

# Mechanical processing and chemical leaching in the recovery of valuable elements from spent lithium batteries

Deyber Alexander Ramirez-Quintero <sup>I</sup>  
Marcos Batista Cotovia Pimentel <sup>II</sup>  
Sebastião Eleutério Filho <sup>III</sup>  
Carlos Roberto Mendes de Oliveira <sup>IV</sup>

**Abstract:** The implementation of Brazil's Reverse Logistics System, regulated by decree 10,240/2020, encounters significant environmental and technological challenges in post-consumer electrical and electronic waste (e-waste) collection and treatment. To address the adverse impacts of e-waste on the environment and human health, it is necessary to develop sustainable technologies. This includes creating technological routes to reuse valuable materials from e-waste, supporting circular economy principles, and fostering socioeconomic development. Specifically, the rising disposal of lithium batteries requires efficient, low-cost, and environmentally friendly recycling methods. This review explores the establishment of a technological route to recover valuable elements from spent lithium batteries. It emphasizes physical processing without thermal treatment and hydrometallurgical methods involving both inorganic and organic leachants. The aim is to facilitate the adoption of these methods in the country's industrial sector.

**Keywords:** Reverse Logistics System; Lithium Batteries, Mechanical processing; Electrical-Electronic Waste; Leaching process.

<sup>I</sup> Centro de Tecnologia da Informação Renato Archer - CTI, Campinas, SP, Brazil.

<sup>II</sup> Centro de Tecnologia da Informação Renato Archer - CTI, Campinas, SP, Brazil.

<sup>III</sup> Centro de Tecnologia da Informação Renato Archer - CTI, Campinas, SP, Brazil.

<sup>IV</sup> Centro de Tecnologia da Informação Renato Archer - CTI, Campinas, SP, Brazil.

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## Introduction

The increasing demand for lithium batteries (LB) in recent years, due to their high energy density, low maintenance costs, and flexibility (Natkunarahaj, Scharf, Scharf, 2015; Zhao *et al.*, 2020), has raised concerns about the growing generation of electronic waste (e-waste) (Du *et al.*, 2022; Li *et al.*, 2014). Improper disposal of these wastes can cause damage to both the environment and human health, given the toxic elements they contain (Mcmanus, 2012; Meshram, Pandey, Mankhand, 2014; Ordoñez, Gago, Girard, 2016). Conversely, proper disposal and processing of electronic waste can promote circular economy principles, driving social and economic development through the recovery of valuable materials and elements (Awasthi *et al.*, 2019; Savini, 2021; Xavier, Ottoni, Lepawsky, 2021). According to estimates from the United Nations University (Forti *et al.*, 2020), 53.6 million tons of electronic waste were generated worldwide in 2019. In this scenario, Brazil accounted for 2.1 million tons, ranking as the second-highest generator of e-waste in the Americas and the fifth globally. Following global trends (Nature, 2021), the lithium battery market reached \$30 billion in 2017, and the industry projects it to grow to \$100 billion by 2025.

In order to implement the Electronic Waste Reverse Logistics System in Brazil, in October 2019, the Electronic Sector Agreement (MMA, 2019) was signed, a contractual act of the National Solid Waste Policy, Federal Law No. 12,305/2010 (Brasil, 2010), between the government and private sectors, manufacturers, and sellers of electronic products, ratified by Federal Decree No. 10,240/2020. Pimentel, Ramirez-Quintero, and Bezana (2020) presented the framework of the National Electronic Waste Reverse Logistics System framework to be implemented in Brazil. According to the authors, one of the main challenges to be overcome is the development of technological routes that enable the reuse of valuable materials from electronic waste, thus promoting the principles of the circular economy and contributing to social and economic development.

Rechargeable batteries are widely used in mobile electronic devices and electric vehicle fleets (Martins *et al.*, 2021; Narins, 2017). Currently, lithium batteries are considered the best solution for the market due to their compact size, chemical stability, lightweight nature, higher energy density, longer lifespan, and lower self-discharge rate compared to batteries made from other materials (Su, 2022; Turcheniuk *et al.*, 2018). It is estimated that in 2022, 424 million lithium battery-powered digital devices (computers, notebooks, tablets, and smartphones) were sold in Brazil (Fundação Getúlio Vargas, 2020).

Lithium batteries (LB) consist of interleaved layers. The materials within lithium batteries contain potentially toxic and harmful substances, including (i) metals such as copper, nickel, and lead, (ii) electrolytes such as  $\text{LiPF}_6$ ,  $\text{LiAsF}_6$ ,  $\text{LiCF}_3\text{SO}_3$ ,  $\text{HF}$ , and  $\text{P}_2\text{O}_5$ , and (iii) solvents such as DME, methanol, and formic acid (Cheng *et al.*, 2021; Li, Wang, Xu, 2016).

Results presented by Mcmanus (2012) regarding environmental impacts in LB production showed that obtaining the necessary materials significantly contributes to greenhouse gas emissions. Ordoñez, Gago, and Girard (2016) reported that every 4,000 tons of discarded LB generates about 1,100 tons of heavy metals and 200 tons of toxic

electrolytes. Building on these previously mentioned studies, Meshram *et al.* (2020) described the risks to human health posed by each component of LB during disposal and recycling, as shown in Table 1.

**Table 1 – Effects of materials present in lithium batteries**

| Structural Component | Chemical Composition    | Hazardous Effects                                           |
|----------------------|-------------------------|-------------------------------------------------------------|
| <b>Anode</b>         | Copper (metal foil)     | Gastrointestinal problems                                   |
|                      | Grafite                 | It irritates the eyes and mucous membranes                  |
| <b>Cathode Oxide</b> | Aluminum (metal foil)   | Lung damage                                                 |
|                      | Cobalt Oxide            | Respiratory effects, congestion, edema, and lung hemorrhage |
|                      | Manganese Oxide (VI)    | Lung damage                                                 |
|                      | Nickel Oxide            | Skin carcinogenesis                                         |
|                      | Lithium                 | Non-hazardous if ingested                                   |
| <b>Electrolyte</b>   | LiPF <sub>6</sub>       | Toxic smoke during heating/burning                          |
| <b>Binders</b>       | Polypropylene           | Vapors when burned (mucous irritation)                      |
|                      | Polyvinylidene fluoride | Toxic when inhaled; Toxic smoke during heating              |

Font: Adapted from Meshram *et al.*, 2020.

Various methods have been proposed for the recovery of valuable elements from electronic waste, specifically of spent lithium batteries (LB). In the literature, these different approaches fall into one of three methods: pyrometallurgy, hydrometallurgy, and bio-hydrometallurgy (Li *et al.*, 2017; Zhang *et al.*, 2018; Zhao *et al.*, 2020). In academic publications, hydrometallurgical processes predominate, while in the industrial context, pyrometallurgical processes are more commonly employed, although not necessarily directed towards recycling spent LB (Hu *et al.*, 2021). Pyrometallurgy is a fast and efficient process but generates emissions of polluting gases such as dioxins and furans and involves high energy costs (Kim *et al.*, 2016; Ordoñez, Gago, Girard, 2016). According to Hu *et al.* (2021), while hydrometallurgical processes provide high selectivity and lower environmental impact, pyrometallurgical processes are more prevalent in industry due to their high productivity and ease of scaling up. The rapid changes in lithium battery chemistry and the shift to cheaper cathode materials demand adaptable hydrometallurgical processes to stay economically viable (Huang *et al.*, 2018). Thus, despite hydrometallurgy's environmental benefits, pyrometallurgy remains widely used for its efficiency and industrial integration ease (Hu *et al.*, 2021).

Sun and Qiu (2011) presented a comprehensive process involving vacuum pyrolysis and hydrometallurgy for the combined recovery of cobalt and lithium ion spent lithium batteries. The authors used pyrometallurgy to remove non-metallic elements and inorganic acid,  $\text{H}_2\text{SO}_4$ , in hydrometallurgy to increase efficiency in cobalt and lithium recovery. On the other hand, Zhang *et al.* (2020) proposed a method that combines treatment by thermal reduction and inorganic acid leaching to recover nickel, cobalt, manganese, and sodium from spent lithium-ion batteries. The authors investigated sulfuric acid dosage, temperature, time, and acid-electrolyte ratio to determine the most efficient leaching rates, achieving over 97% recovery for Mn and over 99% for Ni, Co, and Li extracted. Dolotko *et al.* (2020) explored the mechanochemical extraction of Co and Li from lithium cobalt oxide ( $\text{LiCoO}_2$ ), used as a cathode material in discarded lithium-ion batteries. The method integrates the first three steps of the conventional recycling workflow—disassembly, initial processing, and chemical conversion—into a single mechanochemical step, achieving recovery rates of approximately 90% for Co and 70% for Li. Hu *et al.* (2021) conducted an analysis of industrialized processes, where hydrometallurgical (Duesenfeld and Recupyl) and pyrometallurgical (Umicore and ACCUREC) processes predominate. The authors noted that recycling in these processes focuses on Co and Ni, which have high economic value, while Li and Mn are not recovered, and processing capacities are still limited. Thus, the hydrometallurgical recycling process presents advantages such as high selectivity, low energy consumption, and recovery of higher-value products, making it applicable to various types of batteries (Hu *et al.*, 2021).

According to Meshram *et al.* (2020), pre-treatment methods play an important role, including solvent dissolution, ultrasonic separation, thermal treatment methods, or mechanical methods. Physical processing can benefit the process of recovering valuable elements, such as reducing operational costs and optimizing the process (Sommerville *et al.*, 2020). Through physical crushing and grinding operations and, subsequently, separation through techniques that exploit differences in electrical conductivity, density, or other properties, the metals of interest can be concentrated and favor the subsequent refining process.

This review presents a combined approach of physical processing through mechanical steps and hydrometallurgy, with acids used in leaching, for the recovery of valuable elements from spent lithium batteries. The aim is to establish a technological route that can be implemented in the country's industrial sector. The choice of mechanical processing and leaching as the main topics in this study is driven by their significant advantages in the context of e-waste recycling. Mechanical processing, including crushing and grinding, simplifies the handling of spent batteries and facilitates efficient separation of components based on their physical properties. This initial step is key as it prepares the material for further treatment. Additionally, leaching with acids is a well-established hydrometallurgical process that effectively dissolves and recovers valuable metals from the separated components. By combining these methods, the strengths of both approaches are leveraged: mechanical processing ensures optimal material preparation, while leaching achieves high recovery rates of metals. This integrated approach aims to enhance the overall efficiency and sustainability of the recycling process, presenting a viable solution

for industrial implementation.

Furthermore, this strategy's development is part of the broader AMBIENTRONIC<sup>+10</sup> Program. This initiative is a collaboration between the Ministry of Science, Technology and Innovation (MCTI), the Ministry of the Environment (MMA), and the Ministry of Industry and Commerce (MDIC), coordinated by DIPAQ/CTI. Since 2008, the program has been focused on creating technologies that promote the sustainability of electronic products, reduce their environmental and public health impact, support a circular economy, and foster the social and economic development of the country.

### Processing of spent lithium batteries

Before the mechanical processing of spent LB, it is essential that they be discharged. Explosions, fires, and the emission of toxic gases are common occurrences that can happen during short circuits or contact of LB elements, posing risks to human health and the environment (Zhang *et al.*, 2021). This can also negatively impact the equipment used in processing, thus affecting the extraction of the metals of interest intended to be recovered from spent LB (Shaw-Stewart *et al.*, 2019). This highlights the risk that the stored energy in spent LB can represent if not discharged before processing.

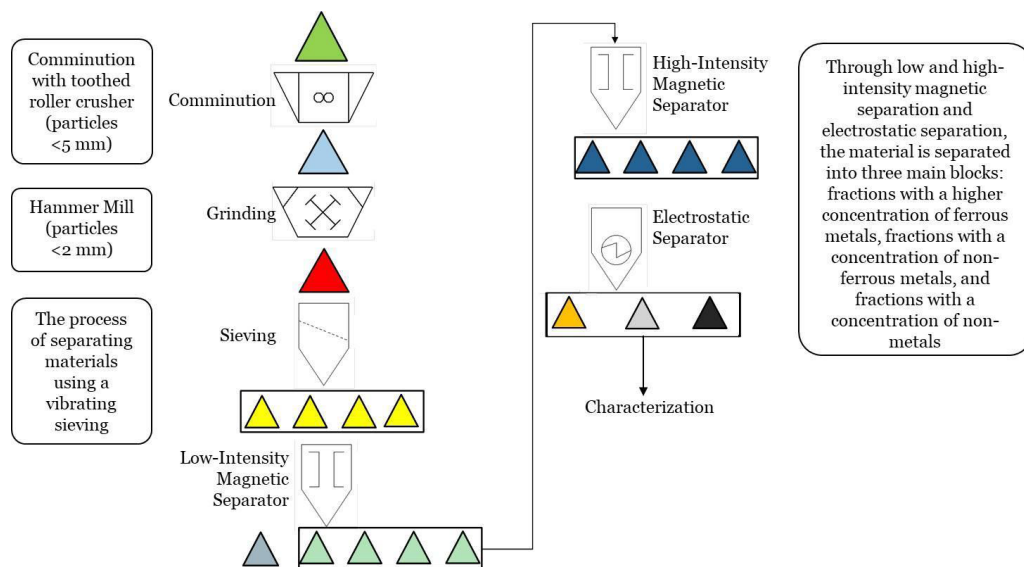
To discharge lithium batteries, Lu *et al.* (2013) used three different concentrations: 1, 5, and 10 wt% of NaCl. The discharge times were 70, 25, and 10 minutes, respectively, resulting in voltages below 0.5 V. The authors punctured the batteries to expedite the discharge process of LB. Li *et al.* (2016) achieved discharges between 73.6% and 76.8% of the original voltage of LB, using concentrations of 5 wt%, 10 wt%, and 20 wt% of NaCl over a period of 24 hours. According to the authors, the best condition was obtained with a concentration of 10 wt% NaCl, resulting in 72% battery discharge in 358 minutes (6 hours). Shaw-Stewart *et al.* (2019) used a concentration of 5 wt% in each of the 26 solutions, including saline and acidic solutions, to discharge LB. After the discharge process, final voltages ranged between 2 and 3 V after 24 hours. The researchers found that solutions providing the best balance between discharge time and corrosion level contained substances such as  $\text{HCO}_3^-$ ,  $\text{HPO}_4^{2-}$ ,  $\text{NH}_4\text{HCO}_3$ ,  $\text{H}_2\text{PO}_4^-$ , and  $\text{NaNO}_2$ . A summary of these studies can be found in Table 2.

Table 2 – Substances found in the literature for discharging lithium batteries

| Author                                       | Battery type                              | Perfo-<br>-ration<br>in<br>battery | Subs-<br>-tances<br>used                                                                                                             | Initial<br>voltage        | Final<br>voltage   | Con-<br>cen-<br>-tration<br>(wt%) | Time                                                                                                                                           |
|----------------------------------------------|-------------------------------------------|------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|---------------------------|--------------------|-----------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| Lu <i>et al.</i> ,<br>2013                   | Coin<br>CR2025                            | Yes                                | NaCl                                                                                                                                 | 60%<br>charge,<br>≈3,85 V | ≈0.5 V             | 1.5 e 10                          | 1% →70 min<br>5% → 25 min<br>10% → 10 min                                                                                                      |
| Li <i>et al.</i> ,<br>2016                   | 18650<br>(typical<br>laptop<br>batteries) | No                                 | NaCl                                                                                                                                 | -                         | -                  | 5.10 e 20                         | 5%→358<br>min→65,0%<br>(max 73.6%)<br>10%→358<br>min→72.0%<br>(max 75.6%)<br>20%→358<br>min→71,4%<br>(max 76.8%)<br><br>max 1460 min<br>(24 h) |
| Shaw-<br>-Stewart<br><i>et al.</i> ,<br>2019 | 18.650                                    | No                                 | HCO <sub>3</sub><br>HPO <sub>4</sub><br>NH <sub>4</sub> H-<br>CO <sub>3</sub><br>H <sub>2</sub> PO <sub>4</sub><br>NaNO <sub>2</sub> | 4.2 V                     | Between<br>2 e 3 V | 5                                 | 1440 min (24 h)                                                                                                                                |

Font: Lu *et al.*, 2013; Li *et al.*, 2016; Shaw-Stewart *et al.*, 2019.

Figure 1 presents a schematic of the mechanical recycling process flow of spent lithium batteries for the initial separation of their constituent materials, with the intention of enhancing the purification levels of the products in subsequent phases, namely leaching and refining. Lithium batteries can be manually disassembled and divided into components such as plastic or metallic casings, polymers, PVC, anode sheets, and cathode sheets; however, using manual disassembly in an industrial processing involving large volumes of batteries would require a dedicated team solely for this initial phase, increasing costs and processing time, impacting the overall feasibility of the process. Physical processing aims to (i) expose encapsulated metals, (ii) eliminate the non-metallic fraction (concentrating the metals of interest), and (iii) pre-separate metals with significant added value from those of little value in the recycled market (Marshall *et al.*, 2020; Sommerville *et al.*, 2020). Therefore, the first step in the route for the mechanical processing of spent lithium batteries is to carry it out through physical crushing and grinding operations. Subsequently, components are separated using techniques that exploit differences in electrical conductivity, density, or other properties. Effective physical methods reduce the cost of subsequent chemical treatment. Some of the current challenges lie in the difficulty of controlling impurities in the recovered products and ensuring that the entire recycling process is more efficient (Makwarimba *et al.*, 2022).

**Figure 1 – Schematic diagram of the mechanical processing flow of lithium batteries.**

Font: Authors, 2024.

After the physical separation of electrode materials, hydrometallurgy is employed through the leaching process. In this stage, the result of mechanical processing is chemically treated, giving rise to a chemical solution containing the metals of interest. Silva, Afonso, and Mahler (2018) used lithium batteries from three different manufacturers, produced between 2010 and 2014, extracted from mobile phones in Brazil to investigate the efficiency of different acids in the leaching process. The authors found that the electroactive mass (anode, cathode, and electrolyte) constitutes 40% of the total battery mass by weight. Within this electroactive mass, cobalt and lithium are the most abundant metals, making up 40% and 12% by weight of the electroactive mass, respectively. Other elements identified in small quantities were aluminum, copper (both resulting from the exfoliation of the sheets), calcium, nickel, and phosphorus; the latter suggests that the electrolyte is lithium hexafluorophosphate ( $\text{LiPF}_6$ ). Table 3 presents the mass percentage of lithium battery components.

### Acids in Leaching

Once the initial separation using physical processing is performed, chemical processing is employed for the selective separation of elements of interest (Miao *et al.*, 2022; Zhao *et al.*, 2020). The chemical processing used in recovering valuable elements from lithium batteries (BL) is related to the hydrometallurgical method (Ordoñez, Gago, Girard, 2016). This method is dominant as it is simple and provides high material recovery rates, and it can be repeated through cyclic purification operations (Meshram *et al.*, 2020).

**Table 3 – Average composition of lithium batteries from three different manufacturers.**

| Components                     | Percentages (w/w) |
|--------------------------------|-------------------|
| Cathode + Anode + Electrolyte* | 40.0%             |
| External plastic casing        | 23.0%             |
| Steel shielding                | 10.5%             |
| Non-aqueous solvent            | 4.5%              |
| Copper foil                    | 8.2%              |
| Aluminum foil                  | 6.1%              |
| Polymeric separator            | 5.1%              |
| Electrical contacts            | 2.6%              |

\* Carbon accounts for 30-32% w/w of these components (12-13% w/w of the total sample).

Font: Silva, Afonso, and Mahler, 2018.

In the hydrometallurgical technique, various processes are employed to dissolve and extract metals in an aqueous medium. These processes include acid leaching (Meshram; Pandey; Mankhand, 2015; Paulino; Busnardo; Afonso, 2008), chemical precipitation (Guzolu *et al.*, 2016; Sun *et al.*, 2017), solvent extraction (Paulino, Busnardo, Afonso, 2008; Sun *et al.*, 2018), and electrochemical separation (Battistel *et al.*, 2020). The preliminary step involves the dissolution of the metals of interest, such as Co, Li, Ni, and Mn, through acid leaching. Subsequently, these metals are extracted from the leaching solution by selective methods. The use of hydrometallurgical treatments offers several advantages, such as greater flexibility and reliability, lower environmental impact compared to conventional pyrometallurgical methods, lower energy consumption, high chemical reaction rates, and obtaining metals with high purity; this approach allows the extraction of all metals present in spent lithium batteries (Garcia *et al.*, 2008; Sun, Qiu, 2012).

The leaching agents used in the literature can be mainly classified as inorganic and organic acids (Huang *et al.*, 2018) as shown in Table 4. The variety of techniques using different acids for leaching reported in the literature is extensive, including inorganic acids such as hydrochloric acid (HCl) (Guzolu *et al.*, 2016; Wang *et al.*, 2009), nitric acid (HNO<sub>3</sub>) (Castillo *et al.*, 2002; Lee, Rhee, 2002), and sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) (Chen Ho, 2018; Zhu *et al.*, 2012); and organic acids, such as citric acid (C<sub>6</sub>H<sub>8</sub>O<sub>7</sub>) (Chen, Zhou, 2014; Fan *et al.*, 2016; Li *et al.*, 2010a), oxalic acid (H<sub>2</sub>C<sub>2</sub>O<sub>4</sub>) (Chen *et al.*, 2011; Sun, Qiu, 2012; Zeng, Li, Shen, 2015), ascorbic acid (C<sub>6</sub>H<sub>8</sub>O<sub>6</sub>) (Li *et al.*, 2012), DL-malic acid (C<sub>4</sub>H<sub>5</sub>O<sub>6</sub>) (Li *et al.*, 2010b; Sun *et al.*, 2017), succinic acid (C<sub>4</sub>H<sub>6</sub>O<sub>4</sub>) (Li *et al.*, 2015), L-aspartic acid (C<sub>4</sub>H<sub>7</sub>NO<sub>4</sub>) (Li *et al.*, 2013), L-tartaric acid (C<sub>4</sub>H<sub>6</sub>O<sub>6</sub>) (Cheng, 2018; He *et al.*, 2016, acetic acid (CH<sub>3</sub>COOH) (Golmohammadzadeh, Rashchi, Vahidi, 2017), mild phosphoric acid (Chen *et al.*, 2017), and iminodiacetic acid (C<sub>4</sub>H<sub>7</sub>O<sub>4</sub>N) (Nayaka *et al.*, 2016) used to reduce environmental pollution (Natarajan, Boricha, Bajaj, 2018). The use of inorganic

acids can lead to high water and chemical consumption and, in the long term, increase equipment corrosion and the generation of secondary waste (Innocenzi; De Michelis; Vegliò, 2017; Tesfaye *et al.*, 2017). Rocchetti *et al.* (2013) evaluated the emission of gases from inorganic acids in the processing of electronic waste and concluded that the use of these acids emits gases such as CO<sub>2</sub>, Cl<sub>2</sub>, SO<sub>2</sub>, and ethane. Another disadvantage of using inorganic acids is that the solution's pH (leaching liquid) is very low, preventing the direct extraction of metals from the solution, making the process more complex (Yao *et al.*, 2018). With inorganic acids, the disposal of water containing acids and acid leachates is the main problem leading to economic and energy losses (Meshram *et al.*, 2020).

Table 4 – Acids used in the literature for leaching.

| Inorganic Acids        |                                            |                     |                                     | Organic Acids    |                               |                     |                                          |
|------------------------|--------------------------------------------|---------------------|-------------------------------------|------------------|-------------------------------|---------------------|------------------------------------------|
| Substance              | Reference                                  | Concen-<br>-tration | Efficiency<br>(%)                   | Substance        | References                    | Concen-<br>-tration | Efficiency<br>(%)                        |
| Hydrochlo-<br>ric Acid | Wang <i>et al.</i><br>(2009);              | 4 M                 |                                     | Citric<br>Acid   | Fan <i>et al.</i><br>(2016);  | 1.25 M              |                                          |
|                        | Shuva<br>and Kurny<br>(2013);              | 3 M                 | Co: 97-99<br>Li: 97-98<br>Mn: 98-99 |                  |                               |                     | Co: 90-97<br>Li: 89-100<br>Mn: 28-98     |
|                        | Guzolu <i>et al.</i><br>(2016);            | 5 M                 | Ni: 97-99                           |                  | Zheng <i>et al.</i><br>(2016) | 4 M                 | Ni: ≈93                                  |
|                        | Silva <i>et al.</i><br>(2018).             | 12 M                |                                     |                  |                               |                     |                                          |
| Nitric Acid            | Lee and<br>Rhee<br>(2002);                 | 1 M                 | Co: 50-95<br>Li: 80-95<br>Mn: ≈20   | Oxalic<br>Acid   | Sun and<br>Qiu (2012);        | 2 M                 | Co: 97-98<br>Li: ≈98                     |
|                        | Castillo <i>et al.</i> (2012).             | 2 M                 | Ni: ≈40                             |                  | Zeng <i>et al.</i><br>(2015)  | 15 g/L              |                                          |
| Sulfuric<br>Acid       | Chen and<br>Ho (2018);                     | 2 M                 |                                     | Malic<br>Acid    | Li <i>et al.</i><br>(2010a);  | 1.5 M               |                                          |
|                        | Meshram,<br>Pandey,<br>Mankhand<br>(2015); | 1 M                 | Co: 66-98<br>Li: 90-99<br>Mn: 50-98 |                  |                               |                     | Co: 46-98<br>Li: 82-99<br>Mn: ≈99        |
|                        | Silva <i>et al.</i> ,<br>(2018);           | 9 M                 | Ni: 96-98                           |                  | Sun <i>et al.</i><br>(2017).  | 1.2 M               | Ni: ≈99                                  |
|                        | Zhu <i>et al.</i><br>(2012).               | 2 M                 |                                     |                  |                               |                     |                                          |
| Hydrofluoric<br>Acid   | Silva <i>et al.</i><br>(2018).             | 20 M                | Co: ≈98<br>Li: 80-97                | Tartaric<br>Acid | Cheng<br>(2018);              | 1 M                 | Co: 46.6-<br>99.31<br>Li: 82.7-<br>99.07 |
| Formic Acid            | Silva <i>et al.</i><br>(2018).             | 10 M                | Co: ≈85<br>Li: ≈83                  |                  | He <i>et al.</i><br>(2017).   | 2 M                 | Mn: 99,3<br>Ni: 99.31                    |

Font: Authors, 2024.

Leaching with organic acids such as citric, oxalic, malic, and tartaric acids can achieve efficiencies comparable to, and in some cases exceed, those of inorganic acids like nitric acid. Table 4 shows that these organic acids are effective in recovering metals like cobalt and lithium, often performing similarly to hydrochloric and sulfuric acids. Organic acids, termed green leachants, offer advantages due to their biodegradability and absence of emission of harmful gases into the atmosphere (Chen, Zhou, 2014; Horeh *et al.*, 2016; He *et al.*, 2017; Li *et al.*, 2017). These studies highlight benefits such as the non-emission of harmful gases, reduced equipment corrosion, and decreased risks for operators, in addition to the selective leaching of valuable metals present in discarded

LIBs. Furthermore, organic acids can be recycled after the leaching process (Chen, Zhou, 2014). Although the initial cost of leaching with organic acids may be higher, Pathak, Vinoba, and Kothari (2021) and Urias *et al.* (2020) emphasize that this approach can be offset by greater selectivity and positive environmental benefits.

## Conclusions

The determination of appropriate parameters for each stage of the process is achieved through chemical characterization, aiming to maximize the efficiency of the physical processing. This enables the identification of the highest concentration of elements of interest, leading to an enhancement in the purification levels of products in subsequent phases.

In the particular case of lithium battery recycling, hydrometallurgy stands out as dominant compared to other recycling techniques, proving to be a viable technology for extracting precious metals from lithium batteries.

Literature studies have revealed that organic acids exhibit good efficiency in the extraction of lithium, nickel, cobalt, and manganese from lithium batteries, making them a viable option in recycling processes, despite having slightly lower efficiency than inorganic acids. Organic acids still need to be more comprehensively examined experimentally for lithium battery leaching, helping to avoid toxic agents harmful to the process (fluorine, chlorine, and sulfur), reducing process management complexity, and thus, minimizing energy loss.

Experimental research has further shown that organic acids are environmentally friendly, as they do not emit greenhouse gases and can be recycled after use. Therefore, the possibility of using organic acids in leaching for the separation of elements from lithium batteries can create an advantageous situation both economically and environmentally.

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**Deyber Alexander Ramirez Quintero**

✉ [deyber@unicamp.br](mailto:deyber@unicamp.br)

ORCID: <https://orcid.org/0000-0003-3130-1511>

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**Marcos Batista Cotovia Pimentel**

✉ [marcos.pimentel@cti.gov.br](mailto:marcos.pimentel@cti.gov.br)

**Sebastião Eleutério Filho**

✉ [sebastiao.eleuterio@cti.gov.br](mailto:sebastiao.eleuterio@cti.gov.br)

**Roberto Mendes de Oliveira**

✉ [carlos.oliveira@cti.gov.br](mailto:carlos.oliveira@cti.gov.br)

# Processamento mecânico e lixiviação química na recuperação de elementos valiosos de baterias de lítio

Deyber Alexander Ramirez-Quintero  
IMarcos Batista Cotovia Pimentel  
Sebastião Eleutério Filho  
Carlos Roberto Mendes de Oliveira

**Resumo:** A implementação do Sistema de Logística Reversa do Brasil, regulamentado pelo decreto nº 10.240/2020, enfrenta desafios ambientais e tecnológicos significativos na coleta e tratamento de resíduos elétricos e eletrônicos pós-consumo (e-waste). Para mitigar os impactos adversos do e-waste no meio ambiente e na saúde humana, é necessário desenvolver tecnologias sustentáveis. Isso inclui a criação de rotas tecnológicas para reutilizar materiais valiosos do e-waste, apoiando os princípios da economia circular e promovendo o desenvolvimento socioeconômico. Especificamente, o crescente descarte de baterias de lítio exige métodos de reciclagem eficientes, de baixo custo e ambientalmente amigáveis. Este estudo explora o estabelecimento de uma rota tecnológica para recuperar elementos valiosos de baterias de lítio esgotadas. Enfatiza o processamento físico sem tratamento térmico e os métodos hidrometalúrgicos que envolvem lixiviantes inorgânicos e orgânicos. O objetivo é facilitar a adoção desses métodos no setor industrial do país.

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**Palavras-chave:** Sistema de Logística Reversa; Baterias de Lítio; Processamento mecânico; Resíduos Eletroeletrônicos; Processo de lixiviação.

# Procesamiento mecánico y lixiviación química en la recuperación de elementos valiosos de baterías de litio

Deyber Alexander Ramirez-Quintero  
IMarcos Batista Cotovia Pimentel  
Sebastião Eleutério Filho  
Carlos Roberto Mendes de Oliveira

**Resumen:** La implementación del Sistema de Logística Inversa de Brasil, regulado por el decreto 10.240/2020, enfrenta desafíos ambientales y tecnológicos significativos en la recolección y tratamiento de residuos eléctricos y electrónicos postconsumo (e-waste). Para mitigar los impactos adversos del e-waste en el medio ambiente y la salud humana, es necesario desarrollar tecnologías sostenibles. Esto incluye la creación de rutas tecnológicas para reutilizar materiales valiosos del e-waste, apoyando los principios de la economía circular y fomentando el desarrollo socioeconómico. Específicamente, el creciente descarte de baterías de litio requiere métodos de reciclaje eficientes, de bajo costo y respetuosos con el medio ambiente. Este estudio explora el establecimiento de una ruta tecnológica para recuperar elementos valiosos de baterías de litio agotadas. Se enfatiza el procesamiento físico sin tratamiento térmico y los métodos hidrometalúrgicos que involucran lixiviantes inorgánicos y orgánicos. El objetivo es facilitar la adopción de estos métodos en el sector industrial del país.

**Palabras-clave:** Sistema de Logística Inversa; Baterías de Litio; Procesamiento mecánico; Residuos Electroelectrónicos; Proceso de lixiviación.

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