JOURNAL of ELECTROCHEMICAL SCIENCE and TECHNOLOGY

RESEARCH ARTICLE

Development of an Eco-Friendly Cathode Material Recycling Process Without a Separation Step

J. Hyuk Kim[1] | JM One[1] | SH Lee[1] | Jeong H. Cho[1] | Min Seo Choi[1]
Yun-Hyeok Choi[1] | San Kang[2] | Jong-Tae Son[1]*

[1]Department of Nano-Polymer Science & Engineering, Korea National University of Transportation, 50, Daehak-ro, Daesowon-myeon, Chungju-si, Chungcheongbuk-do, 27469, Republic of Korea

[2]Department of Energy Materials Science & Engineering, Korea National University of Transportation, 50, Daehak–ro, Daesowon-myeon, Chungju 27469, Korea

ABSTRACT

Among the recycling technologies for lithium-ion batteries (LIBs), commercialized hydrometallurgical processes are currently widely used to separate and recover valuable metals, such as Ni, Co, and Mn, from used NCM cathode materials. However, these processes are limited by their ability to recover only limited amounts of Li, which requires post-extraction. In this study, reductive roasting and water leaching were applied to selectively pre-extract more than 99% of Li, which was then used to synthesize lithium carbonate (Li_2CO_3). Furthermore, instead of separating each valuable metal individually from used cathode materials, a coprecipitation reaction was employed to synthesize a precursor, which was subsequently mixed with the synthesized Li_2CO_3 to recycle $LiNi_{0.6}Co_{0.1}Mn_{0.3}O_2$ cathode material. Electrochemical performance evaluation showed that the initial discharge capacity and capacity retention of the recycled cathode materials were 1.5 mAh/g and 4.7%, respectively, lower than those of the virgin cathode materials; however, their overall performance was comparable. These results confirm that the proposed recycling process is effective for high-efficiency lithium recovery and cathode materials recycling.

KEYWORDS

Used cathode materials, Hydrometallurgical process, Lithium pre-extraction, Cathode materials recycling, Electrochemical performance

CORRESPONDENCE
T: +82-43-841-5467
E: jt1234@ut.ac.kr
https://doi.org/10.33961/jecst.2025.00834

VOLUME 17 ISSUE 1 FEBRUARY 2026

RECEIVED 16 June 2025 ACCEPTED 22 August 2025

INTRODUCTION

Lithium-ion batteries (LIBs) are characterized by high energy densities, operating voltages, and long cycle lives. Owing to their excellent performance, LIBs are widely used in various applications such as electric vehicles, mobile phones, and laptops [1]. With the continuous commercialization of LIBs, the number of used batteries is also increasing [2].

Among the materials used in LIBs, lithium, nickel, cobalt, and manganese require stable supply chains owing to their limited reserves and uneven global distributions. Landfilling or incinerating batteries can lead to severe environmental pollution because organic electrolytes and toxic heavy metals may contaminate groundwater and soil. Therefore, extensive studies have been conducted on battery recycling to promote resource circulation and develop environmental protection strategies [3–5]. The currently employed commercialized recycling technologies for cathode materials are primarily based on hydrometallurgical processes such as leaching and extraction. In the leaching step, metals such as Li, Ni, Co, and Mn are dissolved in solutions using inorganic acids [6,7]. However, the presence of Li in the leachate complicates the synthesis of high-quality precursors. Consequently, solvent extraction is often required to separate and recover individual metals [8,9]. However, even after the sequential extraction of Mn, Co, and Ni, Li remains at low concentrations in the residue. Furthermore, solvent extraction involves high costs, extended processing times, and the generation of large volumes of wastewater, which pose additional challenges [10]. Therefore, recovering Li and recycling cathode materials from used batteries using more efficient methods is essential. However, studies on the direct recycling of used cathode materials without metal separation steps remain scarce.

In this study, we propose an integrated recycling process that enables the selective extraction of lithium from Li–Ni–Mn–Co oxide (NCM) cathode materials through a combination of reduction roasting and water leaching, prior to the conventional leaching step [11,12]. Instead of separating individual metals from the leachate, a co-precipitation reaction was induced to synthesize a high-purity precursor, which was subsequently used to regenerate the cathode material. A schematic comparison of the proposed process with conventional hydrometallurgical methods is presented in Fig. 1. Furthermore, the electrochemical performance of the recycled cathode material was evaluated and compared with that of the virgin cathode material.

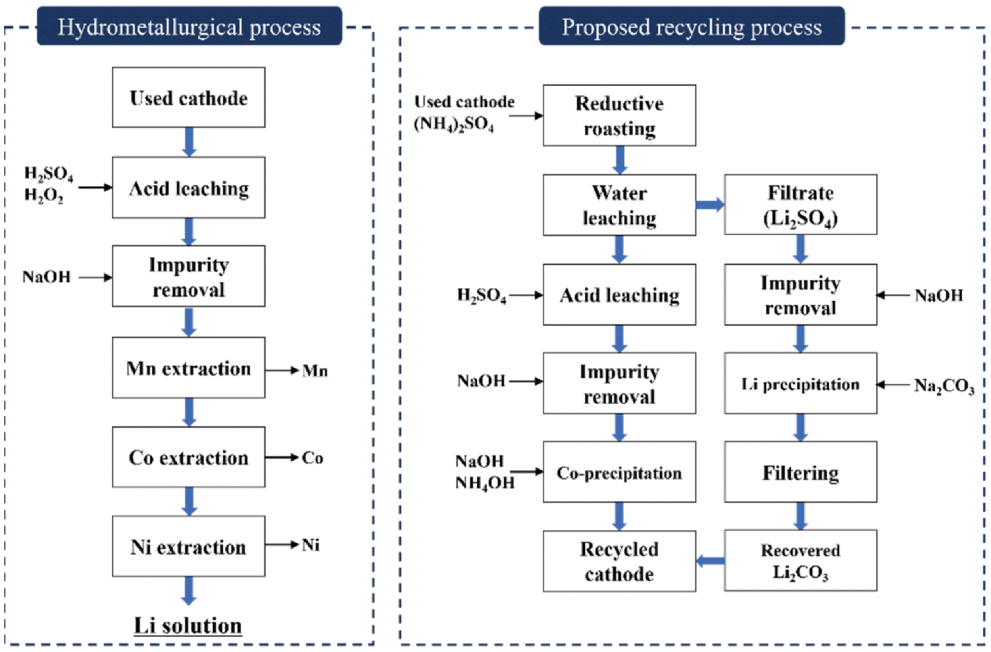

Fig. 1. Process flow diagrams of the conventional hydrometallurgical process and the proposed recycling process.

EXPERIMENTAL METHODS

Reductive Roasting and Water Leaching

In this study, the experiments were conducted using cathode materials provided by SungEel HiTech Co.,Ltd. The used cathode materials were mixed with ammonium sulfate ($(NH_4)_2SO_4$, 99%, SAMCHUN) at a specific molar ratio and placed in a crucible. The mixture was subjected to reductive roasting at 550°C for 1 h under a nitrogen atmosphere [13]. After the reaction, the mixture was cooled to room temperature, and water leaching was performed at a liquid-to-solid ratio of 5 mL/g, with stirring at 450 rpm for 1 h. After leaching, the mixture was filtered and washed to separate the residue, which was then dried in a vacuum oven at 120°C [14–16].

Acid Leaching and Impurity Removal

The dried residue was subjected to acid leaching without using a reducing agent, using sulfuric acid (H_2SO_4, 98%, Matsunoen), for 6 h [17]. After leaching, the product was filtered and washed to remove residual carbon and unreacted impurities. Next, sodium hydroxide (NaOH, 30%, SAMCHUN) solution was added to the leachate to increase its pH and thus enable the precipitation and removal of metallic impurities such as Al, Fe, and Cu. To achieve the target molar ratio of Ni:Co:Mn = 6:1:3, stoichiometric amounts of $NiSO_4$, $CoSO_4$, and $MnSO_4$ were added to the purified leachate. Subsequently, a 2 M mixed-metal sulfate solution was formulated and used for the synthesis of NCM precursors.

Lithium Carbonate Synthesis

To recover lithium, sodium carbonate (Na_2CO_3, 99.5%, SAMCHUN) solution was added to the lithium-containing filtrate. The reaction progressed at 90°C for 1 h, precipitating lithium in the form of Li_2CO_3. The precipitated Li_2CO_3 was filtered and washed with hot distilled water to remove residual SO_4^{2-} and Na^+ ions. The final product was dried in a vacuum oven at 105°C for 6 h [18,19].

Precursor and Cathode Materials Synthesis

A hydroxide coprecipitation method was used to synthesize the recycled $Ni_{0.6}Co_{0.1}Mn_{0.3}(OH)_2$ precursor. Sodium hydroxide (NaOH, 30%, SAMCHUN) and ammonium hydroxide (NH_4OH, 25–30%, SAMCHUN) were added together with the prepared leachate in a 5 L beaker to maintain the pH of 11.5. The reaction progressed at 55°C for 8 h under a nitrogen atmosphere. After the reaction, the precursor was filtered and washed with distilled water to remove residual NH_3^+ and SO_4^{2-} ions impurities. The washed precursor was dried in a vacuum oven at 120°C for 12 h. The dried precursor and synthesized Li_2CO_3 were weighed at a molar ratio of 1:1.07 and thoroughly mixed. The mixture was placed in a crucible and calcined in two steps—first, at 500°C for 5 h, and then, at 880°C for 12 h—under an oxygen atmosphere to synthesize the $LiNi_{0.6}Co_{0.1}Mn_{0.3}O_2$ cathode material [20,21].

Material Characterization

Phase changes after reductive roasting and the structure of the synthesized Li_2CO_3 were analyzed using X-ray diffraction (XRD, Bruker, D2 Phaser). The leachate composition and impurity content were analyzed both qualitatively and quantitatively using inductively coupled plasma optical emission spectroscopy (ICP-OES, PerkinElmer, Avio 550). The morphology and crystal structure of the synthesized cathode materials were analyzed using scanning electron microscopy (SEM, JEOL, JSM-7610F) and XRD. Cu $K\alpha_1$ radiation (λ = 1.54 Å) was used, and scanning was performed in the 2θ range of 10°–80° at a rate of 2°/min.

Electrode Fabrication and Electrochemical Performance Evaluation

The electrode slurry was prepared by mixing the cathode materials, a conductive additive (Super-P), and a binder (polyvinylidene fluoride) in a weight ratio of 8:1:1, using N-methyl-2-pyrrolidone as the solvent. The slurry was coated onto aluminum foil, which was used as a current collector, to a thickness of 25 µm using the doctor blade method. The coated electrodes were dried in a vacuum oven at 120°C for 10 h and punched into circular disks, each with a diameter of 14 mm. Coin cells (CR2032) were assembled under an inert atmosphere inside a glove box using a 1 M $LiPF_6$ solution, in a mixed solvent of EC:DEC = 3:7, as the

electrolyte. Electrochemical performance was evaluated at room temperature within a voltage range of 3.0–4.4 V. The cells were formed at 0.1 C and then subjected to charge–discharge cycling at 1C for 100 cycles [22].

RESULTS AND DISCUSSION

Reductive Roasting and Water Leaching

Fig. 2(a) shows the phase transformations of the used cathode materials, as analyzed by XRD, depending on the amount of $(NH_4)_2SO_4$ added. At a molar ratio of n[$(NH_4)_2SO_4$] : n(2Li) = 1.2, the amount of $(NH_4)_2SO_4$ is insufficient to fully convert Li into Li_2SO_4, leading to the partial retention of the layered NCM phase. This result indicates that the addition of $(NH_4)_2SO_4$ contributes to the decomposition of the cathode's crystalline structure [11]. As the molar ratio is increased from 1.2 to 1.4, peaks corresponding to the layered NCM phase become undetectable, and new diffraction peaks corresponding to $Li_2Mn(SO_4)_2$ and water-soluble Li_2SO_4 become visible. Furthermore, as the amount of $(NH_4)_2SO_4$ increases, the intensity of the $Li_2Mn(SO_4)_2$ diffraction peaks increases.

Fig. 2(b) shows the metal leaching efficiency as a function of the molar ratio. As the molar ratio increases from 1.2 to 1.4, the Li leaching efficiency increases drastically from 24.6% to 99.2%. However, when the molar ratio exceeds 1.4, the Li leaching efficiency decreases, while that of Mn continues to increase. This result suggests that the formation of Li_2SO_4 is preferred over that of the sulfates of Ni, Co, and Mn, and that lithium can be selectively extracted using a simple water leaching process. The chemical compositions of the original used cathode materials and water-leached residue, measured using ICP-OES, are presented in Tables 1 and 2, respectively. Li in the water-leached residue was reduced to undetectable levels, while

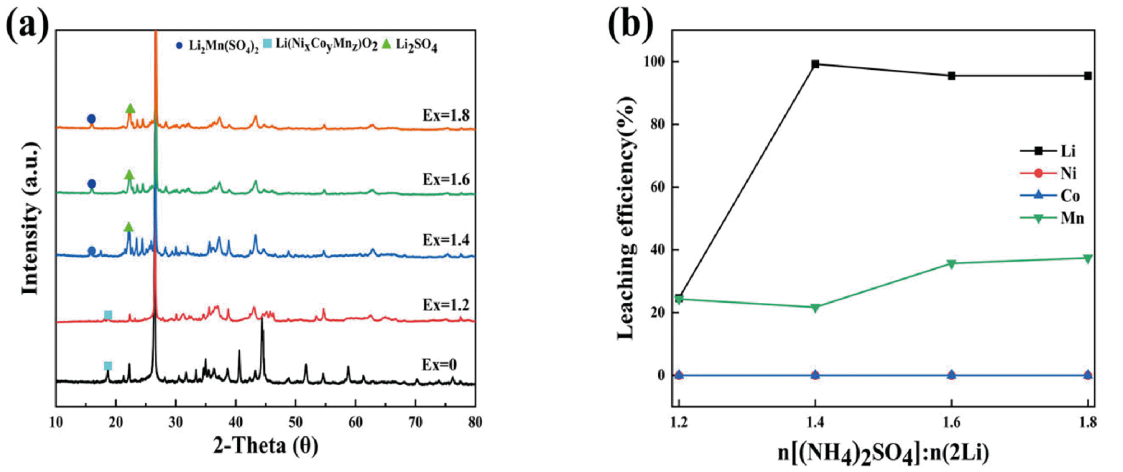

Fig. 2. (a) XRD patterns of reduction products with varying $(NH_4)_2SO_4$ dosages; (b) Leaching efficiency of metals as a function of $(NH_4)_2SO_4$ dosage.

Table 1. Mass fractions of metals in the as-received used cathode materials (wt%).

Element	Li	Ni	Co	Mn	Cu	Fe	Al
Mass (%)	5.1	13.6	4.3	11.5	7.4	0.2	6.5

Table 2. Mass fractions of metals in the water-leached residue after treatment (wt%).

Element	Li	Ni	Co	Mn	Cu	Fe	Al
Mass (%)	-	16.2	4.1	6.2	8.9	0.2	9.7

5.3 wt% of Mn was extracted. This result can be attributed to the formation of water-soluble $Li_2Mn(SO_4)_2$ during the reduction roasting process, which leads to partial Mn dissolution during water leaching. Although a portion of Mn was leached, the optimal lithium leaching efficiency was achieved at a molar ratio of $n[(NH_4)_2SO_4] : n(2Li) = 1.4 : 1$.

Acid Leaching and Impurity Removal

Following water leaching, acid leaching was conducted using only H_2SO_4, without the addition of any reducing agent, to recover the remaining metals from the residue. As shown in Fig. 3(a), Ni and Co exhibited high leaching efficiencies of 90.13 wt% and 98.26 wt%, respectively. In contrast, Mn exhibited a relatively lower leaching efficiency of 70.34 wt% under the reductive roasting conditions. According to the report by Yang et al. [10], thermodynamic calculations indicate that the stability of metal sulfates follows the order: $Li_2SO_4 > MnSO_4 > CoSO_4 > NiSO_4$. In particular, Li_2SO_4 can form stably even under low SO_3 partial pressure and exists as a water-soluble compound. $MnSO_4$ also exhibits greater stability than $CoSO_4$ and $NiSO_4$, allowing a portion of Mn to dissolve into the solution. These properties suggest that the relatively low acid-leaching efficiency of Mn may be attributed, in part, to its thermodynamic stability. The removal efficiencies of metallic impurities from the leachate are shown in Fig. 3(b). The impurities were removed by increasing the pH with a NaOH solution to induce precipitation. As a result, Fe was completely removed (100 wt%), while Cu and Al were also effectively eliminated, with removal efficiencies of 98.34 wt% and 97.27 wt%, respectively. However, trace amounts of Cu and Al remained in the leachate.

Lithium Carbonate Production

Fig. 4(a) shows the XRD pattern of Li_2CO_3 synthesized from selectively extracted lithium. Li_2CO_3 was precipitated by adding Na_2CO_3 to the lithium-containing solution. Its characteristic peaks matched well with the standard diffraction pattern (PDF No. 01-083-1454), and no impurity peaks were observed. These results confirm the successful synthesis of Li_2CO_3 and demonstrate the efficiency of lithium extraction and purification [18]. Fig. 4(b) shows an FE-SEM image of the synthesized Li_2CO_3, revealing densely aggregated plate-like single crystals with irregular sizes. This morphology is consistent with previously reported characteristics of Li_2CO_3, where the precipitate forms large agglomerates composed of bar-shaped clusters, further confirming its identity as lithium carbonate [24].

Precursor and Cathode Materials Synthesis

In this study, the leachate was directly utilized without the individual separation or recovery of metal ions for cathode recycling, and the recycled cathode was compared to a cathode synthesized from pure raw materials.

Fig. 4(a) and 4(b) show the FE-SEM images of the virgin and recycled $LiNi_{0.6}Co_{0.1}Mn_{0.3}O_2$ cathode materials. Both samples display typical NCM-type microstructures, in which primary particles aggregate into sec-

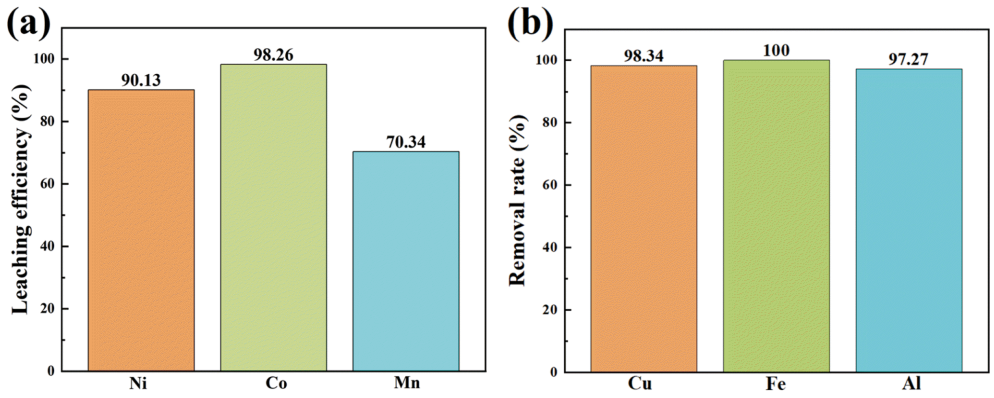

Fig. 3. (a) Leaching efficiency after acid leaching; (b) Removal efficiencies of metallic impurities.

ondary particles. Notably, the recycled cathode exhibits a more porous surface compared to the virgin sample, which may contribute to reduced electrochemical performance [25].

Fig. 5 compares the XRD patterns of the two cathode materials. All samples exhibited a well-developed hexagonal α-$NaFeO_2$ structure (R-3m space group) with no detectable secondary phases or structural distortions. The clear separation of the (108)/(110) peaks indicates high crystallinity in both samples. As summarized in Table 4, the recycled NCM shows a slight decrease in lattice constants (a = 2.8742 Å, c = 14.2468 Å) and unit cell volume (from 101.896 Å to 101.862 Å) compared to the virgin material. Additionally, the (003)/(104) peak intensity ratio decreased from 1.23 to 1.21, indicating increased cation mixing. This structural change is likely due to residual Cu in the recycled cathode, which may substitute for Ni or Mn, reducing structural stability and increasing cation disorder [26].

Electrode Fabrication and Electrochemical Performance Evaluation

Fig. 6(a) compares the initial charge–discharge profiles of the virgin and recycled cathode materials in the voltage range of 3.0–4.4 V at room temperature with a current density of 0.1 C. The recycled cathode exhibited a slightly lower initial discharge capacity than the virgin one, with initial Coulombic efficiencies of

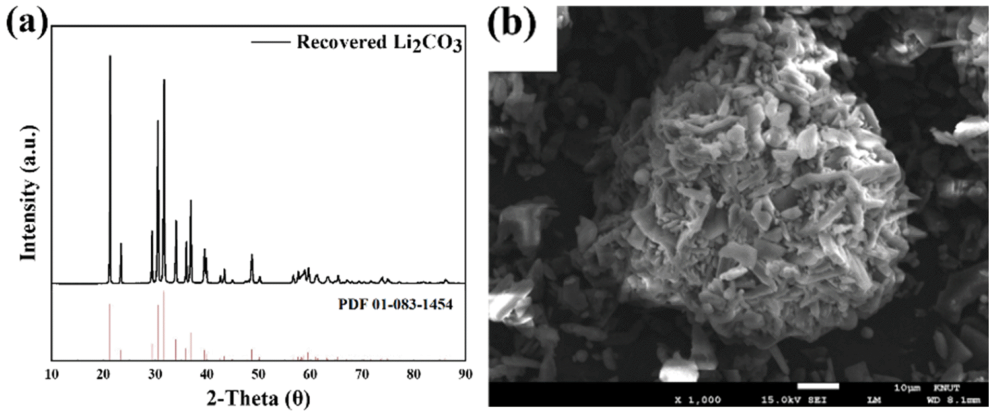

Fig. 4. (a) XRD patterns of the recovered Li_2CO_3, showing consistency with the standard PDF card (PDF No. 01-083-1454); (b) FE-SEM image of the recovered Li_2CO_3 particles.

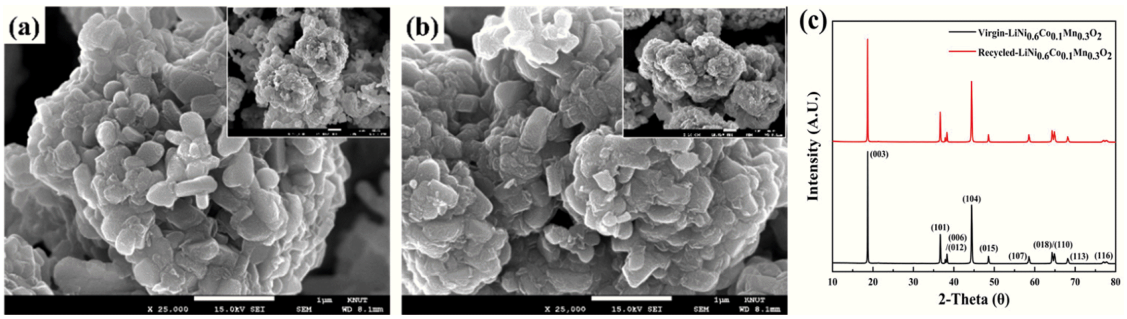

Fig. 5. FE-SEM images and XRD patterns of virgin and recycled $LiNi_{0.6}Co_{0.1}Mn_{0.3}O_2$: (a) and (b) FE-SEM images of virgin and recycled samples, respectively; (c) XRD patterns of both samples.

Table 3. Lattice parameters of virgin and recycled $LiNi_{0.6}Co_{0.1}Mn_{0.3}O_2$.

Composition	a(Å)	c(Å)	Volume	(003)/(104)
Virgin-NCM	2.8745	14.2485	101.896	1.23
Recycled-NCM	2.8742	14.2468	101.862	1.21

96.2% and 96.9%, respectively. This performance degradation is attributed to the residual Al impurity, which is electrochemically inactive. The presence of Al in cathode materials is well-known to reduce both the initial charge-discharge capacity and Coulombic efficiency, which is consistent with the observations in this study [27,28].

Fig. 6(b) presents the cycling performance of the two cathode materials at 1 C. After 100 cycles, the capacity retention of the virgin and recycled samples was 94.8% and 90.1%, respectively. These results imply that residual Al could have negatively affected secondary particle formation during co-precipitation, and Cu may have induced severe cation mixing, as indicated by lattice parameter changes [26,28].

Fig. 6(c) shows the Nyquist plots of the virgin and recycled cathode materials after the initial charge and discharge cycle. The impedance spectra were fitted using an equivalent circuit model comprising R_{sf}, R_{ct}, and Z_w, which correspond to surface film resistance, charge transfer resistance at the electrode–electrolyte interface, and Warburg impedance associated with lithium-ion diffusion within the active material, respectively. This model was selected to accurately reflect the electrochemical behavior of layered oxide cathodes after cycling. EIS measurements were conducted using a two-electrode cell configuration, with lithium metal serving as both the counter and reference electrodes. Consequently, the reported R_{ct} and D_{Li^+} values may include contributions from the lithium electrode. Previous studies [28,29] have reported that this configuration merges the impedance responses of both electrodes, thereby complicating the isolation of the working electrode's individual behavior. This limitation is acknowledged, and a three-electrode configuration is planned for future studies to enable more accurate analysis. As summarized in Table 4, the virgin cathode exhibited a lower total resistance, including surface film resistance (R_{sf}) and charge transfer resistance (R_{ct}), compared to the recycled cathode, which is considered a key factor contributing to its superior electrochemical performance. Moreover, the increase in surface film and charge transfer resistances suggests the formation of a greater amount of non-conductive interfacial films resulting from side reactions with the electrolyte [30,31]. The lithium ion diffusion coefficient (D_{Li}) was calculated from the low-frequency impedance region using the relationship between Zre and the reciprocal square root of angular frequency, as shown in Fig. 6(d) and Equation (1) [31]. After the 0.1 C formation cycle, the D_{Li} was determined

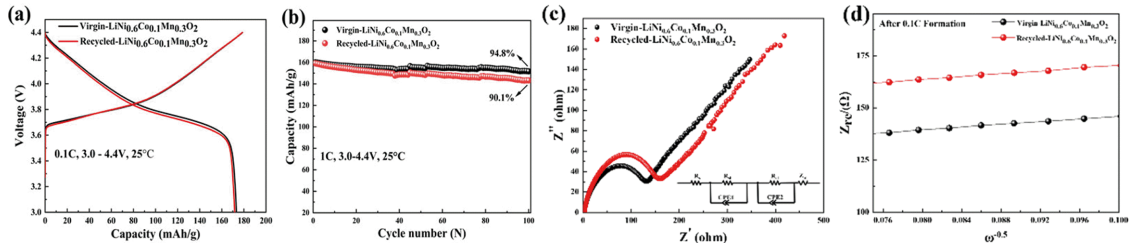

Fig. 6. Electrochemical performance of virgin and recycled $LiNi_{0.6}Co_{0.1}Mn_{0.3}O_2$: (a) initial charge-discharge curves; (b) cycling performance; (c) Nyquist plots; (d) Z' versus ω-0.5 plots after 0.1C formation.

Table 4. Initial charge and discharge capacity of virgin and recycled $LiNi_{0.6}Co_{0.1}Mn_{0.3}O_2$.

	Virgin-NCM	Recycled-NCM
Initial charge capacity	178.7mAh/g	178.5mAh/g
Initial discharge capacity	173.2mAh/g	171.7mAh/g
Coulombic efficiency	96.9%	96.2%

Table 5. Impedance and Li^+ diffusion coeffcients of virgin and recycled $LiNi_{0.6}Co_{0.1}Mn_{0.3}O_2$.

	$R_{sf}(\Omega)$	$R_{ct}(\Omega)$	D_{Li} (cm^2/s)
Virgin-NCM	2.86	45.63	1.43×10^{-15}
Recycled-NCM	2.99	89.33	1.29×10^{-15}

to be 1.43 × 10^{-15} cm^2/s for the virgin cathode and 1.29 × 10^{-15} cm^2/s for the recycled cathode, indicating slightly reduced lithium-ion mobility, likely due to the presence of residual impurities.

CONCLUSION

In this study, an environmentally friendly and simplified recycling process was proposed to selectively extract lithium from NCM-based cathode materials using reductive roasting and water leaching, without relying on conventional organic solvent-based separation. Under optimal conditions (n[$(NH_4)_2SO_4$]:n(2Li) = 1.4:1), a high lithium leaching efficiency of 99.2 wt% was achieved. The recovered Li_2CO_3 was combined with a co-precipitated $Ni_{0.6}Co_{0.1}Mn_{0.3}(OH)_2$ precursor to successfully synthesize $LiNi_{0.6}Co_{0.1}Mn_{0.3}O_2$ cathode materials, which were then compared with those synthesized from virgin raw materials to evaluate performance differences.

The recycled cathode exhibited a 1.5 mAh/g lower initial discharge capacity and a 4.7% reduction in capacity retention compared to the pristine sample. It also showed higher electrochemical resistance and lower lithium-ion diffusion capability. These performance degradations were attributed to trace metal impurities remaining in the leachate. In particular, Cu likely substituted for Ni or Mn sites in the lattice, thereby decreasingstructural stability and increasing cation disorder. Furthermore, Al not only hindered the growth of secondary particles during the co-precipitation process but was also electrochemically inactive, reducingthe initial charge-discharge capacity and Coulombic efficiency. Nevertheless, the overall electrochemical performance of the recycled material remained sufficiently stableto support the technical feasibility of the proposed recycling method.

In conclusion, the lithium-first, separation-free recycling process proposed in this study successfully enables cathode material recovery without the need for complex separation steps. This approach offers a practical solution for lithium recovery and cathode regeneration, while also contributing to resource circularity and environmental impact reduction. Therefore, it presents a promising direction for the development of next-generation lithium-ion battery recycling technologies.

ACKNOWLEDGEMENT

This research was supported by the Korea Institute for Advancement of Technology (KIAT) grant funded by the Korea Government (MOTIE) (RS-2022-KI002562, HRD Program for Industrial Innovation), and by the Ministry of Trade, Industry and Energy (MOTIE) and the Korea Institute for Advancement of Technology (KIAT) through the “Support for Middle Market Enterprises and Regional Innovation Alliances (R&D, RS-2025-02633071)” program.

REFERENCE

[1] S. Kaushik, T. Mehta, P. Chand, S. Sharma, and G. Kumar, J. Energy Storage, 2024, 97(A), 112818.
[2] P. Li, S. Luo, L. Zhang, Q. Liu, Y. Wang, Y. Lin, C. Xu, J. Guo, P. Cheali, and X. Xia, J. Energy Chem., 2024, 89, 144–171.
[3] Y. Yue, S. Wei, B. Yongjie, Z. Chenyang, S. Shaole, and H. Yuehua, ACS Sustain. Chem. Eng., 2018, 6(8), 10445–10453.
[4] G. Azimi and K. H. Chan, Resour. Conserv. Recycl., 2024, 209, 107825.
[5] A. Chagnes and B. Pospiech, J. Chem. Technol. Biotechnol., 2013, 88(7), 1191–1199.
[6] J. C. -Y. Jung, P. -C. Sui, and J. Zhang, J. Energy Storage, 2021, 35, 102217.
[7] Y. Yao, M. Zhu, Z. Zhao, B. Tong, Y. Fan, and Z. Hua, ACS Sustain. Chem. Eng., 2018, 6(11), 13611–13627.
[8] S. Lei, W. Sun, and Y. Yang, J. Hazard. Mater., 2022, 424(D), 127654.
[9] L. Zhang, L. Lijuan, H. Rui, D. Shi, X. Peng, L. Ji, and X. Song, J. Hazard. Mater., 2020, 398, 122840.
[10] C. Yang, J. Zhang, Z. Cao, Q. Jing, Y. Chen, and C. Wang, ACS Sustain. Chem. Eng., 2020, 8(41), 15732–15739.
[11] J. Lin, E. Fan, C. Liu, X. Zhang, H. Cao, Z. Sun, and R. Chen, ACS Appl. Mater. Interfaces, 2020, 12(16), 18482–18489.
[12] S. He, A. Zhou, T. Jiang, and Z. Liu, J. Clean. Prod., 2023, 422, 138511.
[13] Y. Tang, X. Qu, B. Zhang, Y. Zhao, H. Xie, J. Zhao, Z. Ning, P. Xing, and H. Yin, J. Clean. Prod., 2021, 279, 123633.
[14] A. Zhou, D. Zhang, Z. Liu, and Z. Liu, Chem. Eng. J., 2024, 497, 154573.

[15] M. Iturrondobeitia, C. Vallejo, M. Berroci, O. A-Gardoki, R. Mingue, and E. Lizundia, ACS Sustain. Chem. Eng., 2022, 10(30), 9798-9810.
[16] Y. Yue, S. Wei, B. Yongjie, Z. Chenyang, S. Shaole, and H. Yuehua, ACS Sustain. Chem. Eng., 2018, 6(8), 10445–10453.
[17] M. He, X. Duan, S. Rohani, J. Su, H. Wu, X. Jin, P. Zhang, L. Teng, H. Li, Q. Liu, C. ding, and W. Liu, ACS Sustain. Chem. Eng., 2024, 12(40), 14601–14614.
[18] M. Aannir, R. Hakkou, C. Levard, Y. Taha, A. Ghennioui, J. Rose, and I. Saadoune, J. Power Sources, 2023, 580, 233341.
[19] T. T. B. Tran, E.-J. Park, H.-I. Kim, S.-H. Lee, H.-J. Jang, and J.-T. Son, Mater. Lett., 2022, 316, 131810.
[20] H.-J. Jeon, S. A. Monim, C.-S. Kang, and J.-T. Son, J. Phys. Chem. Solids, 2013, 74(9), 1185–1195.
[21] W. Chu, Y. Zhang, X. Chen, YG. Huang, HY. Cui, M. Wang, and J. Wang, J. Power Sources, 2020, 449, 227567.
[22] H. Pinegar, R. Marthi, P. Yang, and Y.R. Smith, ACS Sustain. Chem. Eng., 2021, 9(22), 7447–7453.
[23] B. Han, R. A. Ul Haq, and M. L.-Kultanen, Hydrometallurgy, 2020, 195, 105386.
[24] C. Heubner, A. Nikol, J. Seeba, S. Reuber, N. Junker, M. Wolter, M. Schneider, and A. Michaels, J. Power Sources, 2019, 419, 119–126.
[25] T. Wu, G. Wang, B. Liu, Q. Huang, Y. Su, F. Wu, and R. M. Kelly, J. Power Sources, 2021, 494, 229774.
[26] W. Kim, S. Park, G. Ko, J. Lee, and K. Kwan, Chem. Eng. J., 2023, 475, 146121.
[27] S. Kim, S. Park, M. Jo, M. Beak, J. Park, G. Jeong, J.-S. Yu, and K. Kwon, J. Alloys Compd., 2021, 857, 157581.
[28] R. Raccichini, M. Amores, and G. Hinds. Batteries 2019, 5(1), 12.
[29] E. C. Cengiz, J. Rizell, M. Sadd, A. Matic, and N. Mozhzhukhina, J. Electrochem. Soc., 2021, 168(12) , 120539.
[30] H. Lee, Y.-T. Kim, and S.-W. Lee, Energies, 2023, 16(6), 2759.
[31] T.-J. Park, J.-B. Lim, and J.-T. Son, Bull. Korean Chem. Soc., 2014, 35(2), 357–364.