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Environmental impact assessment of valuable metal recovery from lithium-ion battery black mass using a hydrometallurgical process

Chaisumet Luengyotluechakul[1], Woraratana Pattaraprakorn[1], Pradabduang Kiattisaksiri[2*]

[1] Department of Chemical Engineering, Faculty of Engineering, Thammasat University, 99 Moo 18, Phaholyothin Road, Khlong Luang, Pathum Thani 12120, Thailand
[2] Faculty of Public Health, Thammasat University (Lampang Campus), 248 Moo 2, Phaholyothin Road, Hang Chat, Lampang 52190, Thailand
* Corresponding author's e-mail: Pradabduang.k@fph.tu.ac.th

ABSTRACT

The growing use of lithium-ion batteries (LIBs) in electric vehicles, portable electronic devices, and energy storage applications has resulted in a continuous increase in spent battery generation. This study investigated the recovery of multiple valuable metals from LIBs black mass (BM) using a hydrometallurgical process, and assess its environmental impact. The BM was subjected to leaching, followed by sequential precipitation, pH adjustment, and subsequent evaporation for lithium (Li) concentration. The leaching efficiencies of Al, Cu, Co, Li, Mn, and Ni ranged from 87–99%. Approximately 57% of the initial Li content remained in the Li-rich solution after sequential precipitation. According to the environmental impact assessment using SimaPro 10.2 with the ReCiPe 2016 Midpoint (H) method, the leaching and precipitation stages were the major contributors to the overall environmental impacts. Compared with primary production, the proposed recycling process as a secondary production route showed promising environmental benefits for the assessed impact categories of global warming potential, terrestrial ecotoxicity, and human non-carcinogenic toxicity compared with primary production. However, the recovered materials consisted of mixed-metal products. Consequently, further purification and process optimization are required to achieve higher-value applications. This study provides technical and environmental insights to support the further optimization and development of BM recycling processes prior to industrial implementation, thereby contributing to the transition toward a circular economy.

Keywords: black mass, circular economy, environmental impact assessment, hydrometallurgical processes, lithium-ion battery, metal recovery.

INTRODUCTION

Lithium-ion batteries (LIBs) have been widely used in modern applications, such as portable electronics, home appliances, electric vehicles (EVs) and energy storage systems (Ngoy et al., 2025). The rapid expansion of these technologies has significantly increased the global demand for LIBs and critical raw materials (Bruno et al., 2025). Consequently, the generation of spent LIBs has become a major environmental challenge due to the potential risks associated with improper disposal, including heavy metal contamination, fire hazards, and environmental pollution (Le et al., 2026).

Despite reaching the end of their service life, spent LIBs still contain considerable amounts of valuable materials such as lithium (Li), nickel (Ni), cobalt (Co), manganese (Mn), and graphite (Dobó et al., 2023). These materials are regarded as critical resources for battery manufacturing and energy security. In Thailand, the absence of domestic mineral resources for producing LIBs results in substantial dependence on imported batteries and raw materials.

Therefore, recycling spent LIBs has become an important strategy for reducing reliance on imported resources while promoting sustainable resource management and circular economy development (Zhang et al., 2025).

Among various recycling technologies, hydrometallurgical processing has attracted significant attention due to its relatively low energy consumption, high metal recovery efficiency, and lower atmospheric emissions compared with pyrometallurgical methods (Islam et al., 2025; Shuai et al., 2025). In hydrometallurgical recycling, spent batteries are first dismantled and mechanically processed to obtain black mass (BM), a powder mixture containing cathode and anode materials rich in valuable metals and graphite. Valuable metals can subsequently be recovered through acid leaching-related processes. Acid leaching using sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) is one of the most common methods for valuable metal recovery from BM due to its high leaching efficiency and relatively low operating cost (Conte et al., 2025; Rautela et al., 2023; Tang et al., 2023). Sequential precipitation at different pH conditions further enables selective separation of transition metals such as aluminum (Al), copper (Cu), Co, Mn, and Ni (Rautela et al., 2023). In addition, Li recovery can be achieved through alkalinity adjustment and precipitation in the form of lithium carbonate (Li_2CO_3) (Pattaraprakorn et al., 2023; Wang et al., 2025).

Although hydrometallurgical recycling offers advantages in terms of resource recovery and environmental protection, the process itself still generates environmental impacts associated with chemical consumption, electricity usage, and wastewater generation (Liu et al., 2026). Therefore, environmental impact assessment (EIA) are essential tools for evaluating the environmental sustainability of recycling technologies (Zeng et al., 2026).

This study investigates the recovery of valuable metals from BM obtained from spent LIBs through hydrometallurgical processing, which involves leaching, precipitation, pH adjustment, and evaporation. In addition, the environmental impacts associated with the recycling process are evaluated using the ReCiPe 2016 Midpoint (H) methodology within the SimaPro platform. The findings obtained from this study may provide useful information for the development of sustainable industrial-scale recycling systems involving spent LIBs.

MATERIAL AND METHODS

Materials and chemicals

BM was obtained from spent LIBs provided by the Electricity Generating Authority of Thailand (EGAT). Sulfuric acid (H_2SO_4, 98 wt.%, AR grade, QRec), sodium hydroxide pellets (NaOH, 99%, AR grade, QRec), hydrogen peroxide (H_2O_2, 30 wt.%, ACS reagent, Sigma-Aldrich), and sodium chloride (NaCl, 99.99%, commercial grade, TRS) were used throughout the experiments.

Black mass preparation

The spent LIBs were initially dismantled to remove the battery casing and external terminals, leaving only the internal cells for further processing. The cells were subsequently discharged by immersion in a 10 wt.% NaCl solution for 10 h to safely eliminate any residual electrical charge.

After the discharging process, the cells were air-dried prior to mechanical processing. The dried cells were then subjected to grinding and separation processes to remove plastic separator materials and metallic impurities. Magnetic separation and sieving processes were additionally applied to obtain BM. The obtained BM particles exhibited a particle size range of approximately 71–104 μm.

Hydrometallurgical recovery process

The experimental setup used for metal recovery from LIBs through the hydrometallurgical process is illustrated in Figure 1. The leaching and precipitation processes were conducted in a 100 L borosilicate glass batch reactor equipped with a mechanical agitator, an electric heater, a temperature controller, and a condenser to maintain the operating conditions according to the specific parameters described for each experimental stage. After each precipitation step, the solid precipitates were separated from the solution using a plate and frame filter press fitted with a polypropylene membrane filter (0.8 μm pore size, 300 mm diameter, Shenyang Great Wall Filtration).

This study was conducted according to the experimental workflow illustrated in Figure 2, consisting of four sequential stages, including leaching, precipitation, pH adjustment, and evaporation. The details of each stage are described as follows.

Figure 1. Hydrometallurgical reactor setup used for metal recovery from lithium-ion battery black mass

Leaching

The obtained BM was subjected to acid leaching using 50 L of 2 M H_2SO_4. A total of 10 kg of BM was leached with 50 L of H_2SO_4 solution, followed by the addition of 3.6 L of 30 wt.% H_2O_2 as a reducing agent. The leaching process was conducted at 70 °C under continuous stirring at 150 rpm for 15 h. After leaching, the mixture was filtered to separate the leaching residue from the leachate solution. The obtained solution was subsequently used for the precipitation process.

Precipitation

The leachate was first adjusted to pH 7 by adding 4 M NaOH and stirred continuously at 150 rpm for 2 h to promote complete precipitation. The precipitate formed under this condition (pH 7 PCP) was separated by filter press filtration. The remaining filtrate then underwent further pH adjustment to pH 9 (pH 9 PCP) and pH 12 (pH 12 PCP) using the same procedure.

pH adjustment

The solution obtained at pH 12 was further adjusted to pH 14 by adding 4 M NaOH and stirred continuously at 150 rpm for 1 h to promote the conversion of dissolved Li species into lithium hydroxide (LiOH) prior to evaporation.

Evaporation

The pH 14 solution was subsequently subjected to evaporation on a hotplate (C-MAG HS 7, IKA, Germany) at 80 °C for 6 h to reduce the water content of the solution at a volume reduction ratio of 4:1. After evaporation, the concentrated solution was cooled to room temperature to induce further precipitation. The resulting evaporated residue was separated from the remaining Li solution by filtration. This procedure was repeated until all the pH 14 solutions were processed.

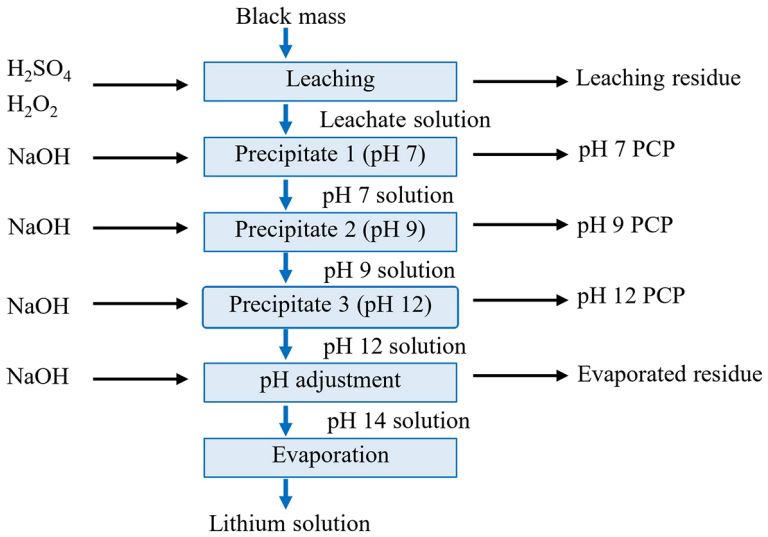

Figure 2. Experimental flowchart of the metal recovery process from lithium-ion battery black mass

Sample characterization and analysis

Samples obtained from the hydrometallurgical recovery process were characterized using an X-ray fluorescence spectrometer (XRF) for preliminary elemental composition analysis, an X-ray diffraction (XRD) for crystalline phase identification, and an inductively coupled plasma optical emission spectrometry (ICP-OES) for quantitative elemental analysis.

XRF analysis was performed using an EDX-LE (Shimadzu, Japan). XRD analysis was conducted using a Miniflex 600 (Rigaku, Japan) equipped with Cu Kα radiation (λ = 1.5406 Å), operating at 40 kV and 15 mA over a 2θ range of 10–80° at a scanning rate of 1°/min. ICP-OES measurements were carried out using an Agilent 5110 ICP-OES (Agilent Technologies, USA). The instrument was operated at an RF power of 1.2 kW with plasma, auxiliary, and nebulizer gas flow rates of 12.0, 1.0, and 0.7 L/min, respectively. The analytical emission wavelengths for Al, Cu, Co, Li, Mn, and Ni were 396.152, 324.754, 228.616, 670.783, 257.610, and 231.604 nm, respectively.

Environmental impact assessment

Environmental impacts were evaluated using SimaPro version 10.2 with the ecoinvent database (version 3.10, cut-off system model). The ReCiPe 2016 Midpoint (H) V1.08/ World (2010) H methodology was selected due to its comprehensive coverage of environmental impact categories and its widespread application in battery recycling and LCA studies (Zhang et al., 2024; Sitcharangsie et al., 2025).

Figure 3 illustrates the scope and system boundary adopted for the environmental impact assessment (EIA) of the hydrometallurgical recovery process. The assessment included four main unit operations: leaching, precipitation, pH adjustment, and evaporation. Material inputs consisted of BM, H_2SO_4, H_2O_2, NaOH, deionized (DI) water, and electricity consumption. The outputs consisted of the leaching residue, metal precipitates obtained at pH 7, 9, and 12, evaporation residue, Li-rich solution, and waste generated during the process. Environmental impacts associated with battery usage, transportation, and downstream purification or utilization of the recovered products were excluded from the system boundary.

To facilitate this preliminary EIA, the following assumptions were made: (1) Sodium carbonate (Na_2CO_3) was added to convert LiOH into Li_2CO_3, with the conversion reaction assumed to proceed to completion. (2) The recovered products were assumed based on the reaction stoichiometry and the experimental results obtained from XRD, XRF, and ICP-OES analyses. These products included graphite, aluminum hydroxide ($Al(OH)_3$), copper(II) hydroxide ($Cu(OH)_2$), cobalt(II) hydroxide ($Co(OH)_2$), manganese(II) hydroxide ($Mn(OH)_2$), nickel(II) hydroxide ($Ni(OH)_2$), and Li_2CO_3, which were assumed to be sufficiently pure and free from cross-contamination. (3) Waste treatment and disposal processes were excluded from the system boundary.

The functional unit was defined as the recovery of valuable products from processing 10 kg of BM, corresponding to one batch of the hydrometallurgical process. Primary production

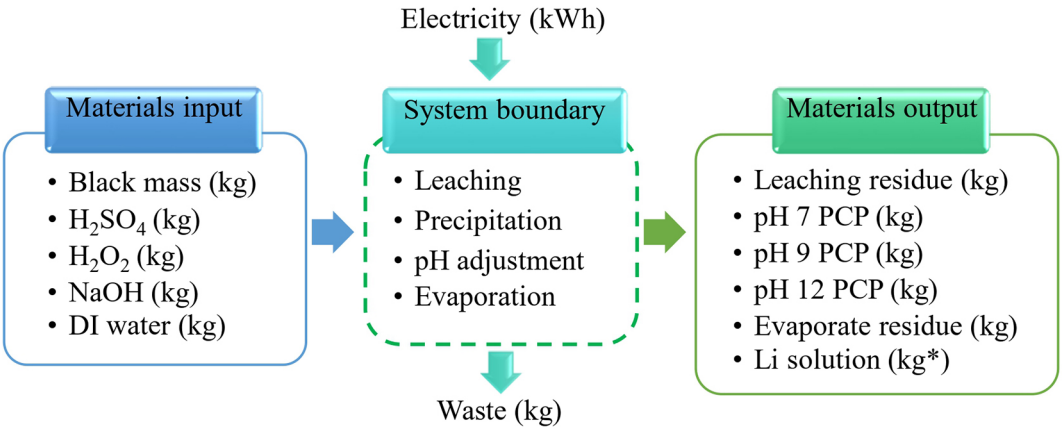

Figure 3. Scope and system boundary for the environmental impact assessment of metal recovery from lithium-ion battery black mass

Note: *A solution density of 1 kg/L was assumed for all aqueous process streams used in the material balance.

refers to the conventional production of battery-related materials from virgin raw materials through upstream extraction, processing, and refining processes, whereas secondary production refers to the recovery of metals from spent LIBs through recycling. Environmental impacts of the proposed secondary production process were compared with primary production routes. The life cycle inventory (LCI) data for primary production, obtained from the ecoinvent database (cut-off system model, unit process), were implemented in SimaPro 10.2 (Rossi et al., 2026). Both primary and secondary production systems were evaluated using the same functional unit to ensure a consistent comparison of environmental impacts.

RESULTS AND DISCUSSION

Black mass characteristics

Preliminary characterization by XRF analysis indicated the presence of major elements including Ni (45.85%), Co (12.30%), Mn (10.40%), Cu (29.53%), and other elements (1.92%, i.e., phosphorus, tungsten, zirconium, and rubidium) within the BM sample. In addition, XRD analysis, as shown in Figure 4, confirmed the presence of graphite and layered Li transition metal oxide phases associated with NMC811 cathode materials, consistent with a previous report (Safdar et al., 2026).

Leaching performance

The hydrometallurgical leaching process demonstrated effective dissolution of valuable metals from BM. H_2O_2 acted as a reducing agent that enhanced the dissolution of transition metals, particularly Ni, Co, and Mn, from the cathode materials (Vieceli et al., 2023).

After the leaching process, most transition metals were successfully transferred into the leachate solution, with leaching efficiencies of 87.48, 98.43, 98.93, 98.69, 98.77, and 98.50% for Al, Cu, Co, Li, Mn, and Ni, respectively.

Among the leached elements, Li is of particular interest due to its high economic value and strategic importance in battery recycling. The Li leaching efficiency achieved in this study was 98.69%, indicating effective dissolution of Li from the BM during the H_2SO_4/H_2O_2 leaching step. This value was comparable to previously reported hydrometallurgical studies using H_2SO_4/H_2O_2 leaching systems, where Li leaching efficiencies of approximately 98–100% have been achieved depending on the leaching conditions and feed materials (Qiu et al., 2022; Wongnaree et al., 2024). These results confirm that the conventional H_2SO_4/H_2O_2 leaching approach can effectively dissolve Li and other valuable metals from spent lithium-ion battery (LIB) materials prior to subsequent separation steps.

To further evaluate the dissolution behavior and identify the remaining solid phases after leaching, the leaching residue was characterized by XRD

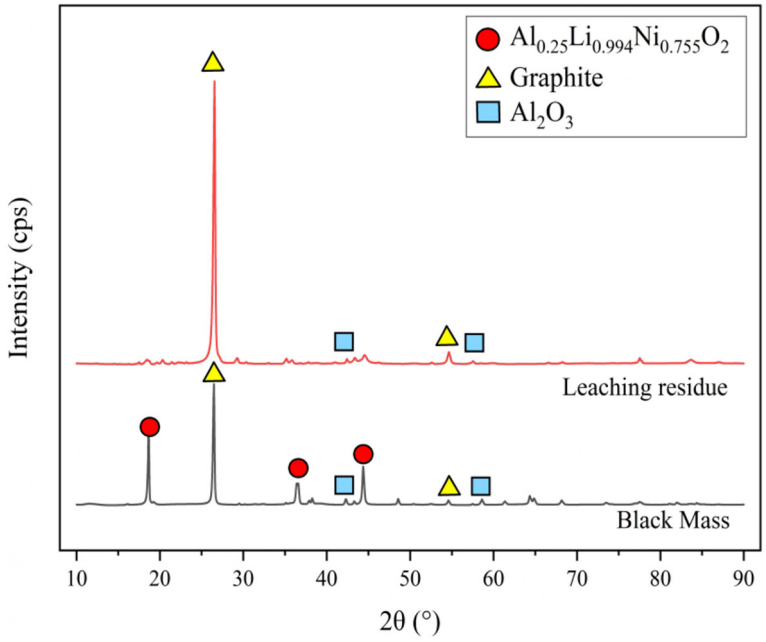

Figure 4. XRD patterns of the lithium-ion battery black mass and leaching residue

analysis. As shown in Figure 4, XRD results confirmed the presence of graphite and minor undissolved phases remaining after the leaching process. In addition, the ICP-OES results presented in Table 1 indicate significant reductions in metal concentrations within the leaching residue compared with the original BM sample, demonstrating effective metal extraction from BM. Similar leaching behavior has been reported in the literature for H_2SO_4 and H_2O_2 leaching systems in LIB recycling processes (Nadimi and Jalalian Karazmoudeh, 2020).

Data in Table 1 reveal that the leaching residue was predominantly composed of Al (12,387 mg/kg), together with other residual metals. Therefore, this fraction should be regarded as an Al-rich mixed residue rather than a pure Al compound. The Al-rich leaching residue may also have potential for use as a supplementary raw material for construction materials after appropriate purification and process optimization, similar to other Al-rich industrial residues (Al-Fakih et al., 2023).

Sequential precipitation behavior

Sequential precipitation using NaOH at pH 7, 9, and 12 enabled selective recovery of metal hydroxides from the leachate solution. The elemental composition of the precipitates changed with increasing pH. At pH 7 (pH 7 PCP), Cu and Ni compounds were predominantly precipitated (91,933 and 76,919 mg/kg, respectively). This observation is consistent with previous reports in which Cu begins precipitation at a lower pH because of its low solubility, followed by Ni precipitating at a near neutral pH (Djoudi et al., 2021; Keller et al., 2024). Consequently, both metals were enriched in the precipitate collected at pH 7. Increasing the solution pH to 9 (pH 9 PCP) and 12 (pH 12 PCP) resulted in precipitates enriched in Ni (159,975 mg/kg) and Mn (117,467 mg/kg), respectively. Li remained predominantly in the solution for subsequent enrichment by evaporation. These results indicate that sequential pH adjustment enabled stepwise separation of valuable metals according to their precipitation behavior. This behavior is consistent with previous studies reporting that pH adjustment facilitates the separation of transition metals through hydroxide precipitation during hydrometallurgical recycling of spent LIBs (Davis and Demopoulos, 2023; Kordloo et al., 2025).

The precipitates obtained at each pH condition were further characterized by XRD analysis, as shown in Figure 5. The XRD results confirmed the presence of metal hydroxide compounds, including $Al(OH)_3$, $Cu(OH)_2$, $Co(OH)_2$, $Mn(OH)_2$, and $Ni(OH)_2$, together with lithium sodium sulfate ($LiNaSO_4$) as the secondary crystalline phase. The formation of $LiNaSO_4$ may be attributed to the interaction between Li-containing species and Na_2SO_4 during the precipitation process, consistent with previous reports on Na-assisted Li recovery (Agarwal et al., 2026).

During metal hydroxide precipitation, a slight decrease in pH was observed after the initial adjustment. This pH drop was likely attributed to the consumption of hydroxide ions during metal hydroxide formation and the hydrolysis of dissolved metal ions, particularly multivalent ions such as Al^{3+}. Therefore, additional NaOH was required to maintain the target pH during the precipitation process.

In addition, the ICP-OES analysis in Table 1 indicates decreasing concentrations of transition metals in the remaining solution after each precipitation stage, demonstrating the effectiveness of sequential precipitation for selective metal

Table 1. Elemental composition of lithium-ion battery black mass precipitates, and Li solution determined by ICP-OES

Sample	Unit	Al	Cu	Co	Mn	Ni	Li
BM	mg/kg	44,036	76,424	44,179	38,138	106,749	26,401
Leaching residue	mg/kg	12,387	2,691	1,060	1,053	3,592	778
pH 7 PCP	mg/kg	15,562	91,933	24,832	15,539	76,919	8,515
pH 9 PCP	mg/kg	247	1,441	79,565	29,497	159,975	7,012
pH 12 PCP	mg/kg	128	<100	5,281	117,467	2,333	14,671
Li solution	mg/L	<100	<100	<100	<100	<100	10,646

Note: Values reported as <100 mg/kg or <100 mg/L indicate concentrations below the laboratory reporting limit (RL) and could not be reliably quantified.

recovery. However, partial co-precipitation between transition metals may still occur under high pH conditions due to partially overlapping precipitation ranges. This behavior is consistent with a previous study showing that pH strongly influences the precipitation behavior and purity of recovered metal products (Ananda et al., 2023).

The precipitates obtained by sequential pH adjustment were enriched in different metals but not chemically pure. These products should be considered as mixed-metal products rather than individual metal products, which could potentially be used as materials for battery production after appropriate purification (Kim et al., 2024). Further purification method, such as selective precipitation or electrochemical pretreatment, may be applied to remove impurity metals and improve product purity for higher-value applications (Klaehn et al., 2023).

Lithium enrichment

Following precipitation, the remaining solution was adjusted to pH 14 to maintain Li as dissolved hydroxide species, remove residual impurities, and prepare the solution for subsequent Li enrichment by evaporation. According to the Li–H_2O Pourbaix diagram, Li remains stable in the form of dissolved LiOH species under highly alkaline conditions (Kumari et al., 2021). During the evaporation process, water content was reduced, resulting in the supersaturation and crystallization of sulfate-containing compounds, including Na_2SO_4 and $LiNaSO_4$, during cooling, as confirmed by the XRD analysis presented in Figure 6. Similar sulfate crystallization behavior has been reported for concentrated sulfate systems (Krumgalz, 2018; Schmidt et al., 2021).

At this stage, Li remained as the predominant target metal in the solution after the sequential precipitation of Al, Cu, Ni, Co, and Mn, while Na introduced from NaOH was expected to remain in the solution. Based on the overall mass balance, 56.88% of the initial Li content could be retained in the Li-rich solution after the purification process. The remaining Li was mainly distributed in the precipitated solids (approximately 41.81%) and leaching residue (approximately 1.31%). Therefore, the 56.88% value represents Li retention in the enriched solution rather than the overall Li leaching efficiency from BM.

The Li-rich solution may contain dissolved Li species that could potentially be converted into Li_2CO_3 through the addition of Na_2CO_3 following conventional Li precipitation approaches reported in hydrometallurgical processes (Lim et al., 2025). The corresponding reactions can be expressed in Equations 1 and 2. Due to the relatively low solubility of Li_2CO_3, Li could potentially be recovered in the form of precipitated Li_2CO_3 through carbonate precipitation in future studies.

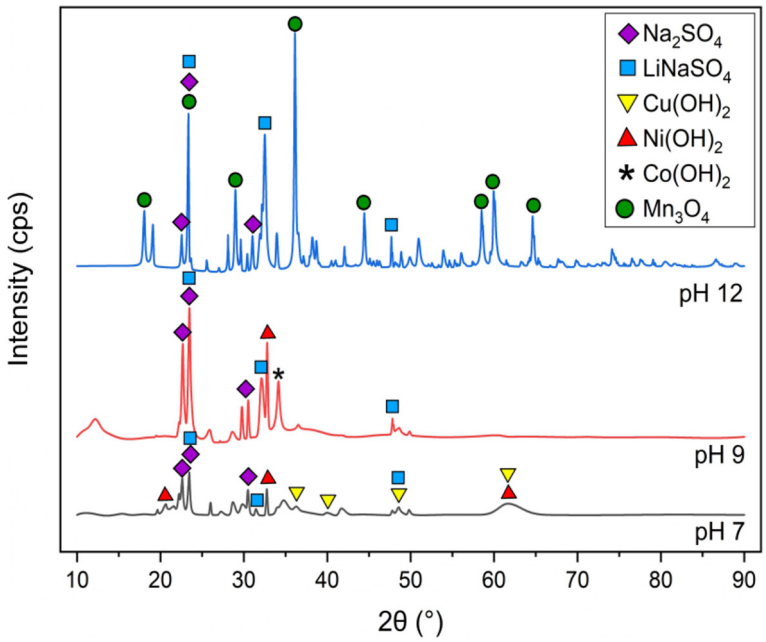

Figure 5. XRD patterns of precipitates obtained at pH 7, 9, and 12 during the sequential precipitation process

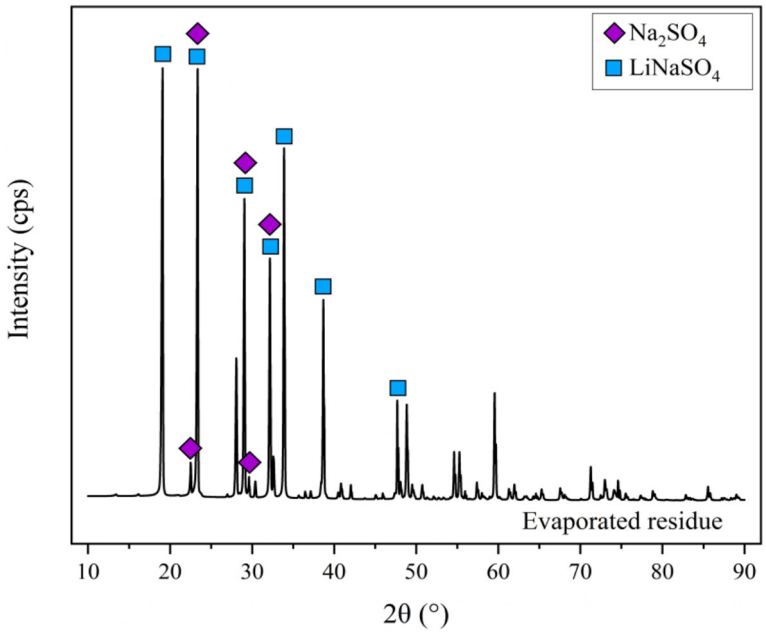

Figure 6. XRD patterns of the solid residue obtained after evaporation of the lithium-rich solution

$$LiOH + H_2O \leftrightarrow Li^+ + OH^- + H_2O \leftrightarrow \leftrightarrow LiOH \cdot H_2O \quad (1)$$

$$2LiOH\,(aq) + Na_2CO_3\,(aq) \rightarrow \rightarrow Li_2CO_3\,(s) + 2\,NaOH\,(aq) \quad (2)$$

Although the concentrations of dissolved impurities (Al, Cu, Co, Mn, and Ni) in the Li-rich solution were below 100 mg/L based on the ICP-OES analysis presented in Table 1, trace amounts of these metals may still be incorporated into the recovered Li_2CO_3 product during precipitation (Suárez et al., 2024). In addition, residual Na-containing species originating from Na_2CO_3 may remain in the product if washing is insufficient. These impurities may affect the suitability of the recovered Li_2CO_3 for battery-grade applications. Therefore, additional purification steps, such as recrystallization and washing optimization (e.g., three washing cycles) may be required to comply with battery-grade specifications (Mazur et al., 2026; Zheng et al., 2026).

Environmental impact assessment

Table 2 summarizes the environmental impacts associated with the metal recovery process from lithium-ion battery black mass (LIB BM)), covering 18 environmental impact categories. The results were calculated based on chemical consumption, electricity use, and other process inputs. The results indicated that chemical consumption and reactor electricity use during leaching, precipitation, pH adjustment, filtration and evaporation were the major contributors to environmental burdens of the hydrometallurgical recycling process, particularly from H_2SO_4 and NaOH consumption and electricity use. Compared with previous hydrometallurgical recycling studies, the present study showed similar environmental impact patterns despite differences in functional unit and system boundary. Global warming potential, terrestrial ecotoxicity, and human non-carcinogenic toxicity were the dominant impact categories, consistent with the findings of Premathilake et al. (2024).

Figure 7 shows the material and energy balance representing the specific outcome of the conventional hydrometallurgical recovery process for valuable metal recovery in this study. The material inputs, outputs, and waste streams were determined from the measured mass flow during the experimental study. The total energy input was derived from the cumulative electricity consumption of all unit operations. Electricity consumption for the leaching, filtration, and precipitation stages was measured directly using a power meter (21.10 kWh), while that for the evaporation unit (52.00 kWh) and vacuum pump (0.13 kWh) was calculated from the rated power and operating time, giving a total electricity consumption of 73.23 kWh. According to the results, the leaching and precipitation stages contributed to the highest environmental impacts due to high chemical

and electricity consumption, as well as waste generation, while reactor heating and evaporation also significantly contributed to the overall environmental burden.

The high contribution of environmental impacts was mainly associated with the consumption of fresh reagents, including H_2SO_4, H_2O_2, NaOH, and DI water. In this study, all fresh reagents were consumed during leaching, neutralization, precipitation, and Li enrichment steps, and therefore not directly reused. However, the recovery and reuse of process reagents could potentially reduce both operating costs and environmental impacts. The evaluation of reagent recovery and recycling strategies is beyond the scope of the present study and should be considered in future work.

Based on the assumed material outputs shown in Figure 8, the environmental impacts of the proposed hydrometallurgical recovery process (secondary production) in this study were compared with equivalent products obtained from the primary production of battery-related materials. For a consistent comparison, the results were normalized to the same assessment basis, corresponding to the recovery of valuable metals from 10 kg of

Table 2. Environmental impact assessment of the metal recovery process from lithium-ion battery black mass

Categories	Unit	Quantity
Global warming	kg CO_2 eq	56.05
Stratospheric ozone depletion	kg CFC11 eq	0.00
Ionizing radiation	kBq Co-60 eq	0.98
Ozone formation, Human health	kg NOx eq	0.04
Fine particulate matter formation	kg PM2.5 eq	0.05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.04
Terrestrial acidification	kg SO_2 eq	0.13
Freshwater eutrophication	kg P eq	0.01
Marine eutrophication	kg N eq	0.00
Terrestrial ecotoxicity	kg 1,4-DCB	308.23
Freshwater ecotoxicity	kg 1,4-DCB	2.91
Marine ecotoxicity	kg 1,4-DCB	3.81
Human carcinogenic toxicity	kg 1,4-DCB	1.33
Human non-carcinogenic toxicity	kg 1,4-DCB	57.88
Land use	m^2a crop eq	0.43
Mineral resource scarcity	kg Cu eq	0.19
Fossil resource scarcity	kg oil eq	3.08
Water consumption	m^3	0.52

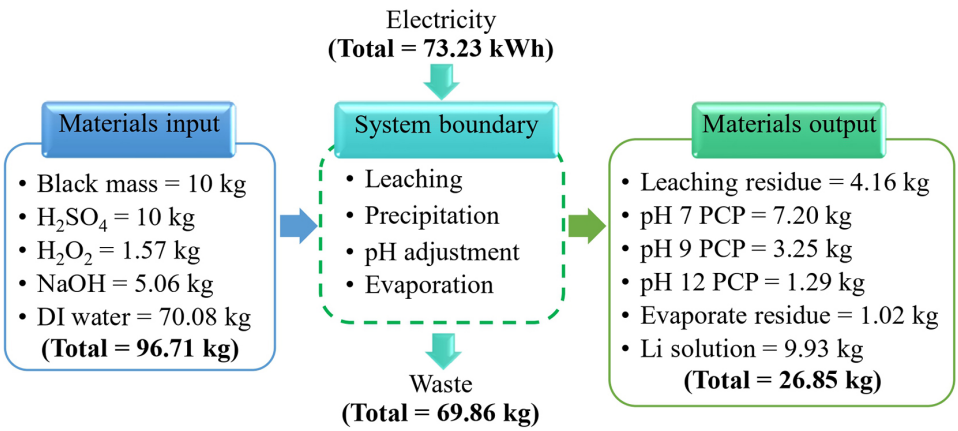

Figure 7. Material and energy balance of the hydrometallurgical recovery process from lithium-ion battery black mass

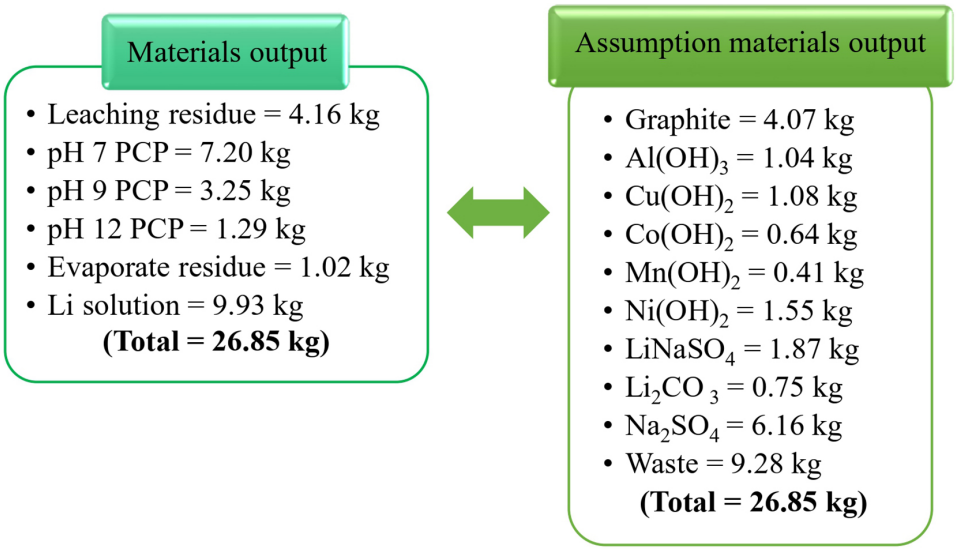

Figure 8. Assumed material outputs for the preliminary environmental impact assessment

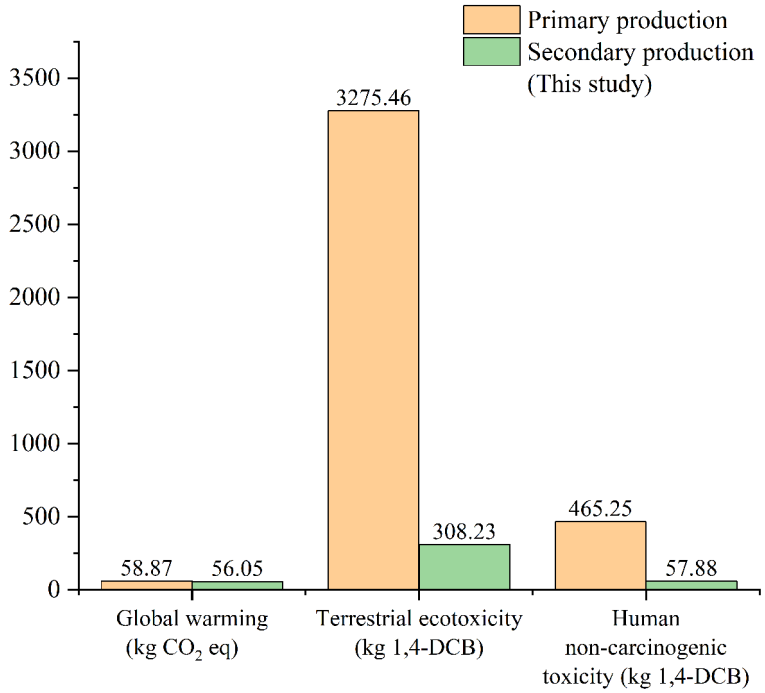

Figure 9. Comparison of environmental impacts between primary metal production and secondary metal production from recycled black mass

BM. The primary production, including NMC811 hydroxide precursor, graphite, $Al(OH)_3$, $Cu(OH)_2$, and Li_2CO_3, were considered for comparison. Three impact categories, including global warming potential, terrestrial ecotoxicity, and human non-carcinogenic toxicity, were selected because they represent major environmental burdens.

According to Figure 9, the recovery of valuable metals from BM in this study resulted in lower environmental impacts than primary production of battery-related materials. The lower impacts are mainly attributed to the avoidance of energy-intensive mining, ore beneficiation, and metal refining processes required for primary production. Recovering valuable metals from BM reduces the demand for virgin resource consumption and its associated environmental burdens, thereby demonstrating the potential of the proposed process to promote sustainable resource management and support a circular economy.

The lower environmental impacts observed in this study are consistent with the inherent advantages of hydrometallurgical recycling. Although the hydrometallurgical process requires substantial chemical consumption, its lower energy demand and reduced atmospheric emissions compared with pyrometallurgical processing may provide environmental advantages when appropriate wastewater treatment and chemical management practices are implemented.

Limitations of the study

This study has several limitations. The recovered products obtained from the hydrometallurgical process should be considered as mixed-metal products rather than individual metal products, limiting their direct application in battery manufacturing without further purification and compositional adjustment. In addition, the EIA was conducted within a defined system boundary that excluded reagent recovery and recycling strategies, as well as battery usage and transportation prior to the recycling stage.

Recommendations for future work

Future studies should focus on further purification and product upgrading strategies, such as selective precipitation or electrochemical pretreatment, to remove impurity metals and achieve battery-grade specifications. In addition, wastewater-related impacts such as chemical oxygen demand (COD), which were not included in the present assessment, together with the integration of reagent recovery and recycling strategies, and an expanded assessment scope covering upstream and downstream processes, should be further investigated to improve the economic and environmental performance of the proposed process.

CONCLUSIONS

This study demonstrated the feasibility of recovering valuable metals from 10 kg BM obtained from spent LIBs through hydrometallurgical processing involving leaching, sequential precipitation, pH adjustment, and evaporation. Leaching with H_2SO_4 and H_2O_2 achieved high extraction efficiencies for Al, Cu, Co, Li, Mn, and Ni of 87.48, 98.43, 98.93, 98.69, 98.77, and 98.50%, respectively, demonstrating the high recovery efficiency of the proposed process. Sequential precipitation at different pH conditions (pH 7, 9, and 12) improved selective metal separation efficiency, while alkalinity adjustment at pH 14 with NaOH and evaporation enhanced Li concentration within the remaining solution, with 56.88% of the initial Li content remaining in the Li-rich solution, indicating that a substantial fraction of Li was redistributed to the precipitated solids during metal separation. The preliminary EIA indicated that the leaching and precipitation stages were major contributors to the overall environmental burden due to high chemical consumption, energy demand, and waste generation, while reactor heating and evaporation also contributed significantly. Compared with primary production of battery-related materials, the proposed process showed lower environmental impacts within the evaluated system boundary, indicating its potential to reduce the demand for newly produced battery materials and support a more circular approach for the recovery of LIBs. Overall, the proposed conventional hydrometallurgical process provides a relatively simple and scalable approach for the sequential recovery of multiple valuable metals from BM, with potential for integration into existing recycling facilities.

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