Mapping and Analysis of the Lithium Battery Recycling Process in Indonesia's Emerging Industry

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**Abstract.**  The demand for Lithium-Ion batteries as energy storage systems is growing rapidly, driven by their use in electronic devices, electric vehicles, and medical equipment. Since these batteries have a limited lifespan, effective recycling management within the lithium battery industrial chain is essential to reduce environmental impacts and mitigate the scarcity of raw materials. In Indonesia, Lithium-Ion battery technology is still emerging, and there has been no comprehensive mapping of the recycling process. Mapping is carried out to determine the direction of the recycling process flow and the stages of the process, while analyzing the constraints and challenges, as well as the solutions that can be applied in the process. Using descriptive qualitative methods, including interviews, observations, and a systematic literature review, the study provides a framework for integrating a circular economy within Indonesia’s lithium battery industry. This framework includes forward logistics flows and the establishment of reverse logistics, with three key process stages: pre-treatment, material recovery, and refining. The study also identifies technical and non-technical challenges that can be addressed through technology development, digitization, improved recycling methods, and strengthened policies, as well as enhanced collaboration among stakeholders.

**Keywords:** Lithium-Ion Battery, Recycling, Mapping, Circular Economy

# INTRODUCTION

Currently, the most widely used energy sources are fossil fuels such as oil, gas, and coal. More consumption of fossil energy can decrease available energy reserves and they can be depleted (non-renewable) in the future[1]. The increase in energy consumed by several sectors and the resulting impacts can endanger economic and environmental development in Indonesia. To keep energy security in the future, there is an urgent need for Indonesia to transition from reliance on fossil fuels to renewable energy sources so that energy sustainability and availability can remain guaranteed [2]. The source of New and Renewable Energy (EBT) is an alternative, using electric vehicles or transportation as stated in the Republic of Indonesia Presidential Regulation Number 55 of 2019 regarding the Acceleration of the Battery Electric Vehicle Program for road transport, where the use of batteries (Lithium-Ion) as the main energy source in electric vehicles to replace or reduce the use of fossil fuels and reach the Net Zero Emissions by 2050 [3] [4].

However, despite the growing interest in electric vehicles, the accelerated shift to EVs brings about a significant increase in demand for Lithium-Ion batteries. The World Economic Forum reported that the total global battery demand in 2030 is expected to increase at an annual rate of around 23% and exceed 3500 GWh, almost ten times higher than demand in 2021. It will keep increasing and exceed 5300 GWh in 2035 with estimates Battery demand in Indonesia reaching around 59.1 GWh . Indonesia's abundant natural resources of key minerals or raw materials for batteries such as nickel ore, crude oil, copper, manganese, and aluminum can result in a competitive advantage in the regional EV battery chain development. Therefore, they can encourage the increase in the battery industry in Indonesia [5]. In January 2020, the government imposed a ban on nickel ore exports to increase value-added opportunities for nickel products and keep supporting local industries [6].

The development of Lithium-Ion batteries in Indonesia for EVs and other devices like power banks and smartphones is still in its early stages, with significant efforts focused on research and development. Although various institutions, including government labs, universities, and private companies, are involved in battery R&D, the growing demand for lithium batteries will inevitably lead to increased battery waste [7]. Both industrial by-products and consumer battery waste will contribute to environmental challenges, especially as batteries reach the end of their lifecycle, which is typically within a few years. Consequently, the lack of proper recycling systems poses a significant threat, as battery waste could lead to environmental pollution and resource depletion [8]. Therefore, there is a clear gap in research on effective recycling strategies to mitigate these negative impacts.

The average life cycle of a cellular telephone or laptop takes 1-3 years while Electric Vehicle (EV) takes around 8-10 years [9]. In the future, as the volume of spent Lithium-Ion batteries (LIBs) grows, it will be critical to develop policies for recycling these batteries to recover valuable materials and reduce environmental damage. Toxic substances like hexafluorophosphates and Polyvinylidene Fluoride (PVDF) binders in batteries can cause fluorine pollution and harm the ozone layer [10]. Furthermore, valuable metals in used LIBs can enter the food chain and pose serious health risks [11]. Research has shown that used LIBs contain significant amounts of valuable metals—5–20% cobalt, 5–10% nickel, 5–7% lithium, and 5–10% copper, along with aluminum and iron [12]. Given the concentration of these materials in spent batteries, there is a strong economic incentive to recover them effectively, especially considering that the lithium content in used LIBs is much higher than in natural ores or brine pools [13]. Therefore, addressing the recycling challenge is essential for environmental protection, resource recovery, and economic sustainability [14].

Despite the importance of recycling, there has been no systematic analysis or mapping of the Lithium-Ion battery recycling process in Indonesia. This research aims to address this gap by mapping the stakeholders involved in the recycling process across the Lithium-Ion battery supply chain in Indonesia. Through interviews with key stakeholders—producers, R&D teams, recyclers, and consumers—this study provides a comprehensive overview of the current recycling processes. Additionally, company visits and a systematic literature review were conducted to develop a deeper understanding of the existing challenges and opportunities for improving the recycling process in Indonesia's lithium battery industry. By filling this gap, the study contributes to the growing body of knowledge on sustainable battery management and offers practical insights for enhancing recycling practices in Indonesia.

# METHODS

The research employed a descriptive qualitative method to thoroughly and deeply describe the recycling process in the lithium battery industry in Indonesia. This approach included interviews, observations, and a systematic literature review to provide a comprehensive understanding of the phenomenon in real-time [15] [16]. Data Collection Techniques:

1. In-depth interview

Interviews were conducted with a range of stakeholders involved in lithium battery management and research. The selection criteria for interview informants included their expertise and direct involvement in lithium battery activities. Key informants were chosen based on their roles in recycling operations, such as recyclers who handle battery waste and consumers who use lithium batteries and are familiar with the recycling process. These interviews aimed to gather detailed insights into the flow of lithium battery waste and the implementation of recycling processes within the industrial chain.

Limitations and Addressing Them:

One limitation of this method was the potential for bias in the information provided by the interviewees, as they might present an idealized view of the recycling process. To mitigate this, a diverse range of informants was interviewed to ensure a balanced perspective and triangulate data with other sources.

1. Observation

Observations were carried out both online and offline. The research team observed various entities, including research groups, startups producing materials for lithium battery cathodes, manufacturing and research organizations, consumers or users of lithium batteries, and workshops/MSMEs involved in battery reuse, customization, production, repair, and sales. The observation focused on activities from raw material handling to the recycling process.

Limitations and Addressing Them:

A limitation of the observation method was the potential lack of access to certain facilities or processes. To address this, the research included both online observations of publicly available information and on-site visits where possible, ensuring a more comprehensive view of the recycling activities.

1. Systematic Literature Review

A structured literature review was conducted using the Scopus, PubMed, and Google Scholar databases, facilitated by the Publish or Perish software. This process identified 536 publications, of which 62 journals or articles met the criteria for full-text review. The review focused on the processes and methods of recycling lithium batteries, as well as the obstacles and challenges encountered. The data obtained from this review provided valuable mapping information, complementing the data collected from interviews and observations.

Limitations and Addressing Them:

One limitation of the literature review was the potential exclusion of relevant studies not indexed in the databases used. To counter this, the review was supplemented with additional sources identified through reference lists and recommendations from experts.

Data Analysis: The analysis employed the Flow Chart technique combined with Miles and Huberman's interactive data analysis model. This model involves three stages: (1) reducing data by focusing and categorizing it into groups, (2) presenting the grouped data in the form of images, graphs, or tables, and (3) concluding the findings from each data collection method. This approach ensured that the mapping of the recycling process was based on a comprehensive analysis of the collected data.

# RESULTS AND DISCUSSION

## INTERVIEW RESULT

Interviews were conducted by involving 4 informants who took activities in lithium batteries. They were producers, RnD, recyclers, and consumers with a code for each informant as reported in **TABLE 1** below.

**TABLE 1**. Informant Coding

|  |  |
| --- | --- |
| Informant Code | Position |
| RA | CEO of PT Batex Energi Mandiri |
| YU | Administrative Staff of PUI Baterai UNS |
| PS | Recycling Researcher of UNS Lithium Batteries |
| PR | Business Owner of SES (*Second Energy Storage*) |

There are discussion topics in the interviews with each informant with the indicators adjusted based on the research objectives which are divided into categories and sub-categories as reported in **TABLE 2** below.

**TABLE 2**. Data Categorization

| Informants | Data Categorization | Sub-Categories |
| --- | --- | --- |
| Producer | Activities | Production, Recycling, Reuse |
|  | Stakeholder | Consumer, Competitor |
|  | Material | Supplier, Kind of Materials |
| RnD | Development | Product, Recycling |
| Administrative Staff | *Startup,* Stakeholder |
| Recycler | Recycling | Stage of Process, discharging, dismantling |
| Facility | Obstacle |
| Material | Used Battery Collection |
| Consumer | Reuse | Stage of Process, Use |
| Facility | Obstacle |
| Material | Used Battery Collection |
| Product | Final Consumer |

The next stage is presenting the data of interview results with each of the following informants.

1. Manufacturer of Lithium Battery

Information was gathered from the CEO of PT Batex Energi Mandiri on October 16, 2023. PT Batex produces up to 1000 lithium battery cells daily, utilizing NMC and LFP types. In 2022, their revenue increased to IDR 4,964,454,397 from IDR 1,632,292,977 in 2021. About 60% of raw materials are imported, mainly from China, with the remainder sourced domestically. Currently, PT Batex does not recycle batteries but reuses and repairs them. Recycling is still in the research phase at UNS and has not been implemented on a large scale.

1. RnD of Lithium Battery

Data was collected from the administrative staff of PUI Battery UNS on August 11, 2023. PUI Battery UNS is involved in producing various lithium battery materials and researching recycling methods, particularly hydrometallurgical techniques. They accept used batteries for recycling and commercialize research through startups like PT Polimikro and PT Batex. Collaborations include institutions such as ITB and UI, and companies like Pertamina.

1. Recycler of Lithium Battery

Information was obtained from a researcher at Pusbangnis UNS on July 31, 2023. The researcher detailed the recycling process for NCA-type lithium batteries using hydrometallurgical methods, including chopping, acid leaching, and coprecipitation. Recycling is currently limited by facility and equipment constraints and is primarily at the laboratory scale. Used batteries are sourced from UNS Battery PUI's collaboration with Pertamina.

1. Consumer of Lithium Battery

Data was collected from the owner of SES workshop on August 25, 2023. The workshop specializes in custom battery solutions, using both new and used cells for various applications like EVs and street lighting. Used batteries are tested for performance and reprocessed into modules or packs. Final consumers include individuals and businesses needing customized battery solutions.

## OBSERVATION RESULT

1. Active Material Manufacturers and Suppliers

The startup that has produced and supplied active lithium battery materials is PT Polimikro Berdikari Nusantara (PBN) with the main products as seen in TABLE 3 below.

**TABLE 3**. Active Material Products of PBN

| Products | Categories |
| --- | --- |
| Lithium | Lithium Carbonate (Li2CO3) |
|  | Lithium Hydroxide Monohydrate (LiOH.H2O) |
| LFP | Lithium Ferro-Phosphate (LFP) |
| NMC | Lithium Nickel Mangan Cobalt Oxide (NMC 442) |
|  | Lithium Nickel Mangan Cobalt Oxide (NMC 622) |
|  | Lithium Nickel Mangan Cobalt Oxide (NMC 532) |
|  | Lithium Nickel Mangan Cobalt Oxide (NMC 111) |
| NCA | Lithium Nickel Cobalt Alumunium Oxide (NCA) |

Apart from cathode active material products (advance), PBN produces and provides custom materials adjusted to customer demands such as making Lithium Cobalt Oxide (LCO) and providing functional materials of lithium hydroxide, nickel chloride, nickel sulphates, and other chemical materials that have been marketed through e-commerce Tokopedia Polimikro Official. PBN has currently collaborated and become a supplier of active lithium battery materials to PT Batex, PT Lectro, and PT International Chemical Industry (ABC).

1. Lithium Battery Research and Development (RnD)

RnD at PUI-PT UNS Electrical Energy Storage Technology is part of a government program under Kemendikbud Ristek Dikti, which funds the RISPRO initiative to support electric vehicle innovation through academic-business collaboration. Research results include various cathode materials (LFP, LCO, LMO, NCA, NMC111, NMC622, and nickel-rich NMC) and anode materials (Graphite, LTO, LZO, Silica, Lithium Vanadate, and Metal Organic Framework). These materials have been used in lithium batteries and for recycling research, particularly using hydrometallurgical methods for NCA material. The processes of lithium battery manufacturing research and product downstream can be seen in **TABLE 4** below.

**TABLE 4**. Production and Downstream Process Flow of UNS Battery PUI

| Activities | Stages |
| --- | --- |
| Manufacture of cathode and anode active materials | Formulation and preparation of raw materials, manufacture of raw material solutions, reaction process for the formation of semi-finished materials (precursors), aging process of raw material solutions, deposition, filtering and drying, addition and mix of lithium sources, heating with a furnace, sieving process, and storage raw material. |
| Material testing | X-ray diffractometer (XRD), Fourier Transformed Infra-Red (FTIR), Scanning Electron Microscope (SEM), and Potentiostat tests. |
| Manufacture of 18650 cylindrical cell batteries | Mixing, coating anode and cathode, pressing anode and cathode film with adjusted thickness, winding, welding, electrolyte filling, cell characterization, quality control, testing cycle capacity, and battery temperature, and packing battery cells and ready to use. |
| Product downstream | PT Batex Energi Mandiri is downstream battery cells and packs, PT Ekolektrik Konversi Mandiri is a lithium battery-based vehicle conversion service, and PT Polimikro Berdikari Nusantara (PBN) is a downstream active material/provider and supplier of lithium battery cathodes. |

1. Lithium Battery Consumers

In Indonesia, several consumers are involved in reusing, repairing, or customizing lithium battery cells and packs. PT Ekolektrik utilizes lithium batteries for the conversion of electric vehicles, while PT Lectro Energi Semesta focuses on producing modules and packs for energy storage applications in PJU and PLTS. Additionally, E-Clont Energy Solusi Energi and DYVOLT workshops are engaged in providing and customizing battery modules and packs, contributing to the reuse of used lithium batteries. The flow of lithium battery reuse can be seen in **FIGURE 1** below.

**FIGURE 1**. Lithium Battery Reuse

Reusing used lithium batteries involves repair shops and Micro, Small, and Medium Enterprises (UMKM) that specialize in custom work, repairs, and assembly of battery modules and packs. These entities not only purchase new cells but also collect used batteries from sources like laptops, power banks, and electric vehicles, either through online marketplaces or directly. Usable batteries are refurbished and assembled into new modules, while those that are damaged or at End-of-Life (EOL) are sent for recycling.

1. Lithium Battery Recycling Research and Development Party

In addition to UNS, the Green Battery and Electronic Waste Recycling Research Group (Greenery) at Gadjah Mada University (UGM) is actively involved in lithium battery recycling research. This research group includes departments in mechanical and industrial engineering, chemical engineering, electrical engineering, and information technology. Their work focuses on developing sustainable recycling technologies and circular economy systems to address challenges related to lithium battery waste in Indonesia.

The recycling process starts with collecting and sorting battery waste. Functioning batteries can be reused, but EOL or damaged batteries are first discharged to prevent hazards, then dismantled for material separation. This includes physical, magnetic, and thermal separation of components. The hydrometallurgical process recovers valuable metals such as nickel, manganese, and cobalt, as well as lithium carbonate with high purity, producing a cathode precursor for new battery production.

## SYSTEMATIC LITERATURE REVIEW RESULT

Systematic literature review refers to three databases of Scopus, PubMed, and Google Scholar as a comparison of topics or similar criteria through journal searches by searching keywords adjusted to themes or cases of lithium battery recycling, reverse logistics, circular economy, sustainability, or other research problems. Based on the journal searches, it is found that there are 536 publications in the journals on the three databases, which can be seen in **FIGURE 2** PRISMA Schematic Literature Review below.



**FIGURE 2**. PRISMA Systematic Literature Review

After review, it is found that 62 journals meet the criteria, and 24 journals discuss material recovery and lithium battery recycling methods as reported in **TABLE 5** below.

**TABLE 5**. Lithium Battery Recycling Methods

|  |
| --- |
| Methods |
| **Hydrometallurgy**  The hydrometallurgical process has the highest efficiency compared to other methods and can recover a wide range of metals. This process takes place at moderate temperatures in an aqueous sulfuric acid solution involving leaching, leaching, extraction, and precipitation to convert the solid metal in the residue into a solution or alloy state. Recovery of >99.96% cobalt, >99.90% lithium, and >95% nickel can be recovered from LIBs using hydrometallurgical processes. References: [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] |
| **Pyrometallurgy**  In pyrometallurgical process, LIB is melted by heating to about 1,500° with three temperature zones: pre-heating zone (<300°C for electrolyte removal), plastic pyrolysis zone (around 700°C) and melting and reaction zone (1200-1450 °C), recovering metals such as Co, Ni, and Cu, recovered from the LIB in the form of alloys, and Li, Al, Si, Ca, and Fe, formed in the slag. Pyrometallurgy is a flexible process, recovering only high-value materials including nickel, cobalt, and copper. References: [18] [21] [27] [22] [28] [23] [25] [26] |
| **Hydro and Pyro combination**  The combination of pyrometallurgical and hydrometallurgical approaches can minimize the costs of both processes. Several components, including manganese, aluminum, carbon, electrolytes, polymers, and lithium, are consumed in the pyrometallurgical process, resulting in energy or slag. Other metals, such as cobalt, nickel, and copper, are recovered in alloy form and require advanced hydrometallurgical procedures to separate them. References: [18] [20] [22] [28] [29] [30] |
| **Direct Recycling**  Direct recycling is dismantling the anode and cathode components of a lithium battery, followed by maintenance, processing, and production of the components for reuse. A direct recycling process is a used LIB that is stripped of its subcomponents, including anode and cathode materials, and peeled by using solvent extraction with supercritical carbon dioxide (CO2) or mild heat treatment to remove binders and unwanted organic materials. Used cathode materials can be directly regenerated through a relitration process so that the main metals in them can be recovered in a form that can be directly reused. Direct recycling has advantages in terms of generating higher revenues because more materials can be recovered. Referensi: [19] [22] [27] [30] [31] [32] [33] [34] |

The process and stages of hydrometallurgical recycling based on the full-text review in the table above can be presented in **FIGURE 3** below.

**FIGURE 3**. Hydrometallurgical Recycling Process

Hydrometallurgical recycling takes stages of the recycling process where used lithium batteries (cells, packs, and modules) require dismantling, crushing, and sorting the components in lithium batteries such as plastic, copper (Cu), aluminum (Al), anode material, cathode and electrolyte for the next stage of the process to be recovered. The cathode material is subjected to a leaching process using chemical solutions of inorganic acids such as hydrochloric acid (HCL), sulfuric acid (H2SO4), nitric acid (HNO3), and phosphoric acid (H3PO4) or the use of organic acids in the form of citric, ascorbic, oxalic, formic acids and a combination with hydrogen peroxide (H2O2) in recovering lithium battery cathode materials. The use of a mixture of inorganic and organic acids can restore the cathode material to the maximum. After the acid dissolution process is carried out, the next stage is to precipitate the material for extraction so that more than 99.96% of cobalt, 99.90% of lithium, and 95% of nickel can be recovered. to be used as cathode material in the re-production of new lithium batteries. The stages in the pyrometallurgical recycling process resulting from the full-text review above are presented in **FIGURE 4** below.



**FIGURE 4**. Pyrometallurgical Recycling Process

This pyrometallurgical recycling stage is carried out by collecting the used lithium batteries, both lithium cells, packs, and modules, and then shredding, which is an option or can be melted directly. In general, it is melted to a temperature of 1500˚C by taking three melting stages. The first melting stage is a pre-heating zone with a temperature of <300˚C as the removal of electrolytes in lithium batteries. The second stage is a pyrolysis zone with a temperature of around 700˚C and the third one is a melting and reduction zone with temperatures reaching 1200-1450˚C where this melting will produce alloys and slag. The alloy itself is a material that can be recovered, and the slag is a material that cannot be recovered which is generally disposed of because the material in the slag has low economic value when recovered. The recovered material is in the forms of cobalt (Co), nickel (Ni), and copper (Cu) while the material in the slag has a small possibility of being recovered in the forms of lithium (Li), aluminum (Ai), silicon (Si), manganese (Mn) and iron (Fe). However, alloys and slag can undergo further processing to recover the material by adding a hydrometallurgical process so that the recovered material can be extracted and produce pure material that will be used for the reproduction of lithium batteries later. The stages in the direct recycling process are presented in **FIGURE 5** below.

**FIGURE 5**. Direct Recycling Process

Direct recycling takes a special stage with a lithiation or hydrothermal process in the form of recovering the cathode by adding lithium material to the battery. The recycling process stages immediately begin by dismantling, destroying, and sorting the subcomponents of the used lithium batteries (cells, modules, and packs) such as the anode and cathode components of the battery using physical, magnetic, and thermal separation methods (organic solvents and light heat treatment) to separate and purify the materials. The cathode material can be directly regenerated through a relitivation process in the form of hydrothermal use followed by a solid phase annealing and sintering process by adding back lithium material to restore the components that make up the battery cathode. This direct recycling can make it possible to recover more of the important metals in lithium batteries so that production and reuse can be carried out more effectively and eco-friendly or environmentally friendly. Currently, based on several studies, the direct recycling process is included in the category of new recycling techniques and the development stage on a laboratory scale. The general recycling flow has been explained in 14 journals (see **TABLE 6**).

**TABLE 6**. Recycling Flow

| Recycling Flow | References |
| --- | --- |
| Collection, battery discharge, separation and disassembly, pre-treatment stage, metal extraction (copper, cobalt, lithium, nickel, manganese, aluminum, and silicon), purification and reuse in the form of recovery options (battery recycling, remanufacture of battery, or reuse of battery modules or complete battery packs). | [18]  [20] [27] [35] [36] [28] [37] |
| Raw material supply, cell and module manufacturing, disassembly, module and cell assessment, Reverse Logistics Infrastructure (RLI), battery assessment, reuse and recycling, and IoT information infrastructure. | [38]  [39] |
| Recycling begins with waste collection and then a pre-treatment process involving the separation and classification of various components and elements of the used LIB. The processing stage involves crushing and grinding the used battery cells into a fine powder and then refining the separated metal or taking the material recovery stage involving the recovery of valuable metals such as cobalt, nickel, and copper from used battery cells and returning them to the supply chain for re-production. | [31]  [40]  [33]  [41]  [42] |

The flow in lithium battery recycling is related to the upstream and downstream lithium battery industry in supplying materials for recycling and reusing as presented in **FIGURE 6** based on the results of the full-text review in the table above.

The lithium battery recycling process flow in the lithium battery industrial chain includes the forward supply chain to the reverse supply chain for reuse or production. The forward supply chain begins with the production and supply of initial materials, which at this stage involves the mining industry in processing raw materials and then the RnD and manufacturing industries in the production of cathode and anode components as well as the production of lithium batteries (cells, modules, and packs). The downstream parties’ market and use lithium batteries (cells, modules, and packs) in the electronics industry, electric vehicles, and battery energy storage systems (BESS) as well as other needs that require the use of lithium batteries. A reverse supply chain is implemented to utilize and reprocess the used or end-of-life lithium batteries.



**FIGURE 6**. Lithium Battery Industry Recycling Process Flow

The reverse supply chain consists of collecting, dismantling, and processing the used batteries. In the chain, users' or consumers' roles are quite important to supply used lithium batteries to minimize disposal which results in waste. Processing them can be carried out using the second-life batteries by startups, workshops, UMKM, and industry to select and sort between damaged batteries and those that are still suitable for use, repair battery components, or carry out a re-manufacturing process to be used or resold in the form of different applications. For the batteries that have been damaged, a recycling process will be carried out by recyclers, who have currently been in a laboratory scale (RnD), startups, and research institutions for lithium battery recycling, considering the complexity of lithium battery materials so that there is a need for technology and the application of appropriate methods for recovering the recycled materials. The application of the lithium battery recycling process is included in the new technology category, especially in Indonesia. 41 journals result from a full-text review that discusses obstacles and challenges in implementing lithium battery recycling (see **TABLE 7**).

**TABLE 7**. Obstacles and Challenges in Lithium Battery Recycling

| Categories | Notes |
| --- | --- |
| Technique | **Technology:**  Lithium battery recycling technology has been in the development stage and has not yet fully matured. Recycling results in 38-45% more energy consumption and 16-20% higher air emissions than primary production. lithium battery recycling facilities are insufficient. There is a need for development, research, and investment related to the development of more efficient lithium battery recycling processing in the future. References: [43] [44] [45] [46] [47] [48] |
| **Method:**  The use of pyrometallurgy takes the risk of environmental pollution high costs and low material recovery compared to other methods. It is due to the loss of Li in the slag, oxidation, and reduction processes which can produce toxic gas emissions. Hydrometallurgy takes a long and complicated process time and allows for the danger of chemical waste (solvents) from the recycling process. Improper recycling can cause the risk of explosion/fire, heat, or thermal hazards because it contains flammable materials and chemical hazards such as toxic and non-degradable waste. References: [19] [20] [49] [21] [50] [51] [52] [23] [24] [30] |
| **Materials:**  Lithium batteries have a complex design, so they are quite complicated to recycle. The difficulty in effective separation between the cathode material and the collecting Al foil is due to the strong strength of the organic binder of polyvinylidene fluoride (PVDF). PVDF is difficult to recycle and can pollute the environment during the recycling process. References: [53] [27] [54] [55] [28] [56] |
| Non-technique | **Policy and Regulation:**  The promotion level of the use of electric vehicles is disproportionate to the policies for collecting and managing waste, especially lithium batteries. Regulations and a lack of regulatory environment for collecting and sorting LIBs are unclear or inconsistent. References: [18] [57] |
| **Resources:**  The raw materials for lithium batteries have been imported from abroad (China), especially lithium. The supply of used lithium batteries has not been integrated, so many of them are still disposed of rather than recycled (limited supply of used lithium batteries for recycling). The supplies of raw materials such as cobalt and lithium for battery recovery are limited. The public awareness about the importance of recycling lithium batteries is low. Indonesia does not yet have enough used lithium as raw materials for batteries from the recycling process, so it requires an import policy or regulation. Special skills and knowledge in recycling are required. References: [20] [58] [31] [29] [22] [59] [60] [61] |
| **Information:**  Determining the best disposal alternative (reuse, repair, remanufacture, and recycle) is complicated. The information on recycling economics is limited, so most people dispose of it rather than distributing it to recyclers. References: [38] [33] |
| **Cost:**  Facility costs, recycling or recovery processes, and used battery supply costs are expensive (labor costs, administration, transportation, and processing/testing), so it is necessary to develop more efficient technology and business models. References: [25] [32] [35] [41] [42] [62] [63] |

Several obstacles and challenges in implementing recycling have been classified. 36 journals result from a full-text review that discusses solutions to overcome obstacles and increase effectiveness and efficiency in implementing lithium battery recycling as categorized in **TABLE 8** below.

**TABLE 8**. Solutions for Implementing Lithium Battery Recycling

| Categories | Solutions |
| --- | --- |
| Technology | The supply chain digitization approach by connecting the forward supply chain with the reverse supply chain in an integrated manner with the use of technologies such as Cloud, IoT, AI, and Blockchain can help track output and improve transparency throughout the lithium battery supply chain. The uses of Internet-of-Things (IoT) in Reverse Supply Chain (RSC) and RL simplify collection and save time. The recycling process is carried out by enabling the separation or sorting and classification of used batteries based on data collected by sensors. References: [19] [27] [28] [38] [52] [64] [65] [66] |
| Method | Before recycling, it is necessary to completely discharge or deactivate thermally or inhibit thermodynamically or chemically to prevent explosions, gas emissions, and fires, due to short circuits and self-ignition during the disassembly step. Hydrometallurgy and direct recycling have the potential to be a circular economy solution for more efficient Lithium-Ion battery recycling where the recovery of lithium carbonate by leaching HCl (a hydrometallurgical process) can achieve an efficiency of around 99% for Li, Co, and Mn. Life cycle analysis shows that direct recycling can recover critical elements such as lithium, cobalt, and nickel, as well as all other components significantly reducing costs, energy consumption, and emissions. The combination of recycling methods with mechanical, thermal, and chemical processes (pyrometallurgy, hydrometallurgy, direct recycling, biometallurgy, and others) can result in better and more efficient recovery as well as eco-friendly or environmentally friendly. The sustainable design for next-gen batteries, disassembly, and separation of high-volume and hazardous LIB components needs to use automation to decrease the risks and exposures to workers. References: [18] [22] [23] [24] [26] [34] [37] [49] [50] [55] [56] [63] [67] |
| Policy an | Strict policies and regulations are needed for the electric vehicle, electronics, and other energy storage industries to fulfill the obligation to recycle their waste products, especially the lithium batteries they use. Promoting the development of a sustainable battery supply chain begins with the EV battery reuse market, closed-loop battery recycling systems, and the implementation of a circular economy. It is necessary to implement clear and consistent international battery laws and provide financial incentives for battery recycling. The standardization of design and labeling of materials, collaboration between industry, universities, and laboratories, and government incentives and policies are very crucial. References: [25] [32] [43] [46] [47] [48] [68] [69] [70] |
| Resources | It is necessary to collaborate between the government, producers, and society to create a sustainable lithium battery system. Forward and reverse supply chain planning collaboration and coordination includes coordinated strategic, tactical, and operational planning required to achieve effective battery recovery and efficient use of secondary materials. It is necessary to increase investment, develop technology, recycle infrastructure, and develop more sustainable lithium battery materials such as water-based electrodes and water-soluble binders. It is significant to increase public awareness and education about the importance of recycling lithium batteries and the correct recycling method, such as outreach and providing disposal/storage facilities and other easily accessible facilities where public knowledge about the need for battery recycling is important. References: [20] [31] [51] [54] [60] [71] |

## MAPPING

For the data gathering and processing, the research used the methods of observation and interviews with several industries, startups, and workshops that take a lithium battery recycling process in Indonesia. It also carried out as well as a systematic literature review of 62 national and international journals where 24 journals discuss the lithium battery recycling methods; 14 journals discuss the recycling process flow from the forward chain to the reverse chain; 41 journals discuss the obstacles and challenges; and 36 journals discuss the solutions and strategies in implementing the lithium battery recycling process. They result in a mapping of the supply chain system for the lithium battery industry in Indonesia, beginning with the production stages from raw materials to final use, especially in the lithium battery recycling process. Considering that Indonesia has started producing lithium batteries from startup to industrial scale and the need for lithium batteries is increasing, recycling is very important to overcome the waste it causes and create a sustainable economic system. The overall mapping of the supply chain for the lithium battery recycling process in Indonesia which has been described above can be seen in **FIGURE 7** below.

The mapping as reported in Figure 7 above refers to the results of data processing carried out previously in the form of interviews, observations, and systematic literature reviews as well as a concept based on the lithium battery industry chain flow [72], the lithium battery recycling flow diagram [32], and the reverse logistics framework implemented[73]. Therefore, the lithium battery recycling process consists of several parties involved, starting from the raw material production process (upstream stage) by the industry mining, mostly run by MIND ID (Mining Industry Indonesia) which produces nickel, aluminum, copper, and import processes, especially for lithium materials and other supporting materials for lithium battery precursor needs. The RnD (middle stream stage) of research institutes of higher education in conducting research and development in processing lithium battery precursors to obtain active lithium battery materials (cathode, anode, electrolyte, and separator) or imported from outside and then processed by startups or companies manufacturing lithium batteries into cells, packs, and modules for the needs of end users (downstream stage) such as consumers of electronics, electric vehicles, and other energy storage system needs in the forms of Business to Business (B2B) or Business to Consumer (B2C).

From processing the active material production and making lithium batteries to using in the forward supply chain route and moving to the reverse supply chain route by processing the end of life (EOL) of lithium batteries for a reuse process are generally carried out by several workshops or UMKM that run in the field of energy storage needs. The recycling process stages have currently been carried out by research institutions or higher education such as UNS, UGM, BRIN, and B4T Bandung. The lithium battery manufacturing industries in developing recycling processes are Tianneng Battery Group, Indonesia Battery Corporation (IBC), and PT Indonesia Puqing Recycling Technology, starting from the hydrometallurgical recycling process that has been implemented in Indonesia, pyrometallurgy and direct recycling (development stage) so that cathode and anode active materials can be obtained for re-production from recycled materials until they can be used.



**FIGURE 7**. Supply Chain Mapping of the Lithium Battery Recycling Process

# CONCLUSIONS

Based on the research findings and data analysis of the lithium battery industrial chain in Indonesia, the following conclusions and practical implications are drawn:

1. Mapping and Circular Economy: The study confirms that mapping the lithium battery recycling process within Indonesia's industrial chain is essential for implementing a sustainable economic system. This mapping facilitates the creation of a circular economic flow, integrating the forward supply chain—from raw material extraction to battery production—and the reverse supply chain—focusing on the recycling and repurposing of used batteries. For industry stakeholders, this emphasizes the need for investment in both upstream and downstream processes, ensuring a steady supply of recycled materials and new batteries.
2. Recycling Processes and Stages: The research identifies three critical stages in the recycling process: crushing and grinding, sorting, and recovery. This process involves separating components physically, magnetically, and thermally, and using hydrometallurgical methods to recover pure cathode and anode materials. For policymakers, this highlights the importance of supporting advancements in recycling technologies and ensuring that facilities are equipped to handle these processes efficiently.
3. Challenges and Solutions: The study outlines both technical and non-technical challenges. Technically, the development stage of recycling technology and inadequate facilities pose barriers. Non-technically, unclear policies, high costs, and limited resources are significant issues. Solutions include integrating supply chain digitalization through technologies like Cloud, IoT, AI, and Blockchain; implementing comprehensive recycling methods; enforcing strict policies; and fostering collaboration between government, producers, and consumers. Researchers should focus on digitalization approaches to enhance supply chain transparency and the development of reverse logistics concepts for a more efficient recycling system.

These conclusions underline the need for concerted efforts from industry stakeholders, policymakers, and researchers to create a robust recycling infrastructure, drive technological innovation, and establish clear regulations to support the sustainable management of lithium batteries.

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