

Selective Recovery of Critical Metals from Spent Lithium-Ion Batteries through Direct Bioleaching Using *Citrobacter freundii*

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Abstract. The rapid growth of electrified transportation and the widespread adoption of portable electronic devices have significantly increased the demand for efficient energy storage systems. Lithium-ion (Li-ion) batteries are known for having a higher energy density and a longer cycle life than other types of batteries, making them the most reliable and long-lasting choice. However, the escalating accumulation of end-of-life Li-ion batteries has introduced notable environmental and economic challenges. The intricate composition of these batteries complicates the selective recovery of valuable metals. Traditional recycling techniques, including pyrometallurgy and hydrometallurgy, although effective, are associated with high operational costs, substantial energy consumption, and the generation of secondary waste. As a sustainable alternative, bioleaching utilizes specific microorganisms to mediate the selective solubilization of metals from complex battery matrices through their metabolic activities. In this study, direct bioleaching of lithium-ion (Li-ion) battery black mass was performed over a seven-day period employing the mixotrophic bacterium *Citrobacter freundii* strain SKC-4. Following the bioleaching process, notable metal recoveries were achieved, with extraction efficiencies of 41.4% for lithium (Li), 2.4% for nickel (Ni), 2.9% for cobalt (Co), 9% for copper (Cu), 7.3% for manganese (Mn), and 6.7% for aluminum (Al). These findings demonstrate the efficacy of *Citrobacter freundii* in the direct bioleaching of spent Li-ion battery black mass and highlight its potential as an environmentally sustainable approach for the selective recovery of valuable metals, contributing to the advancement of circular economy practices in battery recycling.

1 Introduction

The transition to electric vehicles (EVs) as a climate change mitigation effort has created new challenges in battery waste management. Lithium-ion batteries, as the main component of EVs, contain heavy metals such as cobalt, nickel, and lithium that can potentially pollute the environment and endanger human health if not managed properly [1]. Additionally, the high fire risk associated with used batteries, especially when stored in large quantities, is a serious concern. The phenomenon of “battery graveyards” in some countries highlights the urgency of comprehensive battery waste management, as this waste not only has the potential to pollute the environment but also poses safety risks. To address these issues, the development of efficient and environmentally friendly recycling technologies is essential. Additionally, strict regulations must be established to ensure that used batteries are managed responsibly throughout their lifecycle.

Beyond being an environmental threat, lithium battery waste also holds significant economic potential. Used batteries contain valuable metals such as lithium, nickel, and cobalt that can be recycled to produce new batteries with performance comparable to primary batteries [2]. The recycling process not only reduces the environmental impact of battery waste but also

contributes to the sustainability of natural resources by reducing dependence on new metal mining [3].

Advancements in recycling technology for lithium-ion batteries have led to various methods, including pyrometallurgy, hydrometallurgy, and biohydrometallurgy. Each method has unique characteristics, advantages, and limitations that must be comprehensively considered [3]. Pyrometallurgy, which uses high temperatures to recycle battery waste, has proven effective in recovering metals but has a significant carbon footprint due to high energy consumption and greenhouse gas emissions [2]. Meanwhile, hydrometallurgy, which relies on dissolving metals in chemical solutions, is efficient in metal extraction but produces liquid waste that can potentially contaminate the environment if not managed properly [4].

Biohydrometallurgy has become a promising alternative for recycling lithium batteries. It is more environmentally friendly and may be cheaper than traditional methods. This process uses microorganisms to dissolve metals in the solid matrix of batteries, resulting in a more selective and efficient solution [5]. This method has several significant advantages, such as lower operational expenses, due primarily to minimal energy consumption and reduced use of chemical reagents [5]. Additionally, biohydrometallurgy

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produces significantly less waste and at lower toxicity levels compared to conventional methods. Another advantage of biohydrometallurgy is its high selectivity in dissolving specific metals, enabling the recovery of valuable metals with higher efficiency [6].

Despite the promising potential of biohydrometallurgy for lithium battery recycling, its industrial-scale application still faces several significant challenges. One of the main obstacles is the relatively slow metal extraction rate compared to conventional methods such as pyrometallurgy and hydrometallurgy [6]. The longer time required to achieve the desired extraction rate can hinder the overall efficiency of the process. Additionally, optimizing operating conditions is an especially difficult task in biohydrometallurgy. Factors such as pH, temperature, and nutrient availability significantly influence microbial activity and metal extraction efficiency [7]. The complexity of the battery matrix also poses a significant barrier. The presence of various components within the battery can hinder microbial access to target metals and reduce extraction efficiency [8].

Biohydrometallurgy has a lot of potential for making lithium battery recycling more sustainable. With ongoing technological advancements and research, biohydrometallurgy could become an effective solution to address battery waste challenges and efficiently recover valuable metals [3]. This approach aligns with the principles of the circular economy, where valuable resources can be optimally utilized through recycling processes, thereby reducing environmental pressure and enhancing the sustainability of the battery industry [9].

Bioleaching is a biotechnological process that utilizes the activity of microorganisms, particularly bacteria, to dissolve metals from solid waste matrices, such as lithium-ion battery (LIB) black mass. The bioleaching mechanism involves acid production by bacteria, oxidation of sulfide compounds, and the formation of organic compounds such as biosurfactants that enhance metal solubility [10]. Bacteria such as *Acidithiobacillus ferrooxidans* and *Leptospirillum* sp. play a central role in this process, with their ability to oxidize sulfide compounds into more soluble forms, thereby facilitating metal extraction from minerals [11].

This study evaluates the potential of *Citrobacter freundii* SKC-4 for the selective extraction of metals from lithium-ion battery black mass through direct bioleaching, with particular emphasis on the role of bioleaching medium composition. During the 7-day bioleaching process, key parameters including pH, redox potential (Eh), and dissolved metal concentrations are periodically monitored to assess leaching behavior and kinetics. The novelty of this work lies in the application of *C. freundii* SKC-4 as a single bioleaching agent without the use of external chemical leaching reagents, providing new insight into biologically driven metal solubilization from complex battery waste. This approach offers an environmentally friendly and cost-effective alternative for critical metal recovery, supporting sustainable battery recycling and circular economy strategies.

2 Materials and methods

The experimental design aimed to evaluate the bioleaching performance of *Citrobacter freundii* SKC-4 for the recovery of critical metals from spent battery-derived materials. All bioleaching experiments and subsequent analytical measurements were conducted in duplicate to ensure reproducibility, and the reported values represent the arithmetic mean of the measurements.

2.1 Preparation of black mass

The used battery waste was acquired from discarded laptop batteries, primarily comprising lithium, nickel, cobalt, and manganese. To guarantee safety during the dismantling procedure, the batteries were discharged by immersing them in a seawater solution for 72 hours to ensure residual voltage was below 400 mV. Following the discharge and drying phases, the batteries were manually dismantled using precision tools to isolate the internal components, including the external casings, separators, and electrode assemblies. The recovered electrode materials were processed using a shredder followed by a high-speed chopper and subsequently sieved through a 200-mesh screen to achieve a uniform particle size distribution. This stabilized black mass was then characterized for its baseline elemental composition (Li, Ni, Co, and Mn) prior to use in the bioleaching experiments.

2.2 Microorganism and culture media

Citrobacter freundii was chosen as a mesophilic bacterium to evaluate its ability to leach the metals of LIB powder. This bacterium obtains its energy source through sulfur-oxidizing and iron-oxidizing. It can convert elemental sulfur to sulfuric acid and, as a result, help in heavy metal dissolution in the medium. Bacterial cultivation was conducted in a Luria-Bertani (LB) liquid medium prepared by dissolving 10 g/L tryptone, 5 g/L yeast extract, and 10 g/L NaCl in deionized water using a magnetic stirrer. The medium was sterilized via autoclaving at 121 °C and 1.5 atm for 15 minutes. Under aseptic conditions, the medium was inoculated and incubated in a shaker at 180 rpm. The culture was maintained for 24 hours to ensure the cells reached the late exponential growth phase before being utilized in the bioleaching experiments.

2.3 One-step direct bioleaching experiments

The bioleaching of LIB powder was conducted using a direct one-step approach to evaluate the immediate interaction between the microbial culture and the black mass. In this setup, the black mass was introduced into the 9K-SKC medium simultaneously with the bacterial inoculum at a pulp density of 2%. The experiments were performed in 250 mL Erlenmeyer flasks with a working volume of 100 mL and maintained in an orbital shaker-incubator at 30 °C and 180 rpm for a duration of 7 days.

Throughout the 7-day period, periodic sampling was conducted to monitor the progress of bioleaching. Physicochemical parameters, including pH and redox potential (Eh), were measured using a calibrated digital multi-parameter meter. For metal extraction analysis, bioleaching solutions were withdrawn and centrifuged at 10,000 rpm for 10 minutes. The resulting supernatant was filtered through a 0.22 µm syringe filter and stabilized with 2% HNO₃ prior to Inductively Coupled Plasma Mass Spectrometry (ICP-MS) analysis to quantify dissolved Li, Ni, Co, and Mn concentrations. At the conclusion of the experiment, the solid residues were collected, washed with deionized water, and dried. Mineralogical transformations were characterized using X-ray Diffraction (XRD), while surface functional groups were verified using Fourier-Transform Infrared Spectroscopy (FTIR).

3 Results and discussion

3.1 Observation of pH and redox potential (Eh) during the bioleaching process

Citrobacter freundii was cultivated in the 9K-SKC medium with an initial pH of 2.5. During the first 24 hours of incubation, a rapid increase in pH to approximately 7.0 was observed across all experimental sets (Fig. 1). This pronounced rise in pH can be attributed to proton consumption during microbial metabolic activity and the possible production of alkaline metabolites, which are characteristic of heterotrophic growth in nutrient-rich media. In addition, the inherently alkaline nature of the LIB black mass exerts a strong buffering effect on the system, further contributing to the neutralization of the acidic medium during the early stages of bioleaching [12].

Redox potential (Eh) plays a critical role in governing metal solubility and microbial metabolic pathways [13]. Throughout the 7-day bioleaching period, Eh values exhibited continuous fluctuations, reflecting the dynamic redox environment of the system (Figure 2). These variations indicate the active involvement of *C. freundii* in electrochemical redox processes mediated by its metabolic by-products. Such shifts in Eh are essential for destabilizing the metal-oxide matrix within the black mass, thereby facilitating the dissolution of valuable metals into the aqueous phase [13].

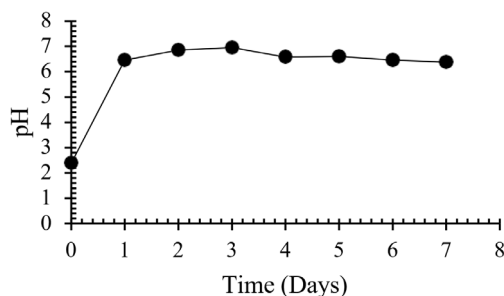


Fig. 1. Changes in pH during the bioleaching of lithium-ion battery (LIB) black mass by *Citrobacter freundii* SKC-4 in 9K-SKC medium over a 7-day incubation period, illustrating the rapid pH increase during the initial stage of bioleaching

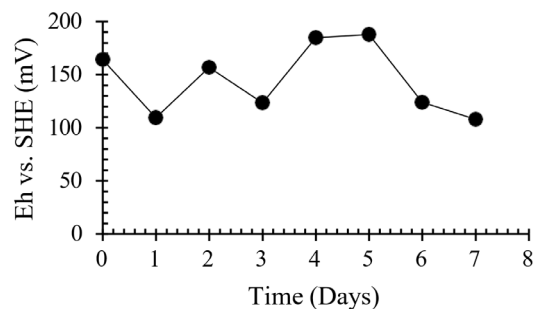


Fig. 2. Changes in redox potential (Eh) during the bioleaching of lithium-ion battery (LIB) black mass by *Citrobacter freundii* SKC-4 in 9K-SKC medium over a 7-day incubation period, reflecting dynamic redox conditions associated with microbial activity.

3.2 Elemental Composition and Metal Extraction Behavior of LIB Black Mass

The initial elemental composition of the LIB black mass was determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) following complete acid digestion. As summarized in Table 1, manganese was identified as the most abundant metallic component at 207,453 ppm, followed by nickel (90,116 ppm), lithium (28,714 ppm), and cobalt (24,620 ppm). Substantial concentrations of aluminium (7,170 ppm) and copper (6,339 ppm) were also detected, which likely originate from current collectors and residual battery casing materials.

Bioleaching experiments using *Citrobacter freundii* SKC-4 exhibited varying degrees of metal solubilization over the 7-day incubation period, as illustrated in Figure

3. Among the target elements, lithium showed the highest extraction efficiency, reaching 41% at the end of the experiment. The preferential leaching of lithium can be attributed to its location within the cathode crystal lattice and its relatively higher solubility in biogenic organic acids compared with transition metals such as Ni, Mn, and Co, which are more strongly bound within the metal-oxide matrix. These results provide a baseline for assessing the effectiveness of the 9K-SKC medium in supporting microbial-driven metal mobilization.

Table 1. Elemental composition of lithium-ion battery (LIB) black mass determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) following complete acid digestion.

Element	ppm	wt. %
Mn	207,453	20.75
Ni	90,116	9.01
Li	28,714	2.87
Co	24,620	2.46
Al	7,170	0.72
Cu	6,339	0.63
Fe	1,000	0.10

The preferential leaching of lithium observed in this study is primarily governed by its structural position and bonding environment within the cathode material, as

well as its favourable interaction with biogenic organic acids produced during microbial metabolism. In layered oxide cathodes such as $\text{Li}(\text{Ni}, \text{Mn}, \text{Co})\text{O}_2$, lithium occupies interlayer sites and is weakly bound through ionic interactions, making it more readily exchangeable and susceptible to dissolution under mildly acidic or complexing conditions. In contrast, transition metals such as Ni, Mn, and Co are embedded within the metal–oxygen framework, forming stronger covalent–ionic bonds that require more aggressive leaching conditions for disruption [6].

During bioleaching, *C. freundii* SKC-4 is known to produce sulfuric acid and biosurfactants, which can effectively solubilize lithium via proton-assisted ion exchange and complexation mechanisms [14]. The biosurfactants preferentially stabilize Li^+ in solution while exhibiting limited chelation strength toward multivalent transition metals, thereby enhancing lithium selectivity [12]. Furthermore, the relatively stable Eh conditions observed during the bioleaching process favor lithium mobilization, as Li dissolution is largely independent of redox reactions, unlike Mn and Co, which often require oxidative or reductive transformations to achieve significant solubilization [13]. Additionally, the buffering effect of the alkaline components in the LIB black mass leads to near-neutral pH conditions after the initial stage of bioleaching, which further suppresses the dissolution of transition metals while allowing continued lithium release. This pH-dependent selectivity has been widely reported in biohydrometallurgical systems and is considered a key advantage of biological leaching routes for targeted lithium recovery [7]. Collectively, these factors explain the higher lithium extraction efficiency achieved in this study and highlight the potential of *C. freundii*-mediated bioleaching as a selective and environmentally benign approach for lithium recovery from spent LIB black mass.

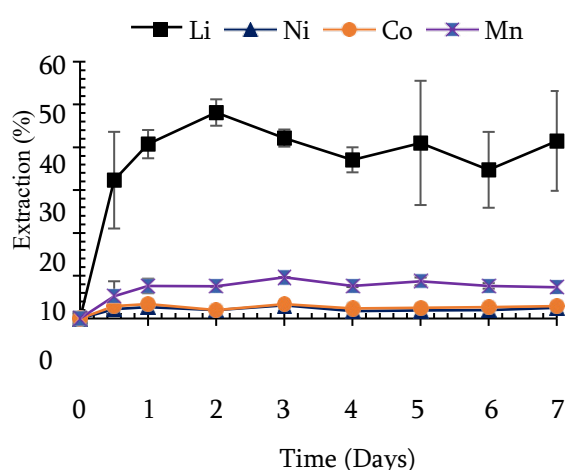


Fig. 3. Metal extraction efficiency of Li, Ni, Mn, and Co during one-step bioleaching of lithium-ion battery (LIB) black mass by *Citrobacter freundii* SKC-4 in 9K-SKC medium over a 7-day incubation period.

3.3 FTIR analysis of LIB black mass and bioleaching residue'

Fourier-Transform Infrared Spectroscopy (FTIR) was employed to identify the functional groups involved in the interaction between *Citrobacter freundii* SKC-4 and the LIB black mass. The FTIR spectra of the black mass before and after the 7-day bioleaching process are compared in Figure 4. The untreated black mass exhibited characteristic absorption bands associated with metal-oxide frameworks and residual organic electrolyte components. Following bioleaching, noticeable shifts and changes in peak intensities were observed, particularly in the regions of $3400 - 3200 \text{ cm}^{-1}$ and $1650 - 1600 \text{ cm}^{-1}$. The broad absorption band centred at approximately 3345 cm^{-1} is attributed to O–H stretching vibrations, which showed increased intensity after bioleaching. This enhancement is likely associated with the formation of biogenic intermediates, increased surface hydroxylation, and the presence of bound water within the bacterial biofilm matrix. Such features are commonly reported in bioleaching systems and indicate active microbial involvement at the solid–liquid interface [15].

The FTIR spectrum of the bioleaching residue exhibits distinct absorption bands at approximately 2920 and 2850 cm^{-1} , 1600 cm^{-1} , and 1063 cm^{-1} , which were absent or significantly less pronounced in the pristine LIB black mass. The bands at 2920 and 2850 cm^{-1} are attributed to the asymmetric and symmetric stretching vibrations of aliphatic C–H groups, indicating the presence of lipid-like organic compounds typically associated with microbial metabolites and biosurfactants. The absorption band near 1600 cm^{-1} corresponds to C=O stretching vibrations of carboxylate or amide functional groups, suggesting the accumulation of organic acids, extracellular polymeric substances, or proteinaceous components produced during microbial activity. In addition, the band observed at 1063 cm^{-1} is assigned to C–O stretching vibrations of polysaccharides or glycolipid-type biosurfactants, further supporting the presence of bacterially derived organic compounds on the solid residue. Collectively, these spectroscopic features confirm that the bioleaching residue is enriched with bacterial metabolic products and biosurfactants, in contrast to the initial LIB black mass, which is dominated by inorganic metal–oxide phases. These bacterially derived organic compounds can subsequently interact with metal species via complexation mechanisms, whereby functional groups such as carboxyl, hydroxyl, and amide moieties act as organic ligands. Such ligands play a crucial role in metal mobilization by forming soluble metal–organic complexes, thereby enhancing metal dissolution during the bioleaching process [14]. Furthermore, alterations observed in the fingerprint region between 400 and 800 cm^{-1} , which is characteristic of metal–oxygen (M–O) vibrations, indicate partial destabilisation of Mn–O and Co–O bonds during bioleaching. A noticeable reduction in peak intensity within this region is observed for the bioleaching residue compared with the pristine LIB black mass, suggesting progressive disruption of the metal–oxide lattice. This attenuation of M–O-related

bands is consistent with the dissolution and release of Mn and Co species into the aqueous phase, confirming that bioleaching effectively promotes metal extraction through the breakdown of oxide structures. Overall, these FTIR results confirm that the bioleaching process is governed by a combined mechanism of biogenic acidification and organic complexation mediated by microbial metabolites.

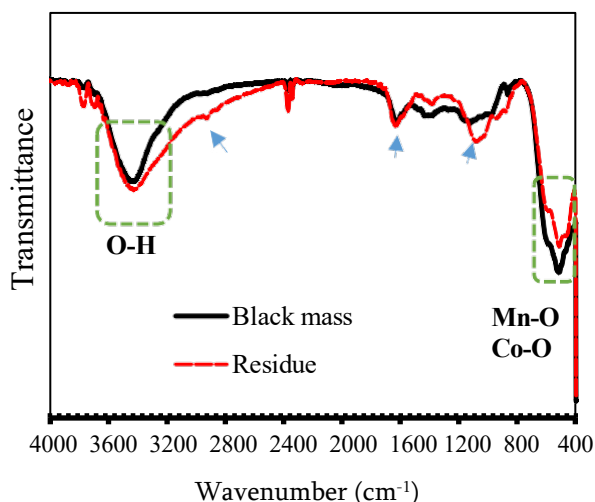


Fig. 4. FTIR spectra of lithium-ion battery (LIB) black mass before bioleaching and the corresponding bioleaching residue after a 7-day treatment with *Citrobacter freundii* SKC-4.

3.4 XRD analysis of LIB black mass and bioleaching residue

The mineralogical phases of the lithium-ion battery (LIB) black mass before and after bioleaching were characterised by X-ray Diffraction (XRD) to assess the structural degradation of the cathode material. The XRD patterns shown in Figure 5 confirm the presence of highly crystalline phases in the pristine black mass, which were substantially diminished following bioleaching. In particular, a pronounced reduction in the intensity of the characteristic layered NMC reflections was observed after the 7-day bioleaching process. This decrease in peak intensity indicates progressive dissolution of the metal-oxide framework and the disruption of long-range crystalline order as Li, Ni, Mn, and Co were mobilized into the aqueous phase.

In addition, the increased background intensity and the emergence of a broad amorphous hump in the diffraction patterns of the bioleached residues further suggest a significant loss of crystallinity. Such features are commonly associated with partial amorphization of cathode materials during leaching and have been reported in both chemical and biological recycling routes for spent LIBs. This structural transformation is attributed to the intensive dissolution of the metal-oxide matrix, coupled with the deposition of non-crystalline biogenic precipitates and extracellular polymeric substances (EPS) on the residual particle surfaces. The accumulation of these bacterially derived organic phases, as evidenced by FTIR analysis, likely contributes to peak broadening and attenuation by masking residual crystalline domains. Overall, the XRD

results corroborate the metal extraction trends and spectroscopic evidence presented earlier, confirming that *Citrobacter freundii* SKC-4, mediated bioleaching induces substantial structural degradation of the NMC cathode material through combined dissolution and biogenic surface modification mechanisms.

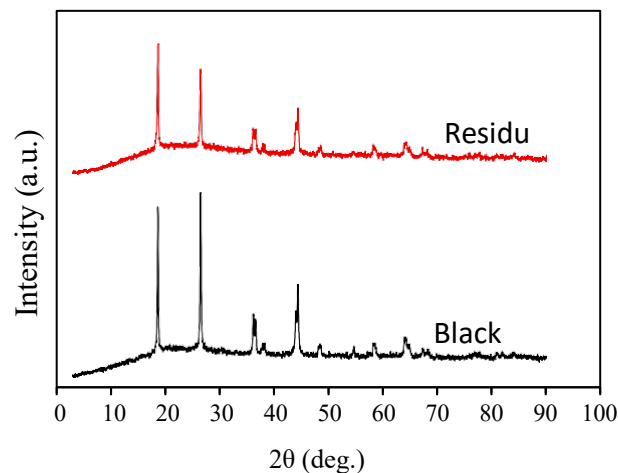


Fig. 5. XRD patterns of lithium-ion battery (LIB) black mass before bioleaching and the corresponding solid residue after 7 days of bioleaching with *Citrobacter freundii* SKC-4.

4 Conclusion

This study investigated the bioleaching performance of *Citrobacter freundii* for the recovery of critical metals from lithium-ion battery (LIB) black mass, with particular emphasis on the influence of operational conditions on metal solubilization. The bioleaching process achieved extraction efficiencies of 41% for Li, 2.4% for Ni, 2.9% for Co, 9.0% for Cu, 7.3% for Mn, and 6.7% for Al. Characterization of the LIB black mass before and after bioleaching using XRD, and FTIR confirmed substantial physicochemical transformations of the cathode material, including partial dissolution of the metal-oxide matrix, loss of crystalline order, and the accumulation of bacterially derived organic compounds on the residual particle surfaces. These findings demonstrate that *C. freundii* exhibits clear potential as a bioleaching agent for LIB recycling.

Notably, this work provides new insight into the role of mixotrophic bacterial metabolism and biogenic organic compounds in governing selective lithium mobilization under near-neutral conditions, distinguishing it from conventional acid-driven bioleaching systems. The integration of metal extraction data with spectroscopic and mineralogical evidence elucidates a biologically mediated dissolution mechanism involving organic complexation and surface modification. While further optimization of process parameters is required to enhance overall recovery efficiencies, this study establishes a mechanistic foundation for the development of selective, low-chemical-input bihydrometallurgical strategies for sustainable LIB recycling.

References

1. K. Richa, C.W. Babbitt, G. Gaustad, Eco-Efficiency Analysis of a Lithium-Ion Battery Waste Hierarchy Inspired by Circular Economy, *Journal of Industrial Ecology* **21** (2017) 715–730. <https://doi.org/10.1111/jiec.12607>.
2. Y. Du, H. Jiang, Study on Recycling and Reuse of Waste Battery of Electric Vehicle, (2018). <https://doi.org/10.2991/mcei-18.2018.59>.
3. M. Pagliaro, F. Meneguzzo, Lithium Battery Reusing and Recycling: A Circular Economy Insight, *Heliyon* (2019). <https://doi.org/10.1016/j.heliyon.2019.e01866>.
4. Z. Xu, Y. Dai, H. Dong, H. Gu, N. Wang, Creative Method for Efficiently Leaching Ni, Co, Mn, and Li in a Mixture of LiFePO₄ and LiMO₂ Using Only Fe(III), *Acs Sustainable Chemistry & Engineering* **9** (2021) 3979 – 3984. <https://doi.org/10.1021/acssuschemeng.0c09207>.
5. P. Thakur, S. Kumar, Exploring Biorecovery Potential of Indigenous *Bacillus* Sporothermodurans ISO1 for Metals Recovery From PCBs Through Sequential Leaching Process, *Waste Management & Research the Journal for a Sustainable Circular Economy* **41** (2023) 1255 – 1266. <https://doi.org/10.1177/0734242x231155102>.
6. B.K. Biswal, R. Balasubramanian, Recovery of valuable metals from spent lithium-ion batteries using microbial agents for bioleaching: a review, *Front. Microbiol.* **14** (2023) 1197081. <https://doi.org/10.3389/fmicb.2023.1197081>.
7. J. Jegan Roy, M. Srinivasan, B. Cao, Bioleaching as an Eco-Friendly Approach for Metal Recovery from Spent NMC-Based Lithium-Ion Batteries at a High Pulp Density, *ACS Sustainable Chem. Eng.* **9** (2021) 3060 – 3069. <https://doi.org/10.1021/acssuschemeng.0c06573>.
8. T. Hanada, M. Goto, Cathode Recycling of Lithium-Ion Batteries Based on Reusable Hydrophobic Eutectic Solvents, *Green Chemistry* **24** (2022) 5107–5115. <https://doi.org/10.1039/d1gc04846c>.
9. R. Lerchhammer, E. Gerold, H. Antrekowitsch, Gluconic Acid Leaching of Spent Lithium-Ion Batteries as an Environmentally Friendly Approach to Achieve High Leaching Efficiencies in the Recycling of NMC Active Material, *Metals* **13** (2023) 1330. <https://doi.org/10.3390/met13081330>.
10. R.A. Bobadilla-Fazzini, I. Poblete-Castro, Biofilm Formation Is Crucial for Efficient Copper Biorecovery From Bornite Under Mesophilic Conditions: Unveiling the Lifestyle and Catalytic Role of Sulfur-Oxidizing Bacteria, *Frontiers in Microbiology* **12** (2021). <https://doi.org/10.3389/fmicb.2021.761997>.
11. P. Soto, C.M. Villegas, Y. Contador, P.A. Galleguillos, C. Demergasso, M. Serón, Characterization of Oxidizing Activity of a Microbial Community in an Industrial Biorecovery Heap, *Advanced Materials Research* **71–73** (2009) 59–62. <https://doi.org/10.4028/www.scientific.net/amr.71-73.59>.
12. J.J. Roy, S. Madhavi, B. Cao, Metal extraction from spent lithium-ion batteries (LIBs) at high pulp density by environmentally friendly bioleaching process, *Journal of Cleaner Production* **280** (2021) 124242. <https://doi.org/10.1016/j.jclepro.2020.124242>.
13. Y. Masaki, T. Hirajima, K. Sasaki, H. Miki, N. Okibe, Microbiological Redox Potential Control to Improve the Efficiency of Chalcopyrite Biorecovery, *Geomicrobiology Journal* **35** (2018) 648–656. <https://doi.org/10.1080/01490451.2018.1443170>.
14. S.K. Chaerun, E.A. Putri, M.Z. Mubarak, Bioleaching of Indonesian Galena Concentrate With an Iron- and Sulfur-Oxidizing Mixotrophic Bacterium at Room Temperature, *Front. Microbiol.* **11** (2020) 557548. <https://doi.org/10.3389/fmicb.2020.557548>.
15. S.K. Chaerun, R. Winarko, R.I. Chaerun, F.R. Mufakhir, S.T. Lumbantobing, A.M.M. Rus, M.H. Masruri, Z.T. Ichlas, W.P. Minwal, I. Santoso, W. Astuti, Sustainable Recovery of Rare Earth Elements from Coal Fly Ash via Biohydrometallurgy Using *Alicyclobacillus* ferrooxydans: Effects of Pulp Density and Pyrite Amendment, *J. Sustain. Metall.* **11** (2025) 3646–3658. <https://doi.org/10.1007/s40831-025-01320-y>.