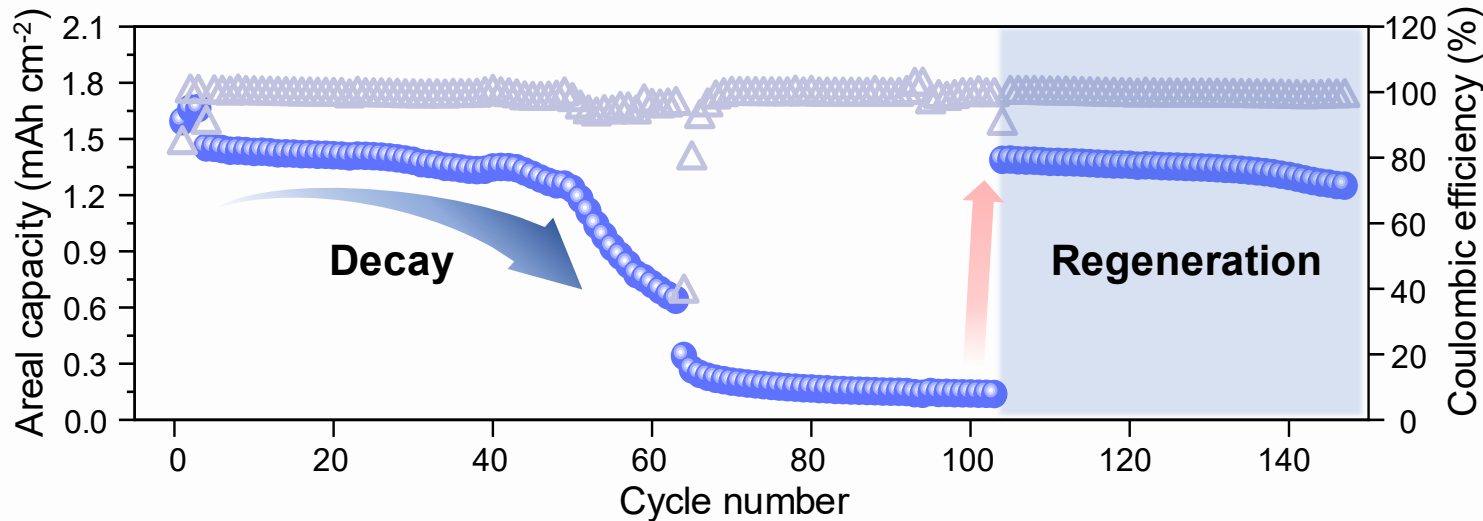
# REGENERATION CONT.

## Regeneration solutions

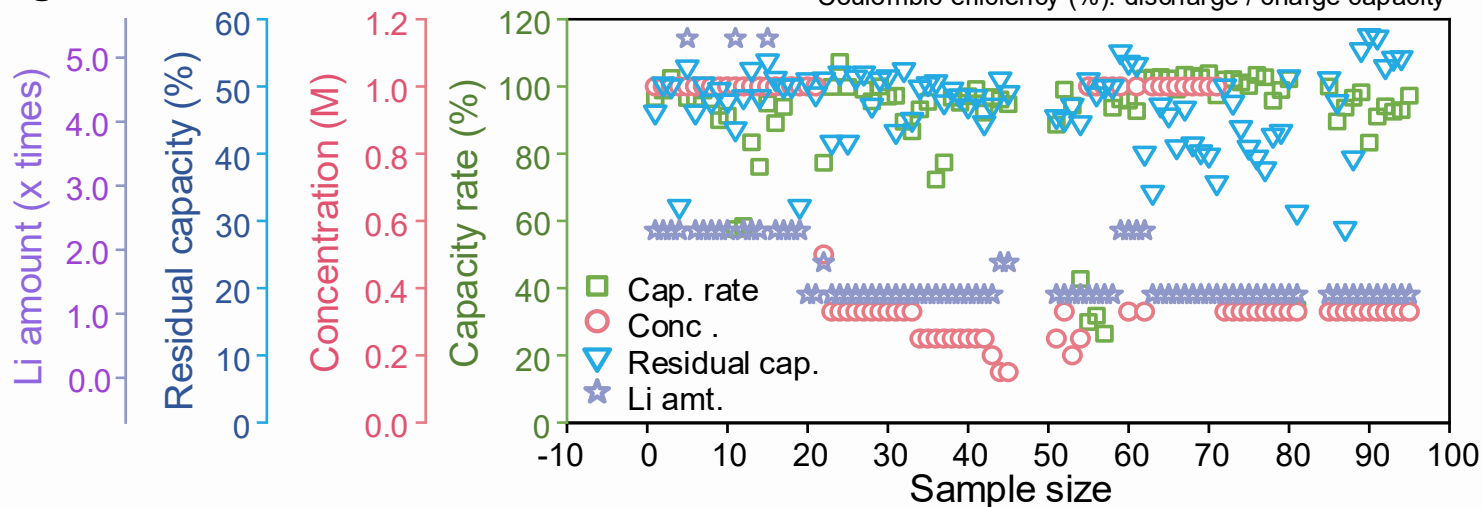


- Lithium
- Reagent
- Pairing solvent A
- Pairing solvent B

## Regeneration

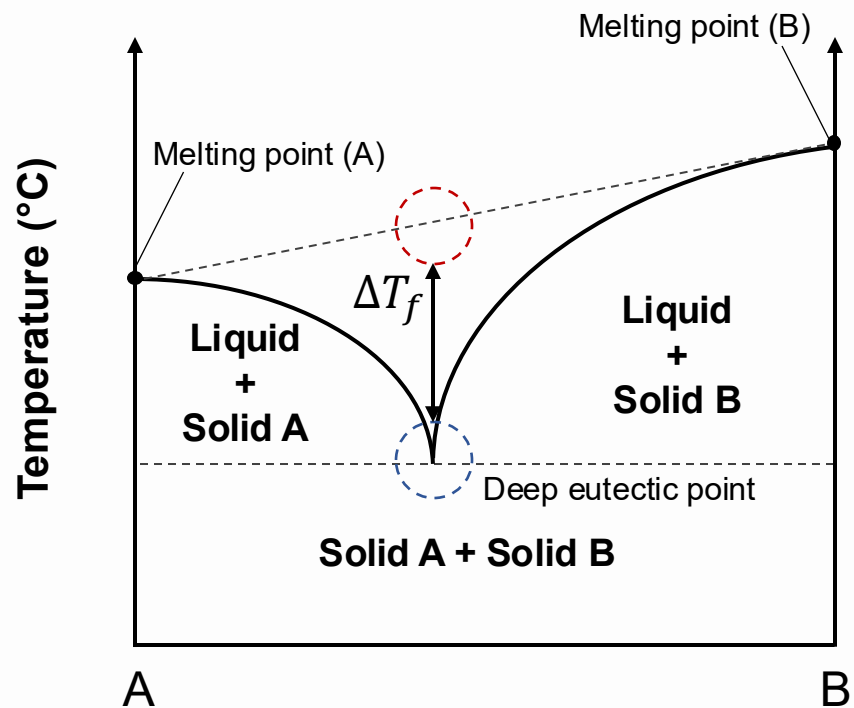


## Regeneration database



Combine multi-condition data → AI-assisted model optimization

# NATURAL DEEP EUTECTIC SOLVENT (NDES)

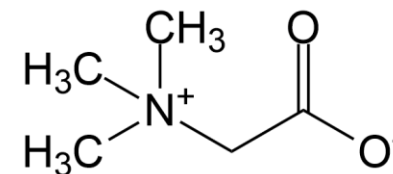


## NDES

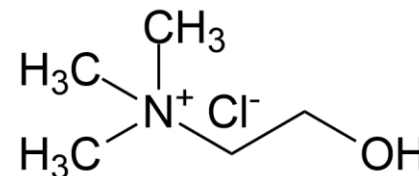
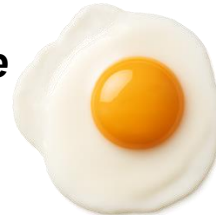
- Low-toxicity
- Biodegradability
- Easy to produce

## Eutectic blends of natural components

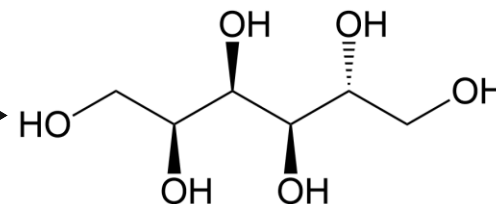
**Betaine**  
from broccoli  
(HBA)



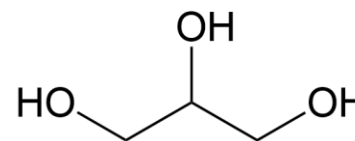
**Choline chloride**  
from egg  
(HBA)



**Sorbitol**  
from carbohydrate  
(HBD/HBA)



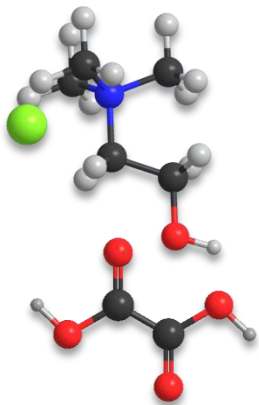
**Glycerol**  
from rapeseed



# UPCYCLING

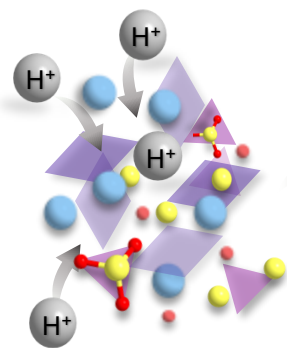
## Method

**NDES**

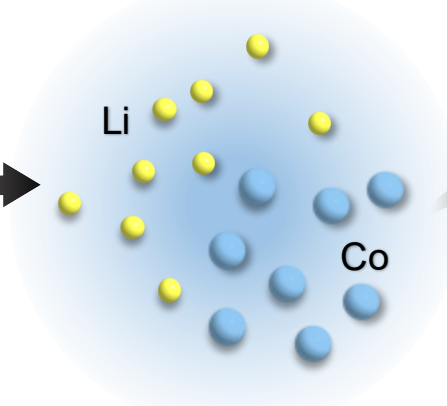


**Process**

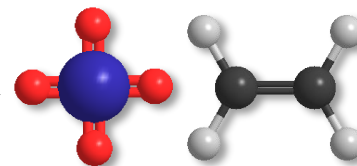
1. Attack



2. Dissolve



3. Bonding

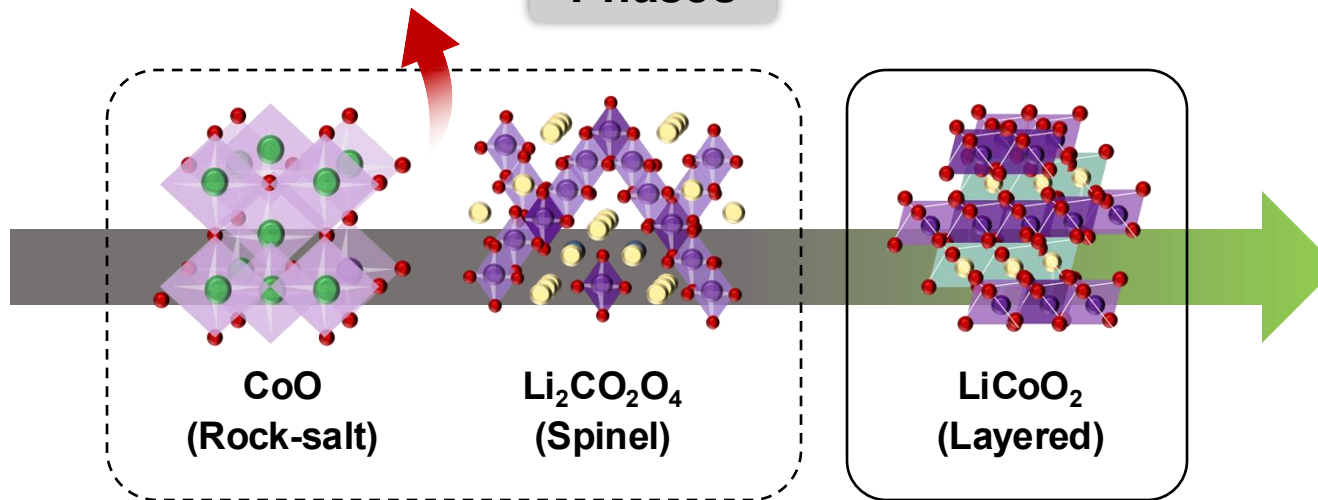
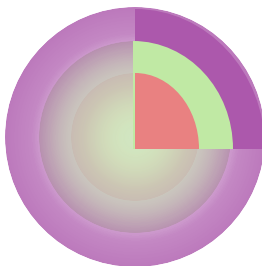


4. Water Precipitate

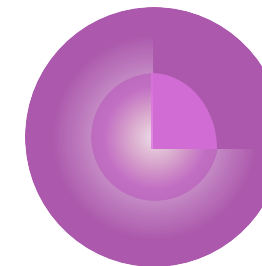


## Phases

**Spent**



**Regenerated**



# ACKNOWLEDGEMENT

## Mechano-Materials & Energy Laboratory



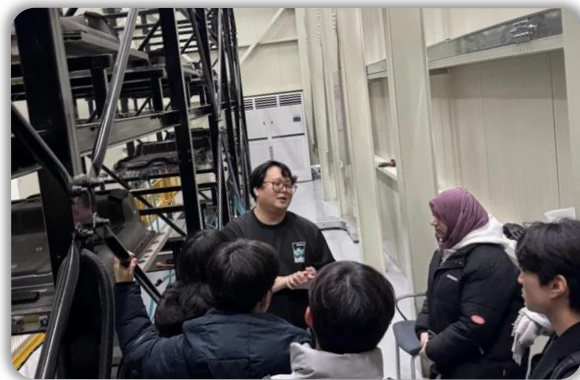
*MEL workshop (2025)*



*KIST visit (2024)*



*PIT-IN industrial visit (2024)*



*MEL workshop (2023)*



### Members

- Gwan Yun
- Jiwon Kim
- Jongheon Kim
- Chanwoo Kim
- Hyunsu Han
- Yoomin Heo
- Woojin Lee
- Min Heo
- Seungeun Park
- Xiu Rui

### Research Interest

- Solid-state electrolytes
- Low-temperature batteries
- Post-metal batteries
- Manufacturing process design
- Recycling & upcycling

### Collaborators

- ◆ Prof. Jai-Young Lee (UOS)
- ◆ Dr. Sun Ju Lee (UOS)