www.envsciarch.com

ENVIRONMENTAL SCIENCE ARCHIVES
ISSN: 2583-5092
Volume V Issue 2, 2026

Received: 2026/07/08
Accepted: 2026/08/25
Published: 2026/09/01

check for updates

REVIEW

OPEN ACCESS

Recycling of Spent Lithium-Ion Batteries through Sustainable and Advanced Processing Technologies

Inamul Haq[1], Modabbir Alam[2] and Naved Ahsan[3]

[1]PhD Scholar, Jamia Millia Islamia University, New Delhi, India
[2]PhD Scholar, Jamia Millia Islamia University, New Delhi, India
[3]Professor, Jamia Millia Islamia University, New Delhi, India
*Correspondence for materials should be addressed to IH (email: inamul2400695@st.jmi.ac.in)

Abstract

Lithium-ion batteries (LIBs) are rapidly gaining acceptance in electric vehicles, energy storage systems and portable electronics, and have brought the need for sustainable end-of-life management to a new level. Again, there is significant recovery value for spent batteries: NMC and NCA cathodes contain 8-15% cobalt and nickel and 1.3-1.9% lithium by mass and LFP cells contain over 43% iron/steel with virtually no cobalt content; therefore, recycling operations need to be chemistry-specific. Hydrometallurgical leaching with 1–4 M inorganic acid (H_2SO_4, HCl, HNO_3) and H_2O_2 as a reductant is able to recover 95–100% of Li, Co, Ni and Mn under moderate conditions (70-95°C and 60-240 min), although pyrometallurgical (smelting) process works above 1000C and tolerates feedstock but losses a substantial amount of lithium and manganese to the slag phase. A number of organic acids (citric, oxalic, lactic and malic acid), which enable comparable Li recovery of 80–100% at 60–100°C, and Co recovery of 80–98%, can also reduce the toxicity of the reagents, but the emergence of deep eutectic solvents (DESs) allows for lower generation of by-products and reactions at even milder conditions (60–90°C), while also presenting challenges in solvent regeneration and selectivity. The use of acidophilic microorganisms like *Acidithiobacillus ferrooxidans* and *Aspergillus niger* is an alternative technology for bioleaching, which can extract 85-95% of Li and Co at ambient conditions with a pH range of 1.2-3.5 and with slower processing time. Selective chemical precipitation is achieved in a controlled pH process, allowing for the ability to separate valuable metals from complex leachates in an economical and scalable fashion downstream. This review brings together the above process routes and compares their recovery efficiencies, consumptions of reagents/energy and scalability, and proposes a hybrid thermal-hydrometallurgical route as the most promising one to reach an economically viable, low carbon LIB recycling.

Keywords: Recycling; Hydrometallurgy; Pyrometallurgy; Leaching; Bioleaching; Cathode; Lithium-ion; Sustainability; Circular-economy

Introduction

Lithium-ion batteries (LIBs) are playing a significant role in various applications, such as electric mobility, portable electronic devices, renewable energy storage, and industrial systems, leading to their fast growth in recent years (Hamdan et al., 2024). They are widely used due to their favorable electrochemical characteristics such as high energy density, long cycle life, low self-discharge and good power-to-weight ratio. The properties make LIBs a key technology for the transition to electrified and low carbon energy systems (Liu et al., 2014). Although there are numerous advantages to using LIBs, recent growth in their use has created significant end-of-life (EOL) management problems (Shahjalal et al., 2021). The increasing stockpile of spent batteries is an environmental and resource issue. Lithium-ion battery (LIB) consists of a complex mixture of materials, including lithium, cobalt, nickel, manganese, graphite, copper, aluminum, polymer binders, separators, and electrolyte solvents (He et al., 2019).

Many of these materials are non-renewable and come from areas with geopolitical tensions and/or ecological fragility. An example of this is the fact that a significant amount of the production of cobalt is taking place in the Democratic Republic of Congo and lithium is being extracted mainly in South America within the Lithium Triangle (Brink et al., 2020).

The extraction and processing of these resources are energy intensive and often associated with environmental damage and social issues. Moreover, if spent LIBs are not disposed of or handled properly, they can create fire hazards, release toxic fumes (including fluorinated) and contaminate the soil and water with metal leaching (Krishnan et al., 2024).In this context, the development of effective recycling technologies is crucial. The recovery of materials from EoL LIBs helps to minimize primary resource extraction, reduces impacts on the environment, and supports the circular economy goals (Srinivasan et al., 2025). To design efficient recycling pathways, however, it is essential to have a detailed knowledge of the chemical composition of different battery chemistries (Choi and Rhee, 2020). Table 1 shows the mass distribution of the main components for the key commercial LIB chemistries (Winslow et al., 2017), such as NCA ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$), LMO ($LiMn_2O_4$), NMC ($LiNiMnCoO_2$), LCO ($LiCoO_2$) and LFP ($LiFePO_4$). The different compositions of these systems have important implications for recycling strategies. LCO batteries have relatively high content of Cobalt, which may become economically viable for the recovery of Cobalt, but may also introduce ethical and environmental issues in the supply chain. On the other hand, LFP batteries have a high content of iron and phosphorus, and a small amount of cobalt and nickel, reducing the value of rare earth metals and other critical materials. NMC and NCA chemistries also have significant levels of nickel, cobalt and manganese, which can be recovered in conjunction with other high value metals. Furthermore, the high proportion of graphite that is found in all chemistries emphasizes the need to account for carbon recovery in integrated recycling processes (Li et al., 2020). Process selection is directly affected by these differences in materials. Co- and Ni-rich cathode chemistries are especially well suited for hydrometallurgical methods which allow selective and efficient extraction of metals (Wang et al., 2022). On the other hand, batteries with lower content of valuable metals, like LFP and LMO, might need optimization of the process, cost-reduction measures, or large-scale processing to become economically viable (Kasri et al., 2024). Recycling systems need to be flexible and chemistry-specific, therefore. Overall, it is important to create a flexible, environmentally friendly, and composition-aware recycling system for sustainable LIB management. A scheme of this kind should be flexible enough to cater for differences in battery technology; should maximize the recovery of materials of value; and should be in keeping with national objectives of resource security, clean energy development and minimisation of waste.

Table 1. Mass Percentage Composition of Metals and Materials in Different Lithium-Ion Battery Chemistries (Winslow et al., 2017).

Material	NCA	LMO	NMC	LCO	LFP
Aluminum	21.9	21.7	22.72	5.2	6.5
Cobalt	2.3	-	8.45	17.3	-
Copper	13.3	13.5	16.6	7.3	8.2
Iron/Steel	0.1	0.1	8.79	16.5	43.2
Lithium	1.9	1.4	1.28	2.0	0.2
Manganese	-	10.7	5.86	-	-
Nickel	12.1	-	14.84	1.2	-
Binder	3.8	3.7	1.39	2.4	0.9
Carbon (non-graphite)	2.4	2.3	3.47	6.0	2.3
Electrolyte + Solvent	11.7	11.8	1.66	14.0	14.9
Fluoride	-	-	4.99	-	-
Graphite	16.5	16.3	5.6	23.1	13.0
Thermal Insulation	1.2	1.2	-	-	-
Oxygen	8.3	12.4	4.52	-	-
Phosphorus	-	-	2.04	-	5.4
Plastics	4.2	4.5	3.29	4.8	4.4

Note: NCA = LiNio.8Coo.15Alo.05O2; LMO = LiMn2O4; NMC = LiNiMnCoO2; LCO = LiCoO2; LFP = LiFePO4.

For reference, Figure 1 depicts a schematic cross section of a lithium-ion cell with its internal structure and material architecture for reference (Yu et al., 2023). The internal structure of a typical LIB cell consists of a number of functionally different elements. Typically made from aluminum, steel or plastic, the case offers containment and support. While the anode is normally made of graphite, silicon or titanium-related materials, the cathode, which is based on $LiNiO_2$, $LiCoO_2$, $LiMn_2O_4$, $LiFePO_4$ or NMC/NCA composites, will determine the performance, energy density, and recyclability of the battery. The electrodes are held on current collectors made of aluminum foil and copper foil respectively. Electrolyte is a mixture of flammable and toxic organic solvents (ethylene carbonate, propylene carbonate and dimethyl carbonate) and lithium salts ($LiPF6$, $LiBF_4$); this combination requires special care both in the handling of the battery and in its recycling. The separator is usually polyethylene or polypropylene that prevents short circuiting between the electrodes, and the binders are PVDF, PTFE or SBR that are used to hold the electrode in place. Additionally, conductive additives, such as graphene, carbon black and carbon nanotubes, improve the electron transport in the electrode matrix.Electrodes: Aluminum foil (cathode) and Copper foil (anode).

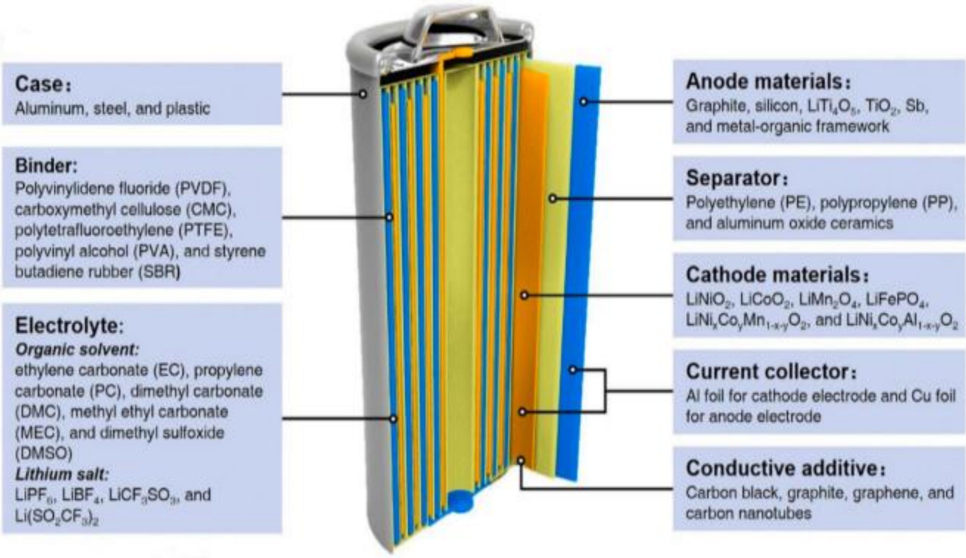

Fig. 1. Structural Diagram of Typical Cylindrical Lithium-Ion Batteries (Yu et al., 2023)

This visual decomposition highlights the multi-layered nature of LIBs and the heterogeneity of the materials, which each have different recovery, reuse and environmental implications. It also underscores the fact that LIB recycling isn't a generic process, and instead is a chemical and component-specific engineering process. The schematic flow diagram of the mechanical–thermal processing route to recycle spent lithium-ion batteries is shown in Figure 2. The discharged LIBs are dried and shredded in N_2, then sieved, crushed and ball milled sequentially to release the electrode materials. Physical separation methods such as magnetic, eddy current and electrostatic separation are used to extract Fe, Al, Cu and plastics, while in thermal treatment (200–600 °C), it is possible to remove the electrolyte and produce black mass. Final vibro-sieving step results in the purified black mass for further hydrometallurgical processing.

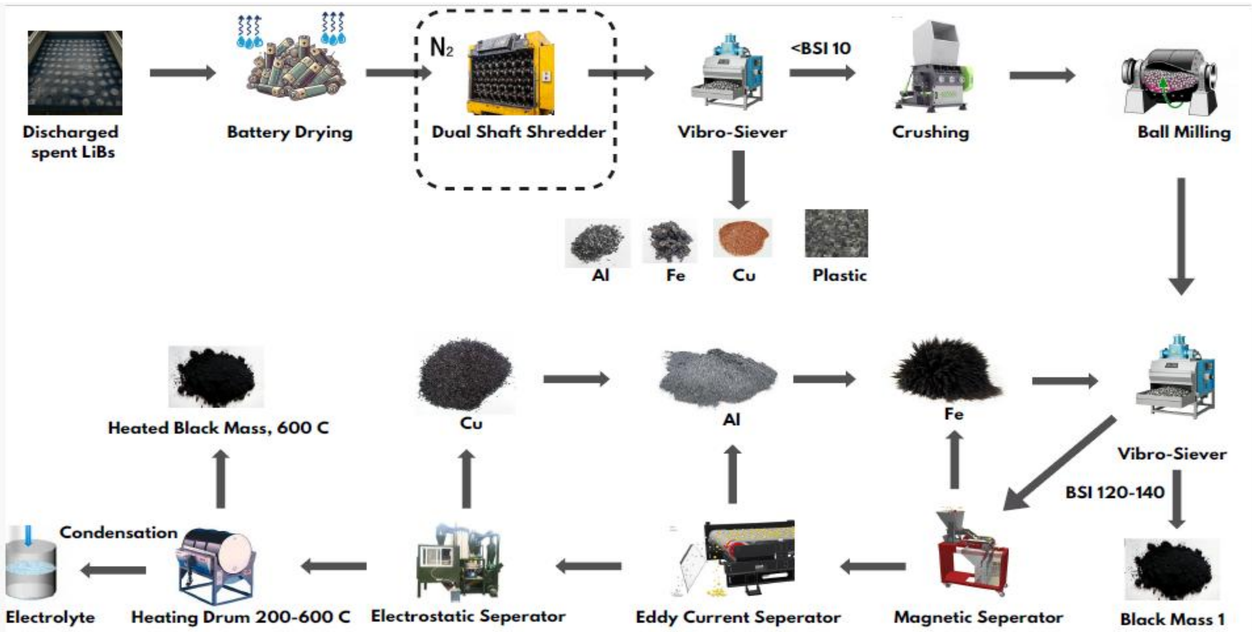

Fig. 2. Illustration showing the operations required to prepare the black mass

LIB Recycling Approaches

Lithium-ion batteries (LIBs) recycling techniques can be classified as direct recycling and indirect recycling, which in turn can be subdivided into pyrometallurgical, hydrometallurgical and hybrid recycling. The different methods have their own pros and cons, including battery chemistry, process economics, scalability and environmental impact (Fan et al., 2020). It is very important to understand the principles, technical details and problems of each category to select or design an optimized LIB recycling framework (Xu et al., 2007) (Wang et al., 2014).

Direct recycling

Direct recycling means that cathode materials can be recovered and reused from the battery without to reducing them to elemental or ionic form (Wang et al., 2014). The aim is to retain the structure of active materials (e.g., $LiCoO_2$, $LiFePO_4$, NMC) as they can be directly used in new batteries (Fan et al., 2020). This process is energy- and material-efficient, thereby reducing the energy and chemical demands for traditional processes, thereby favoring the circularity of the material.

Among various approaches, relithiation to account for lithium loss, thermal treatment to regenerate crystal structure, and surface recoating to enhance electrochemical activity are typical. The processes are designed to restore almost the original function without leading to material disintegration. Direct recycling is more energy efficient and material conserving than indirect recycling. However, it is limited at a large-scale due to the variability in feedstock and sensitivity to impurities, which makes it hard to standardize the feedstock chemistry and state-of-health, and complicates the quality of the product by the presence of the residual contaminants (Zheng et al., 2018; Lv et al., 2018).

Indirect recycling

Indirect recycling is the decomposition of the battery into elemental and/or ionic components and the purification and recovery. The method is tolerant of mixed chemistries and damaged cells, and can be used in large-scale industrial processing (Harper et al., 2019). Pyrometallurgy is an indirect process with high temperature (>1000 °C) that is used to thermally treat, smelt and reduce battery materials into metallic alloys (e.g. Co–Ni–Cu). Strong and able to utilize current metallurgical facilities, however, lithium and aluminum tend to be distributed in the slag, thus requiring extra recovery processes. It has the benefits of feedstock tolerance and simplicity of operation; however, it has significant drawbacks for its sustainability, including high energy requirement, carbon emissions, and less than full recovery of lithium and manganese.

In addition to this, there is another alternative method, namely hydrometallurgy, which is more selective because it is based on leaching of metals in an aqueous solution, for example, H_2SO_4, HCl or organic acids that contain a reductant, such as H_2O_2, to dissolve metals in black mass (Zante et al., 2020). Further separation processes, such as solvent extraction, ion exchange and selective precipitation, allow the recovery of Li, Co, Ni and Mn in the form of high-purity salts. This approach has usually greater metal recovery (more than 90%) and it reduces carbon emissions as compared to pyrometallurgy. Bioleaching, deep eutectic solvents and ionic liquids are other emerging technologies that further increase sustainability (Zante et al., 2020). But the key issues of process control, reagent management, and effluent treatment are still some challenges.

Hybrid processes involve thermal pre-treatment followed by hydrometallurgical recovery to better leach the metals and to be more selective and less reagent consuming. Future developments focus on the modular integration of mechanical, thermal and chemical operations as well as on the use of artificial intelligence for sorting and process optimization in order to make the process more flexible and economical (Wood III et al., 2014).

Thermal Pre-Treatment

It is commonly employed as mechanical processing to chemical recovery transition phase. The second stage is a process of controlled heating to break down organic binders, burn off electrolyte residues and to oxidise some battery components (Bhar et al., 2023). The purpose and results of this step can be different, depending on the atmosphere (inert, pyrolysis, or oxidative, calcination). Thermal treatment can be advantageous to achieve the structural integrity of some active material which can be re-used, while oxidative treatment can be beneficial for recovering metal through modifying its chemical state to make it more leachable in inert conditions. Normal process temperatures are 300 to 700°C, and are carefully optimized to ensure that volatile organics are readily broken down while minimal loss of material is experienced. Thermal treatment also helps to minimize the risk of hazardous gas emissions during hydrometallurgical leaching of the black mass, as well as to make handling the black mass safer (Schwich et al., 2021). The emissions from this phase are subjected to gas scrubbing or filtration to meet the environmental standards, especially those related to fluorinated compounds or volatile organics (Mousa et al., 2022).

Leaching Technologies

This is an essential step in the recycling of lithium-ion batteries (LIBs) especially in hydrometallurgical processes (Fan et al., 2020). It includes a process of dissolving metal components from black mass in a liquid medium to produce a leachate containing valuable elements such as lithium, cobalt, nickel and manganese (Zhang et al., 2018). This process enables selective recovery of metals which can be selectively purified and precipitated. There are actually a number of techniques with different advantages and disadvantages, depending on the leaching agent employed. The inorganic acid leaching, organic acid leaching, deep eutectic solvent (DES) leaching, and bioleaching are the leaching methods (Lv et al., 2018).

Inorganic Acid Leaching

The most developed technology for recovering metals from spent LIBs is by inorganic acid leaching, which generally uses H_2SO_4, HCl, HNO_3 as leaching agents and sometimes uses reducing agents like H_2O_2, $NaHSO_3$ or $Na_2S_2O_3$ to increase the leaching rate. The sulfuric acid systems have a high level of recovery (> 95%) for Li, Co, Ni and Mn under moderate conditions (50-90 °C) and are the most widely used. Extraction efficiencies are similarly high and leaching times are much shorter with hydrochloric acid; nitric acid shows high extraction efficiencies for lithium and cobalt but has less application because of its high reagent costs and NOx related issues. Although inorganic acid leaching has good kinetics and metal recovery, it generates a lot of acidic effluents and is not environmentally sustainable at the industrial scale because of the demanding wastewater treatment.

Table 2. Hydrometallurgical Recycling using different Inorganic Acid

Spent LIB	Leaching reagent	Experimental condition	Yield	Reference
Spent NMC cathode	2 M H_2SO_4 and 10% H_2O_2	70°C 90 min, L:S 30 g/l	Li 99.76%, Ni 98.56%, Co 98.46%, Mn 98.62%	Chen et al., 2018
MIX	1 M H_2SO_4 + 0.075 $NaHSO_3$	95°C for 240 min, L:S 20 g/L	Li 96.7%, Co 91.6%, Ni 96.4%, Mn 87.9%	Meshram et al., 2015
LCO	3 M H_2SO_4 + 0.25 $Na_2S_2O_3$	90°C for 180 min, L:S 66.7 g/L	Li 99.71%, Co 99.95%	Wang et al., 2012
LCO	3 M H_2SO_4 + 5% ethanol	90°C for 160 min, L:S 20 g/L	Li > 99%, Co > 99%	Zhao et al., 2019
LCO	3 M H_2SO_4 + 0.4 g/g glucose	95°C for 120 min, L:S 25 g/L	Li 96%, Co 98%	Chen et al., 2018
MIX	4 M HCl	80°C for 60 min, L:S 20 g/L	Li 99.5%, Co 99.9%, Ni 99.8%, Mn 99.8%	Wang et al., 2009
LMO	2 M HNO_3	80°C for 120 min	Li 100%, Mn 95%	Castillo et al., 2002
LCO	1 M HNO_3 + 1.7% H_2O_2	75°C for 30 min, L:S 20 g/L	Li > 95%, Co > 95%	Lee and Rhee, 2002

Note: L:S = liquid-to-solid ratio (g/L).

Organic Acid Leaching

Organic acids leaching is an eco-friendly method as compared to mineral acids, which utilizes less harmful reagents like Citric acid, Oxalic acid, Lactic acid, Malic acid and Acetic acid which are biodegradable. These acids are leaching agents, complexing agents and are known to form stable metal–organic complexes. High recoveries are frequently difficult to obtain, because their lower acidity results in the need for higher temperatures or reductants (such as H_2O_2). Optimized systems can achieve recovery rates of over 95% for Li, Co, Ni and Mn, and biomass-assisted systems improve sustainability and further driving the recovery rates. O rga nic systems are slower than the inorganic acids but produce fewer hazardous effluents, and are appealing for recycling in an environment-conscious manner.

Table 3. Hydrometallurgical Recycling using different Organic Acid

Spent LIB	Leaching reagent	Experimental condition	Yield	Reference
LCO	2 M citric acid, 1.25% H_2O_2	60 °C for 5 h., S/L: 30 g/L	Li 99.80%, Co 96.46%	Golmohammadzadeh et al., 2017
NMC	1.5 M lactic acid, 0.5% H_2O_2	70 °C for 20 min, L:S 20 g/L	Li 97.7%, Ni 98.2, Co 98.9, and Mn 98.4%	Li et al., 2017
LCO	1.0 M oxalate, 10% H_2O_2	80 °C for 120 min, S:L 50 g/L,	98% reaction efficiency	Sun et al., 2012
Spent Cathode	1.5 M Citric Acid + 5 g L^{-1} orange peel	100 °C for 240 min, S:L 25 g/L,	Li 80.5%, Co 91.3%, Mn 92.2%, Ni 90.1%	Wu et al., 2020
LCO	100 Mm Citric Acid + 20mM Ascorbic Acid	80 °C for 360 min, S:L 2 g/L,	Li 100%, Co 80.0%	Nayaka et al., 2014
LCO	1.5 M Malic Acid + 12 gL^{-1} grape seed	80 °C for 180 min, S:L 20 g/L,	Li 99.0%, Co 92.0%	Zhang et al., 2018
LCO	1.5 M Citric Acid + 12 g L^{-1} tea waste	90 °C for 120 min, S:L 30 g/L,	Li 98.0%, Co 96.0%	Chen et al., 2015

Note: L:S/S:L = liquid-to-solid (or solid-to-liquid) ratio (g/L)

Deep Eutectic Solvent (DES) Leaching

Deep eutectic solvents (DESs) are new green leaching materials, which are composed of a hydrogen bond donor (e.g., urea, glycerol) and a quaternary ammonium salt (e.g., choline chloride). They are able to be recycled, tuneable, and low volatiles, and are suitable for selective metal extraction. Moderate temperature (60–90 °C) and low level of toxic by-products have been reported in the effective leaching of Li, Co and Ni from black mass. However, there are some challenges in solvent regeneration, selectivity, and process stability for large-scale applications (Batkal et al., 2025).

Bioleaching

Bioleaching uses the microorganisms capable of producing acid (such as *Acidithiobacillus ferrooxidans*, *Aspergillus niger*) to dissolve the metals in mild acidic condition (pH 1.2-3.5). Low energy, low chemical consumption, the recovery rate of Li and Co is 85-95% under the optimized conditions. The process is environmentally friendly, but it does not proceed as quickly as chemical leaching and has to be carefully managed by microbes. It has a good potential for sustainable and decentralized recycling systems.

Table 4. Hydrometallurgical Recycling using different Microorganism

Spent LIB	Micro organism	Experimental condition	Yield	Reference
LCO	*Aspergillus niger*	pH 3.5, S:L 2.5 g/l, 3 days	Li 100%, Co 82%	(Biswal et al., 2018)
LCO	*Aspergillus niger*	pH 6, S:L 10 g/l, 16 days	Li 95%, Co 45%, Mn 70%, Ni 38%	(Horeh et al., 2016)
LCO	*Leptospirillum ferriphilum* and *Sulfobacillus thermosulfidooxidans*	pH 1.25, S:L 50 g/l, 1.5 days	Li 98%, Co 96%	(Liu et al., 2020)
LCO	Unidentified sulfur-oxidizing and iron-oxidising bacteria	pH 1.5, S:L 10 g/l, 6 days	Li 73%, Co 80%	(Xin et al., 2009)
LCO	*Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans*	pH 1.5, S:L 10 g/l,35 days	Li 85%, Co 67%	Marcinčáková et al. (2016)
LCO	*Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans*	pH 1.5, S:L 40 g/l, days	Li 99.2%, Co 50.4%	(Heydarian et al., 2017)
LCO	*Acidithiobacillus ferrooxidans*	pH 2, S:L 10 g/l, 0.5 days	Li 67%, Co 19%, Mn 50%, Ni 34%	(Nazerian et al., 2023)
LCO	*Acidithiobacillus ferrooxidans*	pH 2, S:L 100 g/l, 3 days	Li 60%, Co 94%	(Roy et al., 2020)
NMC	*Acidithiobacillus ferrooxidans*	pH 2, S:L 100 g/L, 3 days	Li 89% , Ni 90% , Co 82% , Mn 92%	(Roy et al., 2020)

Note: S:L = solid-to-liquid ratio (g/L)

Downstream Processing Techniques

Dissolved metals are recovered and purified through downstream processing after the leaching. The methods that are used separate and concentrate complex leachates to lithium, cobalt, nickel, and manganese. The choice of material is based on the concentration of metal, chemistry of the solution, the desired purity, the cost and environmental factors. Solvent extraction, precipitation, ion exchange, membrane separation and electrochemical recovery are some of the common methods used.

Solvent Extraction

Solvent extraction has demonstrated to be a well-proven and industrially scaleable process for the selective separation of metal ions from LIB leachates using extractants like D2EHPA, Cyanex 272/301, Cyanex IL 102, TODGA or Alamine 336. It is done in a series of extraction and stripping processes to obtain high selectivity and purity in the product. It is especially good for the separation of Co/Ni/Mn, because these three elements are extracted under different pH conditions under controlled conditions. High metal recoveries and good selectivity are reported for the systems, and the results are highly sensitive to the type of extractant, the properties of the diluent and the phase ratio. Even though efficient and well-developed, solvent extraction is a pH and temperature sensitive process and demands careful handling of solvents to reduce environmental and operational risks.

Ion Exchange and Membrane Techniques

Another common technique used in metal separation is ion exchange, which is based on the ability of solid resins to selectively adsorb ions. This is achieved by exchanging metal ions in the leachate with metal ions (with similar charges) on the surface of functionalized ion-exchange resins. The resins can be chemically modified to target specific metals and this is commonly done (Zhang et al., 2018). This process is efficient for the recovery of low concentration metals (Fan et al., 2020), for example lithium from a mixed-metal solution.

Table 5. Extraction of Critical Metal using different Solvents

Solvents	Dilutant	Extraction %	Optimal Condition	References
Cyphos IL 102	Toluene	Li 99.6%, Co 98.6%, Mn 99.9%	10 min, 10 C - 60 C, O/A 1/1	Dhiman et al.,2019
D2EHPA (20 %vol)	Kerosene	Co 1%,, Ni <0.5%, Mn 69.3%	90 min, 40 C, O/A 1/1	Nadimi et al., 2019
TODGA,	Kerosene	Mn 99%	O/A 1/1	Zante et al., 2020
D2EHPA and Alamine 336	Kerosene	Co 98.8%, Ni 92.2%, Mn 91.3%	2 for Co, 1 for Mn	Ngayun et al., 2020
Alamine 336	Kerosene	Co 96.2%	O/A 2	Xuan et al., 2021
Cyanex 301	Kerosene	Ni 98.5%	–	Zheng et al., 2021

Note: O/A = organic-to-aqueous phase ratio

Additionally, membrane technologies such as nanofiltration, electrodialysis, and diffusion dialysis processes are under investigation for LIB recycling because they allow the separation of ions based on the size, charge and diffusivity (Zante & Boltoeva, 2020). These techniques have the benefits of low chemical consumption, continuous operation, etc. But there are drawbacks such as fouling of the membranes, low selectivity for some ions, and high initial setup costs (Harper et al., 2019). The addition of ion exchange or membrane to other downstream processes can achieve greater recovery and minimize environmental effects (Lv et al., 2018).

Precipitation Processes

Chemical precipitation is one of the simplest and most economical methods of extracting metals from leach solutions. This approach involves a variety of chemicals, including sodium carbonate, oxalic acid, or ammonium phosphate, that react with certain metal ions in the leachate to create insoluble compounds that can be removed through filtration or centrifugation (Fan et al., 2020; Zhang et al., 2018). Examples include the precipitation of lithium as lithium carbonate, cobalt and nickel as oxalates or hydroxides (Wang et al., 2022). Precipitation is very efficient for bulk metal removal and purification, however, it is usually not very selective for separating metals that have similar properties (Lv et al., 2018). Solution pH, reagent concentration, temperature and competing ions have significant influence on the efficiency of this process (Zante & Boltoeva, 2020). Further purification, for example via redissolution or recrystallization, might be needed to produce battery-grade material purity. Precipitation is often used in conjunction with other separation methods such as solvent extraction to increase selectivity and yield (Harper et al., 2019).

Electrochemical Recovery

Electrochemical methods are used, such as electrowinning and electrodeposition, to directly extract metals from the leachate using an electric current. This method particularly works well for high purity metals such as cobalt and nickel (Fan et al., 2020; Zhang et al., 2018). The process setup consists of an electrolytic cell composed of an anode and cathode immersed in leachate; the current density, electrolyte composition, and electrode material are important factors to consider and will affect the rate and purity of deposition (Zheng et al., 2018). The electrochemical recovery has many advantages, such as few chemicals, high selectivity and direct output of metal (Lv et al., 2018). In general, however, it is more energy intensive and not very suitable for the recovery of lithium, requiring extra steps or other methods (Zante & Boltoeva, 2020). Recent research has investigated the possibility of combining renewable energy with electrochemical cells to increase the sustainability of this approach (Harper et al., 2019). Optimized, electrochemical recovery is an important last step to generating battery-grade materials for use in the production of LIBs.

Scalability and Industrial Relevance

To be industrially viable, LIB recycling processes must be stable, have high throughput, and be economically competitive under variable feedstock conditions. Scalability potential is the highest for hydrometallurgy because of the moderate operating temperatures (<100 °C), the ability to be integrated in continuous stirred-tank or reactor cascade systems, and being integrated into existing solvent extraction and precipitation circuits. The modular design allows for incremental growth and flexibility to new cathode chemistries.

Challenges are related to feedstock heterogeneity, impurity handling (binders, fluorinated species, Al/Cu residues) and reagent use. Closed-loop recovery of acid, optimization of reductant, efficient lithium precipitation, and minimal discharge of effluent are the pillars to achieving industrial viability. For large-scale production, the use of process control strategies including real-time pH measurement, redox potential control and automatic dosing are critical in ensuring selectivity and purity of the product.

Kinetics and chemical demands can be optimized, which increases throughput through hybrid thermal–hydrometallurgical integration. In the end, scalable LIB recycling will depend on feedstock-tolerant hydrometallurgical platforms with safe and sustainable environmental impact, high recovery efficiency and low specific energy consumption, and high-quality battery-grade materials.

Key challenges and bottlenecks

Although lithium-ion battery (LIB) recycling has made significant strides, there are significant challenges to scaling and commercializing recycling. The process standardization and automation and the efficiency of recovery are hindered by material heterogeneity in chemistries (LCO, NMC, NCA, LFP), formats and states of health. Poorly labeled and mixed waste streams compromise purity of products and add up to reagent consumption, pointing to the need for flexible, chemistry-driven recycling systems.

Pyrometallurgy is industrially-ready, but energy intensive and inefficient for lithium recovery. Variability of feedstock and the need for process control are the main limitation of direct recycling. Acid-based hydrometallurgy processes produce secondary waste and complex chemical management, with low environmental and economic performance at scale, while high selectivity and recovery efficiency are achieved. Other factors impede implementation at the system level. Less process efficiencies and investment confidence due to fragmented collection networks, less integration between manufacturers and recyclers, and regulatory inconsistencies. Furthermore, there is no harmonisation on material quality of recycled materials which hampers reintegration in battery production.

Taken together these challenges make it clear that there is a pressing research need for developing scalable, selective, and environmentally optimized hydrometallurgical processes that can be resilient to feedstock variability, be less chemically intensive, and fit in the changing regulatory and supply chain environments. The gaps need to be addressed to realize economically viable, industrially deployable and circular LIB recycling systems.

Conclusion

This review has evaluated the principal hydrometallurgical, pyrometallurgical, and hybrid pathways for recycling spent lithium-ion batteries, establishing that no single route simultaneously optimises recovery efficiency, reagent toxicity, energy demand, and industrial scalability. Compositional analysis confirms that recyclable value is strongly chemistry-dependent: NMC and NCA cathodes contain 8–15 wt% cobalt and nickel and 1.3–1.9 wt% lithium, whereas LFP cells contain over 43 wt% iron/steel and negligible cobalt, indicating that process selection must be tailored to feedstock chemistry rather than standardised across battery types. Inorganic acid leaching remains the most efficient route, with optimised systems (2 M H_2SO_4, 10% H_2O_2, 70°C, 90 min) recovering 95–100% of Li, Co, Ni, and Mn, albeit at the cost of substantial acidic effluent. Organic-acid systems achieve comparable recoveries—80–100% for lithium and 80–98% for cobalt—under milder conditions (60–100°C), offering a reduced environmental footprint, while deep eutectic solvents operate at similarly moderate temperatures (60–90°C) with lower toxic-by-product generation, though solvent regeneration and selectivity remain unresolved barriers to industrial deployment. Bioleaching recovers 85–95% of Li and Co under ambient conditions, providing a low-energy but comparatively slow alternative suited to decentralised operation. Pyrometallurgical smelting (>1000°C) offers superior feedstock tolerance but results in substantial lithium and manganese losses to the slag phase, limiting its suitability where lithium recovery is the primary objective. These findings indicate that hybrid systems integrating thermal pre-treatment with hydrometallurgical or biological leaching represent the most viable pathway toward reconciling feedstock flexibility with high metal recovery. Future research should prioritise reagent recovery within hydrometallurgical circuits, pilot-scale validation of organic-acid and deep eutectic solvent systems, and techno-economic assessment of bioleaching at industrial throughput, in order to advance economically viable, low-carbon recycling infrastructure for lithium-ion batteries.

References

Batkal A, Kamunur K, Mussapyrova L, et al. (2025) Efficient extraction of lithium, cobalt, and nickel from nickel-manganese-cobalt oxide cathodes with cholin chloride/pyrogallol-based deep eutectic solvent. Recycling 10(3):88. DOI: 10.3390/recycling10030088.

Beghi M, Braghin F and Roveda L (2023) Enhancing disassembly practices for electric vehicle battery packs: a narrative comprehensive review. Designs 7(5):109. DOI: 10.3390/designs7050109.

Bhar M, Ghosh S, Krishnamurthy S, et al. (2023) A review on spent lithium-ion battery recycling: from collection to black mass recovery. RSC Sustainability 1(5):1150–1167. DOI: 10.1039/d3su00086a.

Biswal BK, Jadhav UU, Madhaiyan M, et al. (2018) Biological leaching and chemical precipitation methods for recovery of Co and Li from spent lithium-ion batteries. ACS Sustainable Chemistry & Engineering 6(9):12343–12352. DOI: 10.1021/acssuschemeng.8b02810.

Castillo S (2002) Advances in the recovering of spent lithium battery compounds. Journal of Power Sources 112(1):247–254. DOI: 10.1016/s0378-7753(02)00361-0.

Chen M, Ma X, Chen B, et al. (2019) Recycling end-of-life electric vehicle lithium-ion batteries. Joule 3(11):2622–2646. DOI: 10.1016/j.joule.2019.09.014.

Chen W-S and Ho H-J (2018) Recovery of valuable metals from lithium-ion batteries NMC cathode waste materials by hydrometallurgical methods. Metals 8(5):321. DOI: 10.3390/met8050321.

Chen X, Luo C, Zhang J, et al. (2015) Sustainable recovery of metals from spent lithium-ion batteries: a green process. ACS Sustainable Chemistry & Engineering 3(12):3104–3113. DOI: 10.1021/acssuschemeng.5b01000.

Choi Y and Rhee S-W (2020) Current status and perspectives on recycling of end-of-life battery of electric vehicle in Korea (Republic of). Waste Management 106:261–270. DOI: 10.1016/j.wasman.2020.03.015.

Dhiman S and Gupta B (2019) Partition studies on cobalt and recycling of valuable metals from waste Li-ion batteries via solvent extraction and chemical precipitation. Journal of Cleaner Production 225:820–832. DOI: 10.1016/j.jclepro.2019.04.004.

Fan E, Li L, Wang Z, et al. (2020) Sustainable recycling technology for Li-ion batteries and beyond: challenges and future prospects. Chemical Reviews 120(14):7020–7063. DOI: 10.1021/acs.chemrev.9b00535.

Garg N, Pekkinen S, Martínez González E, et al. (2024) Enhanced electrochemical discharge of Li-ion batteries for safe recycling. Sustainable Energy & Fuels 8(12):2777–2788. DOI: 10.1039/d4se00125g.

Golmohammadzadeh R, Rashchi F and Vahidi E (2017) Recovery of lithium and cobalt from spent lithium-ion batteries using organic acids: process optimization and kinetic aspects. Waste Management 64:244–254. DOI: 10.1016/j.wasman.2017.03.037.

Hamdan A, Daudu C, Fabuyide A, et al. (2024) Next-generation batteries and U.S. energy storage: a comprehensive review: scrutinizing advancements in battery technology, their role in renewable energy, and grid stability. World Journal of Advanced Research and Reviews 21(1):1984–1998. DOI: 10.30574/wjarr.2024.21.1.0256.

Harper G, Sommerville R, Kendrick E, et al. (2019) Recycling lithium-ion batteries from electric vehicles. Nature 575(7781):75–86. DOI: 10.1038/s41586-019-1682-5.

He K, Zhang Z-Y, Alai L, et al. (2019) A green process for exfoliating electrode materials and simultaneously extracting electrolyte from spent lithium-ion batteries. Journal of Hazardous Materials 375:43–51. DOI: 10.1016/j.jhazmat.2019.03.120.

Heydarian A, Mousavi SM, Vakilchap F, et al. (2017) Application of a mixed culture of adapted acidophilic bacteria in two-step bioleaching of spent lithium-ion laptop batteries. Journal of Power Sources 378:19–30. DOI: 10.1016/j.jpowsour.2017.12.009.

Horeh NB, Mousavi SM and Shojaosadati SA (2016) Bioleaching of valuable metals from spent lithium-ion mobile phone batteries using *Aspergillus niger*. Journal of Power Sources 320:257–266. DOI: 10.1016/j.jpowsour.2016.04.104.

Kasri MA, Mohd Halizan MZ, Harun I, et al. (2024) Addressing preliminary challenges in upscaling the recovery of lithium from spent lithium ion batteries by the electrochemical method: a review. RSC Advances 14(22):15515–15541. DOI: 10.1039/d4ra00972j.

Kaya M and Delavandani H (2025) State-of-the-art lithium-ion battery pretreatment methods for the recovery of critical metals. Minerals 15(5):546. DOI: 10.3390/min15050546.

Krishnan R and Gopan G (2024) A comprehensive review of lithium extraction: from historical perspectives to emerging technologies, storage, and environmental considerations. Cleaner Engineering and Technology 20:100749. DOI: 10.1016/j.clet.2024.100749.

Lee CK and Rhee K-I (2002) Reductive leaching of cathodic active materials from lithium ion battery wastes. Hydrometallurgy 68(1–3):5–10. DOI: 10.1016/s0304-386x(02)00167-6.

Li L, Fan E, Guan Y, et al. (2017) Sustainable recovery of cathode materials from spent lithium-ion batteries using lactic acid leaching system. ACS Sustainable Chemistry & Engineering 5(6):5224–5233. DOI: 10.1021/acssuschemeng.7b00571.

Li W, Lee S and Manthiram A (2020) High-nickel NMA: a cobalt-free alternative to NMC and NCA cathodes for lithium-ion batteries. Advanced Materials 32(33):2002718. DOI: 10.1002/adma.202002718.

Liu S, Xiong L and He C (2014) Long cycle life lithium ion battery with lithium nickel cobalt manganese oxide (NCM) cathode. Journal of Power Sources 261:285–291. DOI: 10.1016/j.jpowsour.2014.03.083.

Liu X, Liu H, Wu W, et al. (2020) Oxidative stress induced by metal ions in bioleaching of $LiCoO_2$ by an acidophilic microbial consortium. Frontiers in Microbiology 10(748):3058. DOI: 10.3389/fmicb.2019.03058.

Lv W, Wang Z, Cao H, et al. (2018) A critical review and analysis on the recycling of spent lithium-ion batteries. ACS Sustainable Chemistry & Engineering 6(2):1504–1521. DOI: 10.1021/acssuschemeng.7b03811.

Marcinčáková R, Kaduková J, Mražíková A, et al. (2016) Metal bioleaching from spent lithium-ion batteries using acidophilic bacterial strains. Inżynieria Mineralna 1(1). DOI: 10.29227/im-2016-01-18.

Meshram P, Pandey BD and Mankhand TR (2015) Hydrometallurgical processing of spent lithium ion batteries (LIBs) in the presence of a reducing agent with emphasis on kinetics of leaching. Chemical Engineering Journal 281:418–427. DOI: 10.1016/j.cej.2015.06.071.

Mossali E, Picone N, Gentilini L, et al. (2020) Lithium-ion batteries towards circular economy: a literature review of opportunities and issues of recycling treatments. Journal of Environmental Management 264:110500. DOI: 10.1016/j.jenvman.2020.110500.

Mousa E, Hu X, Ånnhagen L, et al. (2022) Characterization and thermal treatment of the black mass from spent lithium-ion batteries. Sustainability 15(1):15. DOI: 10.3390/su15010015.

Nayaka GP, Manjanna J, Pai KV, et al. (2014) Recovery of valuable metal ions from the spent lithium-ion battery using aqueous mixture of mild organic acids as alternative to mineral acids. Hydrometallurgy 151:73–77. DOI: 10.1016/j.hydromet.2014.11.006.

Nazerian M, Bahaloo-Horeh N and Mousavi SM (2023) Enhanced bioleaching of valuable metals from spent lithium-ion batteries using ultrasonic treatment. Korean Journal of Chemical Engineering 40(3):584–593. DOI: 10.1007/s11814-022-1257-2.

Roy JJ, Madhavi S and Cao B (2020) Metal extraction from spent lithium-ion batteries (LIBs) at high pulp density by environmentally friendly bioleaching process. Journal of Cleaner Production 280:124242. DOI: 10.1016/j.jclepro.2020.124242.

Schwich L, Schubert T and Friedrich B (2021) Early-stage recovery of lithium from tailored thermal conditioned black mass part I: mobilizing lithium via supercritical CO_2-carbonation. Metals 11(2):177. DOI: 10.3390/met11020177.

Shahjalal M, Roy PK, Shams T, et al. (2021) A review on second-life of Li-ion batteries: prospects, challenges, and issues. Energy 241:122881. DOI: 10.1016/j.energy.2021.122881.

Srinivasan S, Shanthakumar S and Ashok B (2025) Sustainable lithium-ion battery recycling: a review on technologies, regulatory approaches and future trends. Energy Reports 13:789–812. DOI: 10.1016/j.egyr.2024.12.043.

Sun L and Qiu K (2012) Organic oxalate as leachant and precipitant for the recovery of valuable metals from spent lithium-ion batteries. Waste Management 32(8):1575–1582. DOI: 10.1016/j.wasman.2012.03.027.

Van Den Brink S, Kleijn R, Sprecher B, et al. (2020) Identifying supply risks by mapping the cobalt supply chain. Resources, Conservation and Recycling 156:104743. DOI: 10.1016/j.resconrec.2020.104743.

Wang J, Chen M, Chen H, et al. (2012) Leaching study of spent Li-ion batteries. Procedia Environmental Sciences 16:443–450. DOI: 10.1016/j.proenv.2012.10.061.

Wang J, Zhang Y, Yu L, et al. (2022) Effective separation and recovery of valuable metals from waste Ni-based batteries: a comprehensive review. Chemical Engineering Journal 439:135767. DOI: 10.1016/j.cej.2022.135767.

Wang M, Liu K, Yu J, et al. (2023) Challenges in recycling spent lithium-ion batteries: spotlight on polyvinylidene fluoride removal. Global Challenges (Hoboken, NJ) 7(3):2200237. DOI: 10.1002/gch2.202200237.

Wang R-C, Lin Y-C and Wu S-H (2009) A novel recovery process of metal values from the cathode active materials of the lithium-ion secondary batteries. Hydrometallurgy 99(3–4):194–201. DOI: 10.1016/j.hydromet.2009.08.005.

Wang S, Lai Y, Yang J, et al. (2024) Advances in recycling technologies of critical metals and resources from cathodes and anodes in spent lithium-ion batteries. Separations 12(1):4. DOI: 10.3390/separations12010004.

Wang X, Gaustad G, Babbitt CW, et al. (2014) Economic and environmental characterization of an evolving Li-ion battery waste stream. Journal of Environmental Management 135:126–134. DOI: 10.1016/j.jenvman.2014.01.021.

Winslow KM, Laux SJ and Townsend TG (2017) A review on the growing concern and potential management strategies of waste lithium-ion batteries. Resources, Conservation and Recycling 129:263–277. DOI: 10.1016/j.resconrec.2017.11.001.

Wood DL, Li J and Daniel C (2014) Prospects for reducing the processing cost of lithium ion batteries. Journal of Power Sources 275:234–242. DOI: 10.1016/j.jpowsour.2014.11.019.

Wu Z, Soh T, Chan JJ, et al. (2020) Repurposing of fruit peel waste as a green reductant for recycling of spent lithium-ion batteries. Environmental Science & Technology 54(15):9681–9692. DOI: 10.1021/acs.est.0c02873.

Xin B, Zhang D, Zhang X, et al. (2009) Bioleaching mechanism of Co and Li from spent lithium-ion battery by the mixed culture of acidophilic sulfur-oxidizing and iron-oxidizing bacteria. Bioresource Technology 100(24):6163–6169. DOI: 10.1016/j.biortech.2009.06.086.

Xu J, Thomas HR, Francis RW, et al. (2007) A review of processes and technologies for the recycling of lithium-ion secondary batteries. Journal of Power Sources 177(2):512–527. DOI: 10.1016/j.jpowsour.2007.11.074.

Xuan W, De Souza Braga A and Chagnes A (2021) Development of a novel solvent extraction process to recover cobalt, nickel, manganese, and lithium from cathodic materials of spent lithium-ion batteries. ACS Sustainable Chemistry & Engineering 10(1):582–593. DOI: 10.1021/acssuschemeng.1c07109.

Yu W, Guo Y, Xu S, et al. (2023) Comprehensive recycling of lithium-ion batteries: fundamentals, pretreatment, and perspectives. Energy Storage Materials 54:172–220. https://doi.org/10.1016/j.ensm.2022.10.033

Zante G, Braun A, Masmoudi A, et al. (2020) Solvent extraction fractionation of manganese, cobalt, nickel and lithium using ionic liquids and deep eutectic solvents. Minerals Engineering 156:106512. DOI: 10.1016/j.mineng.2020.106512.

Zeng X, Li J and Singh N (2014) Recycling of spent lithium-ion battery: a critical review. Critical Reviews in Environmental Science and Technology 44(10):1129–1165. DOI: 10.1080/10643389.2013.763578.

Zhang X, Li L, Fan E, et al. (2018) Toward sustainable and systematic recycling of spent rechargeable batteries. Chemical Society Reviews 47(19):7239–7302. DOI: 10.1039/c8cs00297e.

Zhang Y, Meng Q, Dong P, et al. (2018) Use of grape seed as reductant for leaching of cobalt from spent lithium-ion batteries. Journal of Industrial and Engineering Chemistry 66:86–93. DOI: 10.1016/j.jiec.2018.05.004.

Zhao J, Zhang B, Xie H, et al. (2019) Hydrometallurgical recovery of spent cobalt-based lithium-ion battery cathodes using ethanol as the reducing agent. Environmental Research 181:108803. DOI: 10.1016/j.envres.2019.108803.

Zheng B, Kabiri S, Andelkovic IB, et al. (2021) Mechanochemical synthesis of zinc borate for use as a dual-release B fertilizer. ACS Sustainable Chemistry & Engineering 9(47):15995–16004. DOI: 10.1021/acssuschemeng.1c07111.

Zheng X, Zhu Z, Lin X, et al. (2018) A mini-review on metal recycling from spent lithium ion batteries. Engineering 4(3):361–370. DOI: 10.1016/j.eng.2018.05.018.

Author Contributions
IH, MA and NA conceived the concept, wrote and approved the manuscript.

Acknowledgements
Not applicable.

Funding
Not applicable.

Availability of data and materials
The datasets generated and analyzed during the current study are not publicly available due to site-specific and institutional restrictions but are available from the corresponding author upon reasonable request.

Competing interest
The authors declare no competing interests.

Ethics approval
Not applicable.

[*]The authors are solely responsible for the accuracy, integrity and content of this paper. The views, opinions, findings and conclusions expressed herein are those of the authors and do not necessarily reflect the views or policies of the publisher, editors, reviewers or affiliated institutions.

Citation: Haq I, Alam M and Ahsan N (2026) Recycling of Spent Lithium-Ion Batteries through Sustainable and Advanced Processing Technologies. Environmental Science Archives 5(2): 437-448.