Journal of Energy Storage 132 (2025) 117918

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Review article

Optimizing dismantling approaches for recycling of li-ion batteries: Strategies, challenges and economic analysis

Touseef Younas [*], Hossein Shalchian, Misbah Ullah, Francesco Vegliò, Valentina Innocenzi

Department of Industrial and Information Engineering and Economics University of L'Aquila (UNIVAQ), Monteluco di Roio, 67100 L'Aquila, Italy

ARTICLE INFO

Keywords:
Manual dismantling
Automated dismantling
Recycling processes
Regulatory framework
Economic analysis

ABSTRACT

Lithium-ion batteries (LIBs) are widely used in electric vehicles, consumer electronics, and energy storage systems due to their high energy density and long operational life. As demand for these batteries rises globally, their end-of-life management has become a growing concern due to environmental risks, material scarcity, and recycling inefficiencies. This review addresses the urgent need for safe, sustainable, and cost-effective dismantling practices, recognized as the most critical and preparatory step in LIB recycling, by evaluating current methods and proposing future directions. The review examines manual, mechanical and automated dismantling approaches, highlighting their respective advantages and limitations. Manual method offers straightforward material recovery but face safety, labour, and efficiency challenges. Emerging automated solutions using robotics, AI, and machine learning promise improvements in safety, scalability, and disassembly precision. In addition to dismantling strategies, the review discusses regulatory frameworks, environmental implications, and the importance of standardizing battery design for easier disassembly. It also provides future perspectives emphasizing automation, eco-friendly chemical processes, and public participation in battery collection. By organizing scattered knowledge and offering critical insights and recommendations, this review serves as a comprehensive resource for researchers, policymakers, and industry stakeholders. It aims to guide sustainable innovation and foster circular economy practices in LIB end-of-life management.

1. Introduction

The transportation industry is a significant cause of air pollution; it releases dangerous pollutants into towns and is responsible for almost 28 % of the world's greenhouse gas emissions. This pollution shows how important it is for society to reduce carbon emissions, which are bad for health and the environment [1]. The consequences generated by human climate change are evident and necessitate resolution. Different steps have been taken to reduce pollution and lessen its harmful effects. A vital aspect of this shift is the public's willingness to embrace electric vehicles, as the transportation industry needs to move away from fossil fuels and toward renewable energy sources [2]. Accordingly, electromobility plays a vital role in reducing dependence on fossil fuels and is essential for achieving the overarching goal of decarbonizing the transportation sector [3].

The increase in green energy production might substantially reduce emissions from electric cars (EVs), perhaps decreasing them by up to 75 % relative to emissions from fossil fuel-powered vehicles. Recent estimates suggest that electric cars produce 20 % to 40 % less pollution than internal combustion engine automobiles [1,4]. As a result, European countries are dedicated to attaining climate neutrality by 2050, aligning with the European "Green Deal" (GD) to further global climate goals. Europe aims to become the first climate-neutral continent by 2050, with an interim target of reducing greenhouse gas emissions by at least 55 % by 2030 compared to 1990 levels. In this context, electric vehicles have emerged as a key solution for cutting transport-related emissions and supporting the continent's ambitious climate goals [5].

As the adoption of electric vehicles continues to rise, a growing number of EV batteries will inevitably reach end-of-life in the coming decades, necessitating proper disposal or recycling. This challenge is further intensified by public policies promoting electromobility, which are accelerating the number of registered EVs and, consequently, the volume of spent battery systems [6,7]. Additionally, to meet the climate targets set by the European Green Deal, Germany is projected to have approximately 7 to 10 million electric vehicles on the road by 2030. This surge will lead to a substantial increase in end-of-life batteries, which, if not managed responsibly, could result not only in the loss of critical raw materials but also in a significant environmental and waste management

---

[*] Corresponding author.
E-mail address: touseef.younas@gradauate.univaq.it (T. Younas).

https://doi.org/10.1016/j.est.2025.117918
Received 26 February 2025; Received in revised form 8 July 2025; Accepted 27 July 2025

crisis across Europe.

However, recent studies show that only around 18–20 % of LIBs are currently recycled in the European Union (EU), indicating a strong need for more effective and large-scale recycling systems [8]. As nearly all EVs rely on LIBs, the demand for these batteries continues to grow, resulting in substantial volumes of end-of-life batteries requiring effective management. While automakers are responsible for the disposal of end-of-life (EoL) battery packs and actively respond to the need for lithium-ion battery recycling, many companies focus on recovering valuable materials [9]. However, some battery components must be recovered, and certain materials are unrecyclable. Nevertheless, this responsibility is complicated by high shipping costs associated with safety regulations and the varying conditions of the batteries. Moreover, as the electric vehicle sector grows, various procedures that function effectively on a smaller scale may encounter increased management challenges [3,4,10].

Several persistent trends hinder the progress of a circular economy for electric vehicle batteries. Often, these studies lack breadth as they do not concentrate on the disassembly methods employed for recycling and lack a structured approach [9]. For instance, Meng et al. [11] did not use a structured methodology; instead, they concentrated solely on studies from the past five years, explicitly emphasizing deep learning. Xiao et al. [12] highlight the significance of efficient disassembly in the context of reuse. They discuss the necessity of new technologies to enhance material recovery and bolster a circular economy. However, a structured method was not employed to map the literature in their study. It is crucial to emphasize the significance of reusing battery packs and cells for a circular economy. Furthermore, none of these studies have examined the impact on logistics throughout the entire value chain, which is crucial for developing recycling methods that are efficient and cost-effective.

As seen in Fig. 1, this review focuses on different aspects for dismantling LIBs, which is the first step for effective recycling. Although various technologies for the recycling of LIBs exist, the dismantling process is often overlooked in the literature. Therefore, this paper aims to address that gap by providing a structured analysis of manual, mechanical and automated, thermal, and chemical, dismantling and recycling methods. It also discussed the safety concerns, economic constraints, and regulatory barriers. Additionally, in the study, a thorough comparison was performed of existing approaches and their limitations, highlighting the need for integrated, safe, and cost-effective dismantling systems that can support a circular economy.

As previously discussed, the expansion of green energy sources and the implementation of stricter regulations, such as the European Green Deal, are driving the decarbonization of the transport sector and promoting large-scale production and adoption of EVs. However, only 18–20 % of lithium-ion batteries (LIBs) are currently recycled within the EU [8], underscoring the urgent need for improved dismantling and recycling infrastructure. Although manufacturers are held responsible for EoL battery management, the process remains challenging due to safety concerns, logistical complexities, and high associated costs.

This review contributes by organizing scattered knowledge, identifying key limitations, and providing a perspective and proposing recommendations to improve LIB dismantling and recycling systems. In doing so, it supports future research and industrial efforts toward a more sustainable and efficient battery recycling process. Based on the current state of the literature, the authors provide future perspectives and recommendations intended to advance understanding of this critical area within the context of the global energy transition and escalating environmental challenges. These insights aim to guide researchers, policymakers, and industry stakeholders in identifying existing knowledge gaps and developing effective, sustainable solutions for the end-of-life management of lithium-ion batteries.

2. Lithium-ion batteries (LIBs)

According to a current study, most lithium-ion batteries are used in portable electronic gadgets and electric cars. These batteries have exceptional physicochemical qualities, such as low self-discharge rates, no memory effect, and lightweight construction, distinguishing them from other batteries. Comparisons with different kinds of batteries, such as lead-acid batteries, show that lithium-ion batteries have better performance, a longer lifetime, and higher energy density [13,14].

2.1. Structure of LIBs

LIBs consist of four main components: the anode, cathode, electrolyte, and separator, as illustrated in Fig. 2. The anode functions as the negative electrode and stores lithium ions during charging by intercalating them between graphite layers, forming lithiated graphite. On the other hand, the cathode serves as the positive electrode and releases lithium ions into the electrolyte, typically composed of lithium metal oxides [13]. Over the years, various cathode materials have been developed, including $LiCoO_2$, $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ (NMC), Ni-Co-Al, $LiMn_2O_4$, and $LiFePO_4$, each offering different performance characteristics. Among these, $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ is widely preferred in EV batteries due to its high energy density and low self-heating properties [15].

As shown in Fig. 2a, the structure of a typical LIB is depicted, while Fig. 2b presents the main components and their associated hazards in a simplified cloud-based layout. The electrolyte, a solution of lithium salts (e.g., $LiPF_6$, $LiClO_4$) in organic solvents, facilitates ion transport between electrodes during charge/discharge cycles [17]. A separator, or microporous membrane, is placed between two electrodes. This facilitates the unobstructed movement of lithium ions without direct contact, which is essential for battery safety and stability. Research by Hannan et al. [16], Andwari et al. [18], and Li et al. [19] elucidates LIBs technology, its components, and the chemical reactions involved in the charging and discharging processes, which describe not only the battery chemistry but also highlight the risks related to thermal degradation, gas emissions, and long-term stability. The figure aims to visually summarize both the internal structure and the environmental or safety concerns associated with each LIB components.

2.2. Overview of LIBs

Li-ion batteries have emerged as the most suitable energy storage option for electric vehicles and have progressively supplanted conventional batteries [20]. Along this, LIBs are now widely used in portable devices, including laptops, mobile phones, aerospace equipment, power transmission systems, and electric vehicles [19].

2.2.1. Economic barriers

With the growing use of LIBs, many studies have investigated

Fig. 1. Key theme of the dismantling of LIBs.

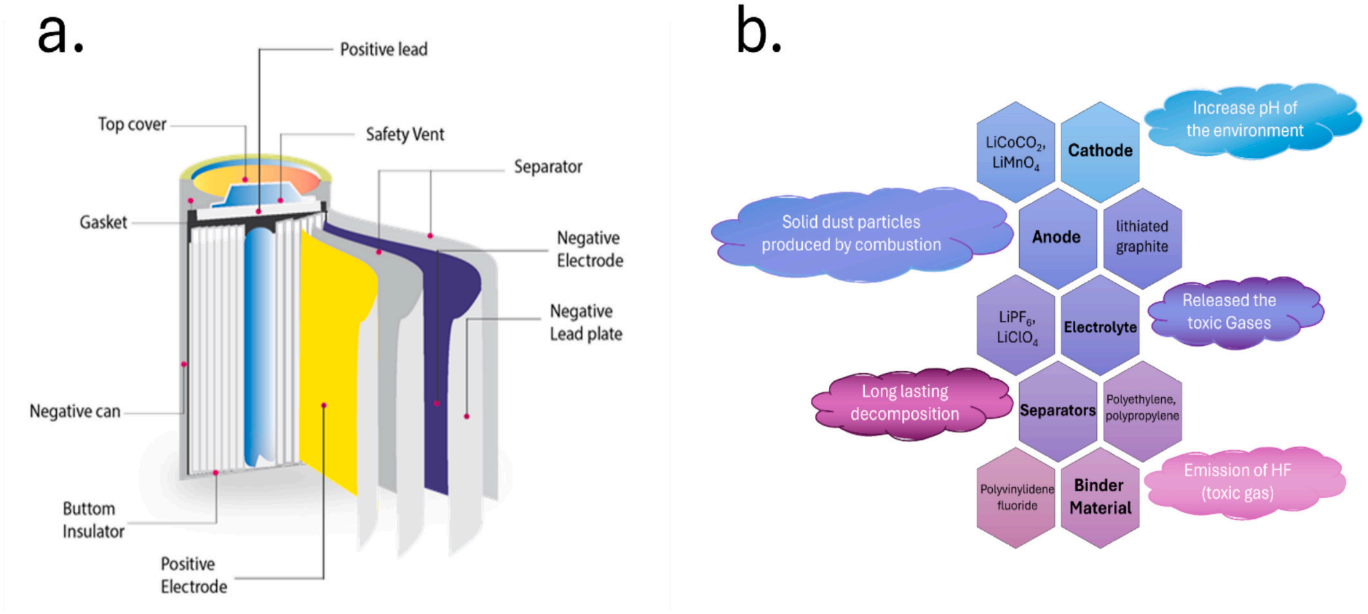

Fig. 2. Illustration of Li-ion-battery: (a) LIBs structure; (b) LIBs components and drawbacks are represented in hexagons and cloud shapes [16].

demand, development, and applied policies [5]. Fig. 3 illustrates the estimated demand for LIBs, along with the development and policies supporting the growth of essential elements such as lithium (Li), graphite (Gr), nickel (Ni), manganese (Mn), and cobalt (Co) [21]. A detailed estimate of LIBs demand from 2022 to 2030 is depicted in Fig. 3a. This surge in demand will also heighten the need for these raw materials. Fig. 3b highlights these elements expected to achieve sustainable growth by 2040 [22]. However, the extraction and processing of these materials are concentrated in only a few countries due to limited mining resources, as shown in Fig. 3c. As a result, many regions, especially within the EU, need more access to these minerals. Consequently, securing a stable and independent supply of these raw materials is crucial. Recycling valuable components from discarded LIBs can facilitate the reintegration of these resources into the production process, increasing the sustainability of the LIBs industry [23,24].

2.2.2. *Regulatory gaps*

New regulations have been introduced in some regions to improve recycling management for LIBs. For example, the European Commission has proposed a mandatory regulation that specifies the required recycled content in new batteries. By 2035, the production of LIBs for electric vehicles must include at least 20 % recycled cobalt, 12 % recycled nickel, and 10 % recycled lithium.

Reducing material costs is essential for the long-term viability production of LIBs, as explained in Fig. 4a. Cathode materials represent the most significant portion of the price for a single battery cell, accounting for 34 %. In contrast, the total material input, including manufacturing, overhead, passive materials, electrolytes, separator, and anode

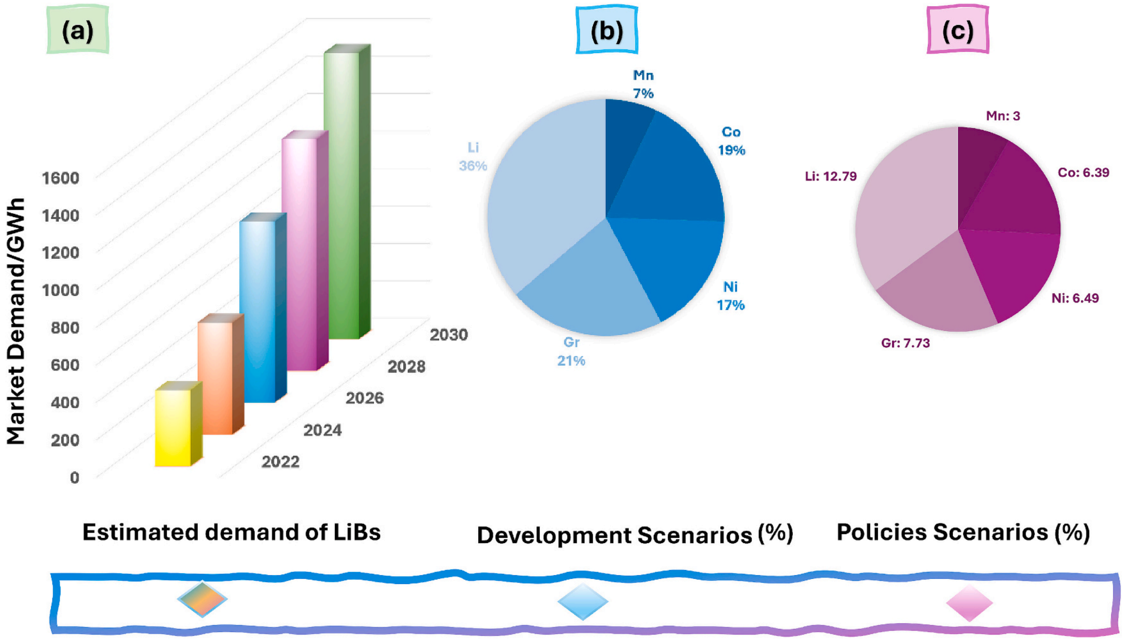

Fig. 3. Estimated demand and development of LIBs: (a) estimated demand for LIBs from 2022 to 2030 [25]; (b) development demand growth of the required elements in 2040 relative to 2022 [26]; (c) applied policies for the required elements in 2024 relative to 2022 [27].

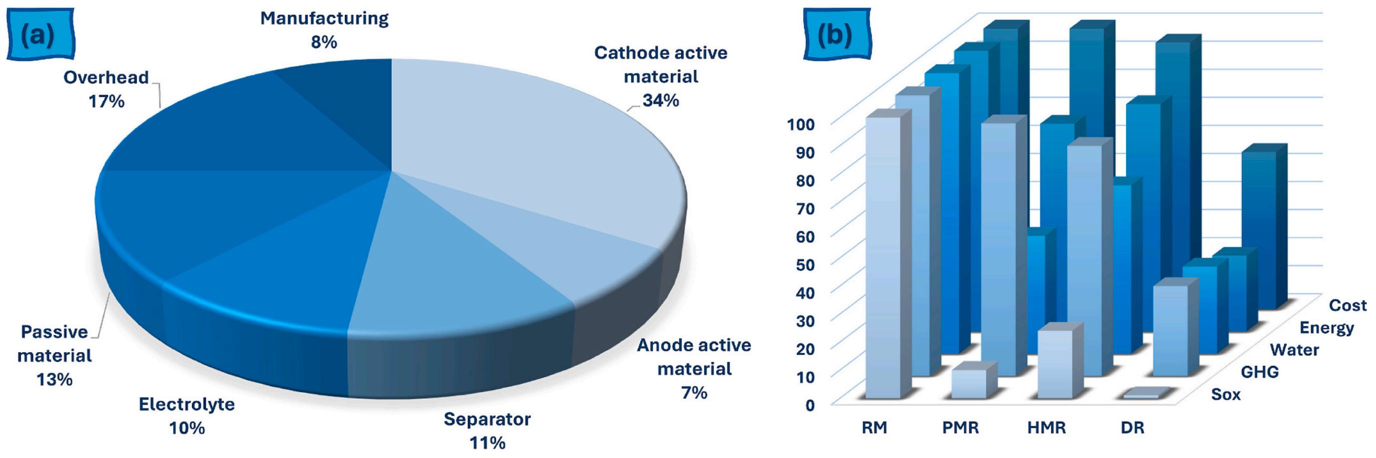

Fig. 4. (a) Estimated price breakdown of electric vehicle battery cells as of 2020 [30]; (b) The cost and environmental impact of producing cathode materials from raw materials compared with those of various recycling methods. RM: Raw material, PMR: pyrometallurgical recycling, HMR: hydrometallurgical recycling, DR: direct recycling, Sox: sulfur oxide, GHG: greenhouse gas [31].

materials, constitutes 64 % of the overall cost. Using recycled secondary materials in LIBs production can lead to cost savings ranging from 5 % to 44 % for Li, Ni, Mn, and Co oxide and 38 % to 43 % for Li and Co oxide, depending on the recovery method used. In addition to their economic advantages, recycling and processing spent LIBs offer significant ecological benefits, including reductions in energy and water consumption, as well as lower emissions of greenhouse gases (GHG_s) and sulfur oxides (SO_x) [28,29], as illustrated in Fig. 4b.

Furthermore, the average lifespan for LIBs is approximately 8–10 years, indicating that many used LIBs accumulate quickly, significantly impacting the recycling market [32]. A thorough estimation of the recycling of valuable materials from scrap LIBs within Europe is shown in Fig. 5a. This effort can help reintroduce these resources into the production cycle, supporting a more sustainable LIBs industry. Considering the average battery composition data was obtained in 2020, recycling retired LIBs could prevent material loss of up to 92 % for lithium, cobalt, and nickel, aligning with the European Commission's targets [33]. By 2035, recycling efforts could supply 22 % of the lithium and nickel and 65 % of the cobalt needed for LIBs production in the EU [34]. Furthermore, the market value of recycled LIBs worldwide was also estimated and is presented in Fig. 5b.

Despite the potential benefits of recycling, collection and recycling rates for used LIBs remain surprisingly low [36]. For example, in 2021, Australia recycled only 10 % of outdated LIBs [29]; Germany reported a collection rate of approximately 32 % or lower [36]. Most used LIBs end up in landfills, posing significant threats to human health and the environment. For example, in the UK 25 % of landfill fires in 2017–2018 were caused by LIBs, resulting in toxic gas emissions [37]. Additionally, leaching and slag deposition can contaminate soil and groundwater.

The low recycling rates are partly due to the high costs associated with recycling processes and the absence of standardized regulations across different regions [37]. However, this scenario is gradually improving as more cost-effective recycling technologies are being developed, and new rules are implemented to address the issue.

2.3. Recycling regulations and policies

The regulatory circumstances for batteries are notably distinct across the EU, the USA, and China, each implementing unique frameworks to enhance sustainability and recycling efficiency, as illustrated in Fig. 6.

2.3.1. EU battery directive

In the European Union, regulations form the Battery Directive and the Waste Electrical and Electronic Equipment (WEEE) Directive to establish specific goals for collection rates and recycling efficiencies. The newly implemented Batteries Regulation, which took effect on August 17, 2023, seeks to reduce the environmental impact of battery manufacturing and use while fostering a circular economy and supporting the EU's Green Deal goals. This regulation mandates that manufacturers create batteries that can be easily dismantled, reused, and recycled. It establishes strict requirements for the lifecycle management of batteries, such as implementing an electronic passport for large batteries to enhance recycling and reuse efforts [38]. It also helps to encourage innovation in battery design to meet high recyclability

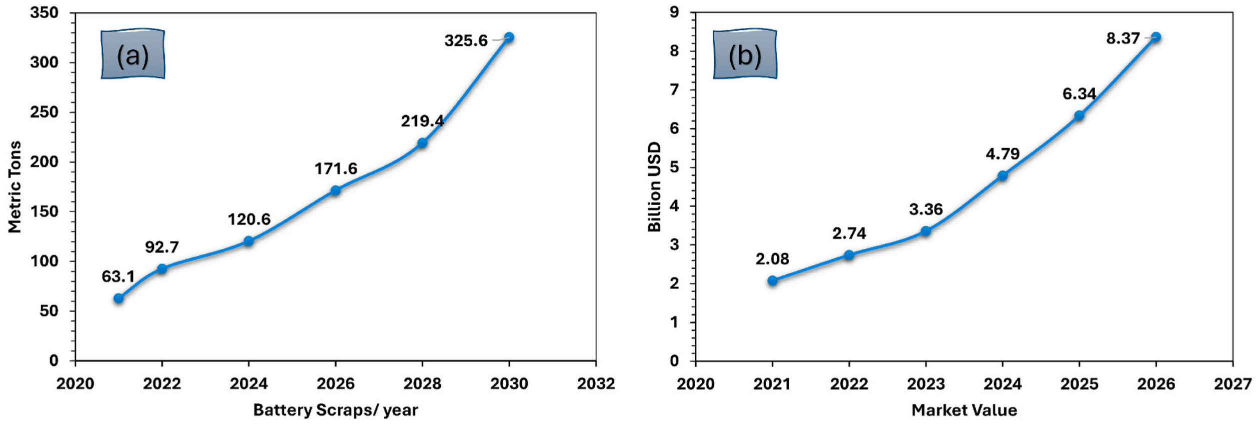

Fig. 5. Estimated recycling of LIBs: (a) available spent LIBs for recycling in Europe and [31] (b) market value for recycling LIBs worldwide [35].

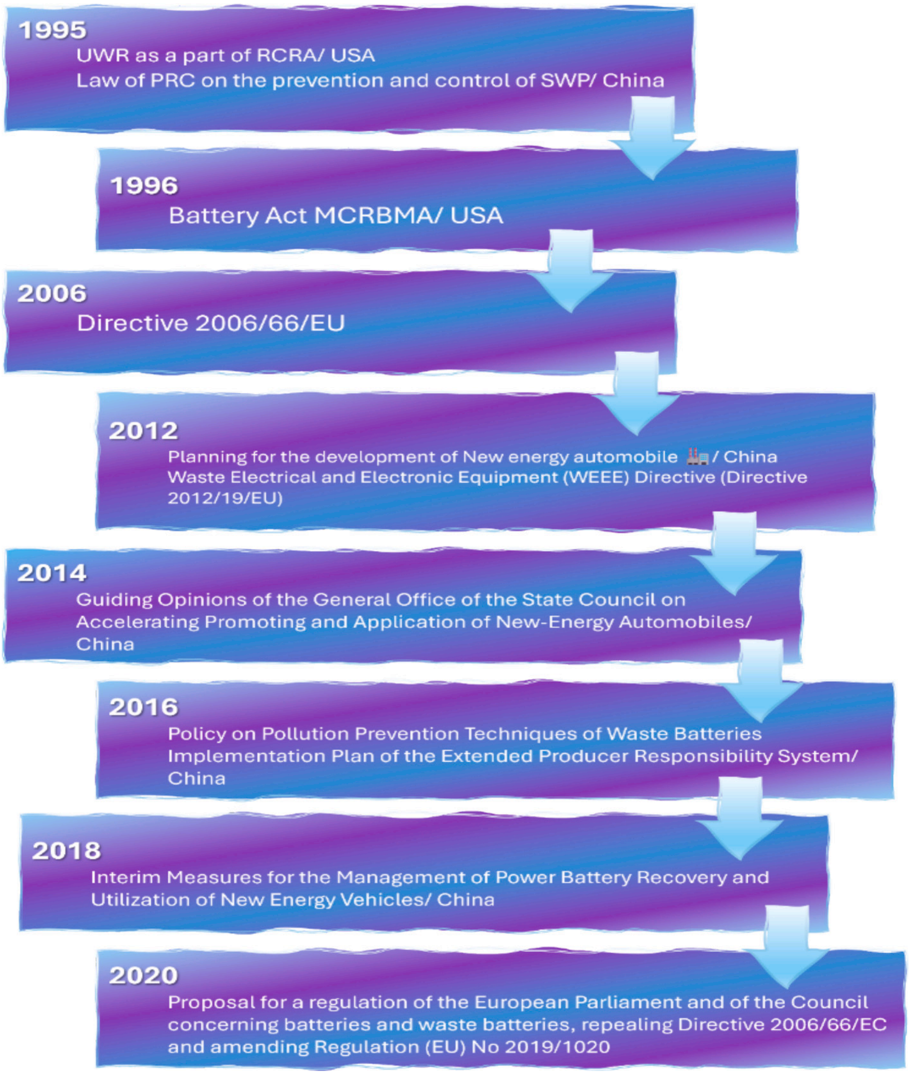

Fig. 6. Selection of the most important federal policies regarding the recycling and treatment of EoL batteries in the EU, USA, and China. UWR: Universal Waste Rule, RCRA: Resource Conservation and Recovery Act, MCRBMA: Mercury-Containing and Rechargeable Battery Management Act.

standards.

2.3.2. *US policies*

The United States (USA) necessitates a more comprehensive regulatory system. The Battery Act of 1996 primarily addresses nickel-cadmium and lead-acid batteries, whereas the Universal Waste Rule facilitates the management of hazardous waste, including batteries [39,40]. Although some states have implemented additional restrictions for lithium-ion batteries, a complete federal regulation governing battery recycling and disposal remains absent. These regulations ensure the safe handling and disposal of hazardous battery materials, promoting public safety and environmental protection by reducing risks linked to toxic waste.

2.3.3. *China's regulations*

China has changed its regulatory approach from overseeing hazardous materials like mercury and cadmium to creating detailed legislation for lithium-ion batteries. The extended producer responsibility (EPR) framework requires producers to manage the entire lifecycle of their batteries, ensuring adherence to established recycling goals. Despite significant technological advancements, the battery recycling industry faces ongoing challenges. The variety of battery types complicates the recycling process [41].

In addition, proper collection and sorting processes are essential for optimizing recycling operations. Recent studies propose several techniques to tackle these difficulties, such as standardizing battery labelling, imposing mandated collection rates, and incorporating decentralized pretreatment systems to boost recycling efficiency. Furthermore, China has one of the most stringent Extended Producer Responsibility (EPR) frameworks globally, compelling producers to assume full responsibility for managing battery lifecycles [42]. The country emphasizes technological innovations to tackle logistical and operational recycling challenges.

2.4. *Recycling techniques for LIBs*

The introduction addresses the need for recycling solutions for sustainable development, namely the recovery of valuable materials from batteries and reintegration into the value chain [43]. Recycling retired lithium-ion batteries from electric vehicles often entails pretreatment activities such as discharging, disassembling, and applying various chemical or heat treatments. Recycling technologies can be classified into five types: mechanical, pyrometallurgical, hydrometallurgical, electrochemical, and direct recycling [44].

Pyrometallurgical methods involve the high temperature melting of valuable metals, which enhances their industrial application due to efficiency and straightforwardness. Common chemicals used in these processes include fluxing agents like silica (SiO_2), lime (CaO), and sodium carbonate (Na_2CO_3). These helps form slag and separate metals. Nonetheless, there is a pressing need to strengthen environmental sustainability because these processes consume significant energy, emit toxic gases, lead to lithium loss during high-temperature operations, and require specialized treatment equipment [45]. Hydrometallurgical procedures involve using a wide range of chemical processes for mineral extraction, including acid-base leaching, solvent extraction, precipitation, ion exchange, and electrolysis. In these processes, strong acids such as sulfuric acid (H_2SO_4), hydrochloric acid (HCl), and nitric acid (HNO_3) are commonly used to dissolve metals. Along this, hydrogen peroxide (H_2O_2) is often added to enhance leaching efficiency. After leaching, organic solvents like Cyanex 272, D2EHPA, or TBP are also used to separate and purify metals like Co, Li, and Ni. Some processes used ammonia (NH_3) or oxalic acid, which helps to selectively precipitate metals.

Because these techniques often operate at lower temperatures and have less effect on the environment, they are especially well-suited for lithium recovery. On the other hand, the hydrometallurgy industry is confronted with its own set of issues, including the development of considerable acid waste, which presents concerns to both human health and the environment, as well as greater disposal costs [46]. Beyond traditional recycling methods like pyrometallurgy and hydrometallurgy, direct recycling is considered a more straightforward approach since it minimizes the number of processes needed to produce new cells [47]. It reduces energy use, lowers battery expenses, and decreases greenhouse gas emissions, ultimately benefiting the environment.

In direct recycling, parts from used batteries are taken out and repurposed to create new batteries while keeping their structure or morphology largely intact, which aids in preserving the quality of the cathode material [48]. Direct recycling employs supercritical carbon dioxide (CO_2) to extract materials from cathodes and anodes, facilitating the recovery of the electrolyte during the dismantling and crushing of the cells. This method enables the separation of cell components via physical techniques, promoting the reuse of cathode materials. [49].

Additionally, specific physical processes can recover materials with minimal structural damage, preserving crystal integrity and electrochemical performance. A brief overview of all these techniques is given in Table 1. After some recycling processes, further refinement may be required to achieve the necessary purity for reuse. These methods can be combined to accommodate different battery chemistries, and some companies have developed proprietary processes based on these techniques. Hydrometallurgy remains the primary recycling option and is often combined with preprocessing methods such as mechanical crushing or pyrometallurgical melting.

Despite the technical feasibility of recycling, the high costs associated with processing electric vehicle batteries, along with their remaining usable capacity, make reuse a more attractive and economically viable alternative. This study highlights the critical preparatory role of dismantling in the three most researched battery end-of-life strategies: reuse, repurposing, and recycling. By organizing fragmented knowledge and focusing on sustainable practices, the study identifies key limitations and proposes a perspective aimed at streamlining processes and eliminating unnecessary steps. Ultimately, it contributes to enhancing the efficiency and sustainability of battery management by supporting future research and industrial efforts to optimize the dismantling process as a foundation for effective end-of-life battery treatment.

2.5. *Dismantling of battery recycling*

Dismantling Li-ion batteries is a crucial step in the recycling process, enabling the recovery of valuable materials like lithium, nickel, cobalt, and other essential elements. Consequently, having a well-planned disassembly strategy and sequence is crucial for achieving a process that is cost-effective, safe, and environmentally friendly [55]. This method significantly reduces the need for extracting raw materials, promoting a more circular economy. Extensive research has focused on improving the dismantling process by exploring various factors, including disassembly sequences, manual and automated techniques, and the development of virtual disassembly tools [56]. Improving the dismantling process boosts material recovery from used lithium-ion batteries, supporting sustainability and reducing the environmental effects of battery production and disposal. Wu et al. [27] carried out a preliminary literature review that explored the disassembly of traction

Table 1
Brief overview and comparison of different recycling methods.

Recycling methods	Advantages	Drawbacks	Recovered materials	Ref.
Mechanical	Works with all types of batteries. Easy and simple process. Energy efficient	Limited metal recovery Minimal purity. Causes a safety risk. Costly in terms of gas clean-up	Li_2CO_3 Cu Al and Black mass	[43,44]
Pyrometallurgy	Simple to operate. Works with all battery types and designs. No pretreatment needed	Cost-effective only for Co and Ni batteries Gas clean-up is needed to prevent emissions. Li is nonrecoverable. Material loss. High energy use.	Co, Ni, Cu While the anode is unstable	[45,50]
Hydrometallurgy	Compatible with all battery chemistries and configurations. Effectively recovering Li. Work at a low temperature. Highly purified materials were obtained.	Economically feasible only for batteries that contain Co & Ni. It involves crushing & adhering to critical safety regulations. Required a pretreatment step. Higher cost.	Cu, Co, Ni, & Al Li_2CO_3	[29,46]
Direct recycling	A wide range of battery materials can be recovered, such as anodes, electrolytes, binders, and foils. Efficient and versatile. Appropriate for LFP batteries and battery waste.	Recovered materials may not match the performance of new materials May lower the value of the recycled product. Hard to Scale	Almost all battery components, excluding separators	[47,48]
Electrochemical Recovery	Reuse the spent electrolyte. Selective metal can be recovered.	Difficult to handle. Slow process as compared to chemical leaching.	Li, Co, Ni	[51]
Mechanical-Chemical Hybrid	Effective for the automation. Safer and easier to handle. Boost the recovery efficiency.	Setup requires a high cost. Need careful integration.	Black mass, Li Cu and Ni	[52–54]

batteries, pinpointing various essential parameters for successful disassembly processes.

This review examined various degrees of disassembly and automation as outlined in current research, providing thorough descriptions of experimental setups and approaches for both manual and automated disassembly techniques. Rettenmeier et al. [57] aim to build upon Wu et al. [27] findings by incorporating additional sources, including grey literature accessed through platforms like Google Scholar. This inclusion is vital for a comprehensive analysis, as highlighted by Haddaway et al. [58], Who emphasizes the importance of diverse sources in research.

3. Dismantling and recycling approaches for LIBs

Dismantling entire battery packs presents significant challenges, with various methods available for planning an optimal disassembly sequence for obsolete LIBs. Most approaches utilize case studies involving manual disassembly to analyze and determine efficient processes. For example, Ke et al. [59] proposed a disassembly planning method based on a frame subgroup structure, which they validated through a manual disassembly experiment. Their study treated the battery pack as a frame, and its components were considered subgroups. Compared with conventional methods, their approach improved the disassembly time and revenue by 12.04 % and 2.54 %, respectively.

Furthermore, Gentilini et al. [60] developed a mathematical model for disassembly planning to reduce human workers' exposure to hazardous voltages, using a Toyota battery pack as a case study. Choux et al. (Choux, Marti Bigorra, and Tyapin 2021) explored a disassembly job planner integrated with an image-processing system, using the Audi A3 Sportback e-tron hybrid battery pack as a case study. They achieved impressive accuracy in screw identification, with deviations under 5 mm. By improving these processes, the sector can drastically reduce its environmental impact while assuring the safe disposal of spent batteries [62].

A systematic flow of the standard dismantling process for LIBs is illustrated in Fig. 7 as the disassembly procedure usually starts with a thorough examination and cautious removal of the batteries. The battery pack is then removed to separate the lithium-ion cells from the other components, which may be done manually or via automated processes. Once removed, the cells are size-reduced and sorted to collect metals, including copper, aluminium, steel, and plastic. The residual black mass, a powdery mixture of cathode and anode materials, electrolytes, and conductive additives, is next treated to extract essential metals [63].

3.1. Manual dismantling

While manually dismantling lithium-ion batteries, many critical processes must be followed to guarantee the safe and efficient recovery of vital components using these batteries. The procedure begins with a comprehensive examination of the battery to determine whether or not the battery is secure and to detect any possible problems. Workers must wear appropriate personal protective equipment (PPE), including goggles, masks, and gloves, to protect themselves from potentially hazardous substances. Immediately after establishing safety precautions, the subsequent step is to disconnect the battery from its power source. This may entail removing the battery from the equipment or vehicle relevant to the situation [64].

After this, the exterior shell, often made of plastic or metal, should be removed with care using various tools such as screwdrivers, utility knives, and pry tools. It is essential to carefully open the battery pack to avoid harming the components located within. After the interior structure has been made accessible, the battery may be dismantled into its numerous components, which include electrolytes, separators, anode foils, and cathode foils.

Because they include precious minerals like lithium, nickel, and cobalt, these elements are essential for recycling because they contain these elements. Recycling these components is necessary for recovering significant resources and reducing environmental impact; each part plays a crucial role in promoting sustainable practices in battery management.

However, many modern recycling facilities are shifting toward a crushing method, often followed by advanced separation techniques such as magnetic separation to extract metallic parts. This approach allows for greater processing capacity, enabling facilities to handle larger volumes of batteries more effectively. After initial crushing, fine crushing and sieving techniques are employed to recover the active cathode material, which is critical for recycling [65]. A systematic representation of the manual dismantling process is illustrated in Fig. 8.

In addition to dismantling, Lander et al. conducted a comprehensive economic analysis of the disassembly of six commercial battery packs from manufacturers such as Renault, Nissan, Tesla, BAIC, Peugeot, and BYD. Their detailed techno-economic assessment focused on disassembly costs, time, and how design features contribute to overall expenses. They compared the disassembly costs and times associated with manual, semiautomatic, and fully automatic processes. For example, their analysis of the BAIC battery pack showed that reducing the number of modules and connecting screws by 50 % could lower disassembly costs by over 24 % and 29 %, respectively. Furthermore, transitioning from manual to fully automated disassembly could yield time savings of up to 88 % and cost reductions of up to 97 %.

Among the battery packs analyzed, the BYD pack features a Cell-to-Pack design that requires the least time and incurred the lowest disassembly costs. This design is particularly advantageous during the recycling phase, as it consists of modules containing multiple cells, leading to higher disassembly efficiency [27]. Additionally, Rosenberg et al. [66] and Rallo et al. [67] investigated the disassembly time, costs, and labor required for the process. Depending on the specific pack, disassembling

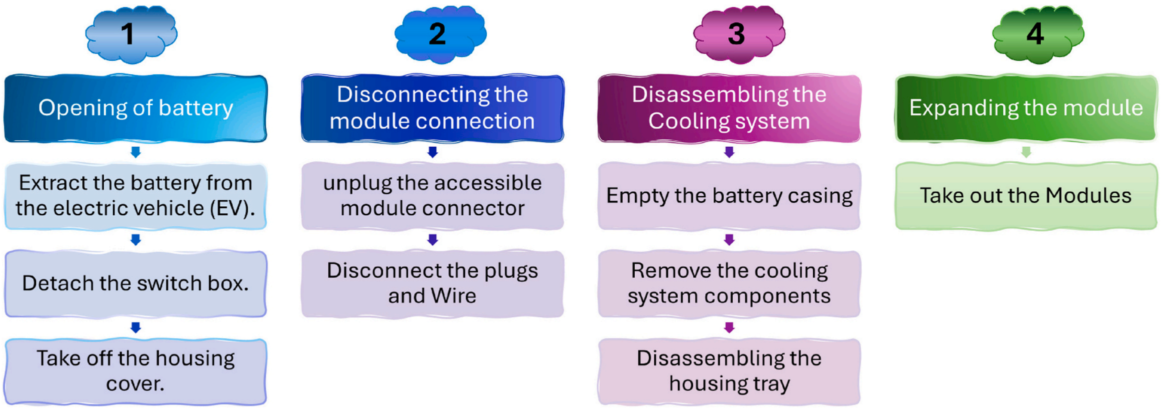

Fig. 7. Systematic representation of the standard dismantling process of LIBs.

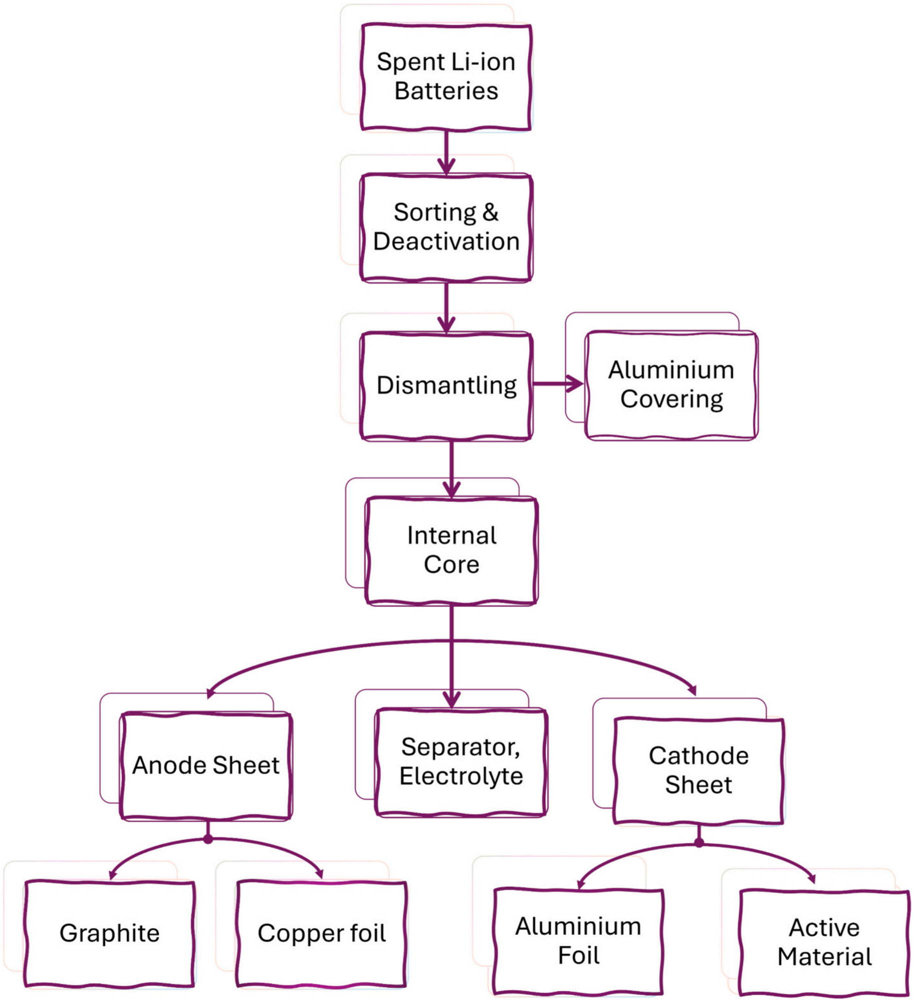

Fig. 8. Systematic representation of the manual dismantling process.

a battery pack into modules takes between 20 and 40 min. For example, Rosenberg et al. [66] reported that one worker could disassemble a Mercedes PHEV pack into modules in 22 min, whereas two workers could complete the task in approximately 16 min.

The total cost for dismantling a pack into modules ranges from EUR 80 to 110 in Germany, depending on the size of the disassembly facility. Rallo et al. [68] focused on disassembly at the laboratory scale, determining that the total cost to disassemble a Smart for Four battery pack into cells is EUR 1325. The cost of dismantling the modules into cells constituted 62.26 % of the total disassembly expenses, excluding the extraction of the pack from vehicles. Both studies highlighted that the analyzed battery packs were relatively lightweight and possessed limited capacity, influencing the prices and duration required for disassembly [69]. This research emphasizes the significance of battery pack design in improving disassembly operations. Improving designs for disassembly enables manufacturers to reduce expenses and enhance efficiency, therefore rendering the recycling of lithium-ion batteries more economically sustainable.

During the dismantling, workers must be aware of any possible release of hazardous gases, like hydrofluoric acid (HF), that can occur if the electrolyte encounters humid air [70]. Additionally, residual lithium on the anode could ignite in moist environments, posing a fire risk. To alleviate these hazards, deconstruction must occur in a dry atmosphere, and personnel should comply with stringent safety measures.

3.2. *Mechanical dismantling*

Manual disassembling can attain a recovery rate of over 80 % of the total battery mass and yield purer components compared to mechanical shredding; nonetheless, it necessitates a substantial workforce, rendering it expensive, particularly in regions with elevated labour costs [71]. Furthermore, Manual dismantling is inefficient due to the hazards associated with handling hazardous materials and the elevated possibility of accidents. Researchers have developed a hybrid approach integrating technology with the deconstruction process to address these issues. The combination of human and automated methods enhances safety and boosts efficiency. This improves the sustainability and efficacy of lithium-ion battery recycling.

The first step in the mechanical dismantling for the recycling process of LIBs entails the gathering and categorizing of materials. Lithium-ion batteries are obtained from various consumer electronics, such as smartphones, laptops, tablets, electric vehicles, and energy storage systems. After collection, the batteries are transported to specialized recycling facilities to reduce the risk of leakage. The batteries are subsequently arranged based on voltage, capacity, and internal resistance.

Mechanical methods are employed to divide various parts of LIBs, allowing the segregation of valuable materials, such as electrode materials, including Li, Ni, Co, and Mn, for individual recovery. Al is sorted via a swirling electric current, and the substance is directed to the air separator, which is sorted based on density, size, and shape variations. Once purified, the recovered materials can be utilized to produce fresh batteries, integrated into the manufacturing process of electronic devices, or used to make EV batteries [72]. In general, the use of recycled battery materials leads to savings in both cost and energy. Furthermore, the cathode determines the capacity and voltage of LIBs, whereas the anode sends electrons through a wire. Electrolytes allow the movement of ions only, and the separator acts as a barrier between the cathode and anode [73].

However, addressing these challenges is essential for the successful mechanical recycling of LIBs. These challenges are associated with the mechanical recycling of LIBs due to their low-recovery materials [52]. As stated before, LIBs are very reactive, making them challenging to manage. Improper handling can cause damage to the ecosystem. Mechanical recycling of LIBs involves high temperatures, powerful acid leaching, and thorough gas treatment, which may produce high levels of dangerous emissions, resulting in environmental harm [74]. Currently, only 5 % of lithium-ion batteries are recycled, leading to high costs for the recycling process.

3.3. *Dismantling followed by thermal and chemical recycling*

The dismantling process can be followed by a thermal or chemical treatment approach to recycle LIBs. This process begins with dismantling using manual or mechanical approach, which is followed by crushing the batteries, after which the shredded materials undergo a separation phase to eliminate passive fragments and larger particles. The resultant powder, termed “black mass,” comprises cathodic active materials and graphite derived from the anodes.

The black mass undergoes thermal treatment, usually via calcination, eliminating binders, carbon, solvents, and various organic materials. After that, the substance is separated and polished using other techniques. A reagent solution is used to dissolve the black material in a short amount of time after it has been crushed and scanned. Metals such as cobalt, manganese, and nickel are methodically retrieved using extractants and chemical precipitants after the early phases of cleaning and drying have been completed.

The most energy-intensive thermal treatments are pyrometallurgical processes, in which residual materials, either before or after sorting and dismantling, are heated to approximately 1700 °C, resulting in the formation of lithium-rich slag and alloys containing cobalt, nickel, and precious metals. Fluxing agents like SiO_2, CaO, and Al_2O_3 are sometimes added to help melt and separate the materials during this process. Na_2CO_3 can also be used to lower the melting point. After that, lithium carbonate is extracted from lithium-rich slag following leaching and filtration methods.

Thermal treatment, while effective, presents disadvantages, including elevated energy consumption and significant greenhouse gas emissions. High-temperature material degradation can impede the overall efficiency of the recycling process. Research has concentrated on multiple chemical treatment methods to tackle these challenges [75]. The initial phase in this technique is to leach black matter using a variety of acids and alkalis, followed by separation and refining. Strong acids such as H_2SO_4, HCl, and HNO_3 are used to dissolve Li, Co, and Ni. In some cases, H_2O_2 is often added as a reducing agent to enhance the leaching efficiency, especially for cobalt oxides. In contrast, organic acids like citric and oxalic acids are also used as eco-friendly alternatives. Oxalic acid helps precipitate Co and Fe after leaching. After leaching, precipitating agents such as NaOH or NH_3 can be added to recover specific metal hydroxides.

Selective separation of dissolved metals is achieved using solvent extraction agents like Cyanex 272, D2EHPA, or TBP, with different efficiencies depending on the pH and metal of interest. These reagents help separation of Co, Ni, and Mn from the solution [76].

Fig. 9 shows a comprehensive overview of the various approaches of dismantling and recycling different components. These methods include mechanical, thermal, and chemical approaches. (See Fig. 10.)

Chemical treatments have benefits over thermal treatments. It reduces energy usage and greenhouse gas emissions by working at lower temperatures. It also focuses on critical metals by selective leaching and precipitation, reducing processing. Despite the advantages of the chemical treatments’ methods, these processes may need specialized apparatus and create additional chemical waste streams, requiring cautious treatment to fulfil environmental laws [77].

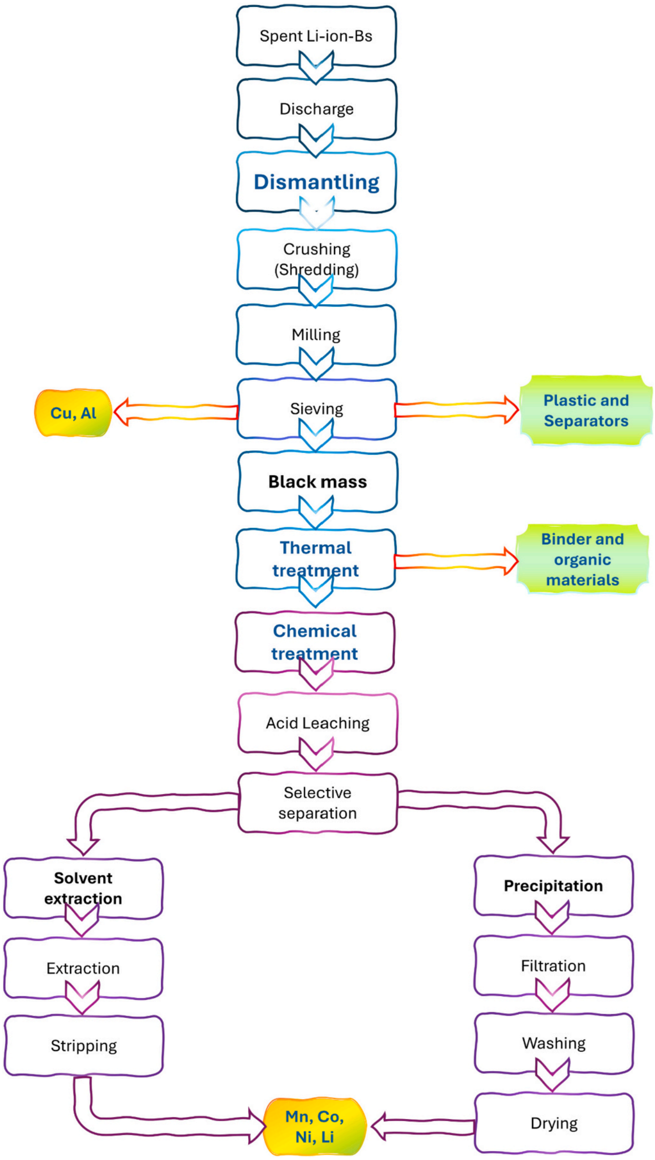

Fig. 9. Detailed illustrations of the methodology of dismantling followed by recycling approaches.

Harper and colleagues performed a detailed investigation that revealed the importance of mechanical fragmentation in recycling lithium-ion batteries from electric vehicles [78]. The study’s findings underscore the necessity of utilizing specialized apparatus for mechanical shredding, which is a highly effective method for deconstructing battery cells and isolating their components for subsequent processing. Manthiram et al. [79] investigated the chemical reactions enabled by solid-state electrolytes in lithium batteries. It is critical to understand the chemistry of a battery before dismantling it. This is particularly true when managing solid-state electrolytes and their consequences for safety and mechanical disassembly methods.

Evers and Nazar introduced unique ways to develop lithium-sulfur battery cathodes with excellent energy density. These techniques demonstrate the development gained in chemical processes. Their findings reveal that chemical techniques have the potential for

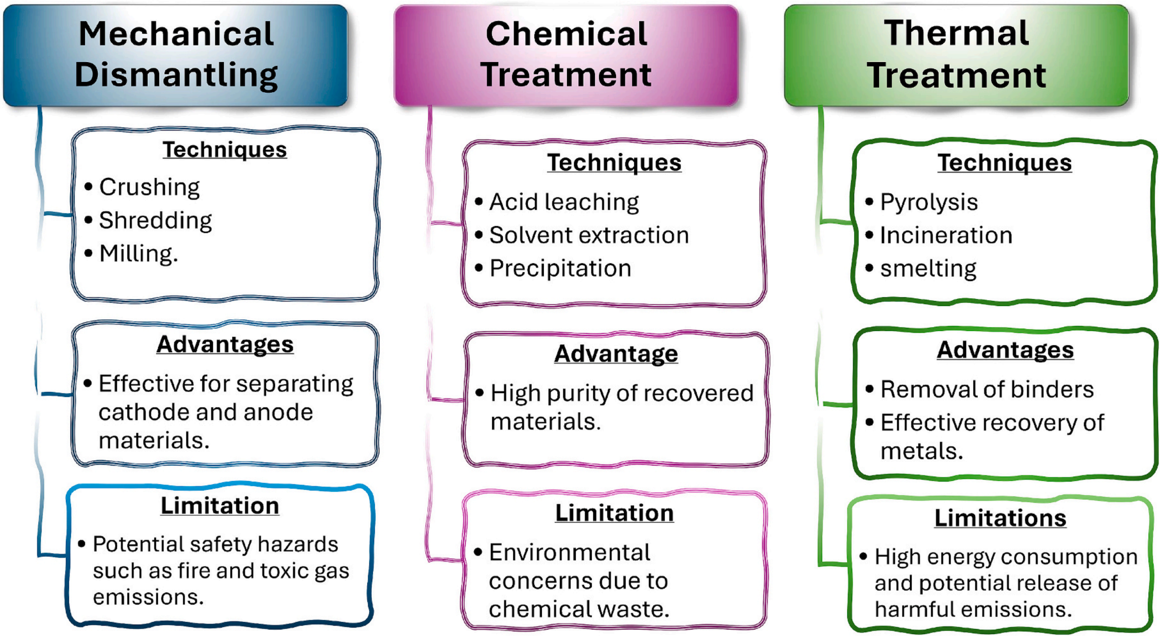

Fig. 10. Systematic representation of a short overview of the mechanical dismantling and chemical and thermal recycling process.

application in the deconstruction of innovative battery technologies; nevertheless, it is vital to emphasize that these methods are not limited to lithium-ion batteries.

The environmental impact of dismantling processes is essential in recycling lithium-ion batteries. By incorporating principles of cocreation and community engagement, as highlighted by Greenhalgh et al. [80], it is possible to develop sustainable and environmentally friendly dismantling methods that minimize adverse effects on local communities. Kim et al. [81] advanced the disassembly process by dismantling battery packs and modules and targeting individual cells. Their focus on pouch cells allowed them to separate these into their components, achieving an impressive lithium recovery efficiency of over 96 %. Additionally, they recovered approximately 90 % of other valuable metals, including cobalt, manganese, and nickel. Santos et al. [82] introduced comprehensive recycling technology for Li-ion cells that encompasses conditioning, disassembly, and separation stages. Their research utilized mass variation monitoring to analyze disassembly efficiency. It was revealed that more than 90 % of the active materials were recovered from LCO cells, whereas NMC cells accounted for approximately 80 % of the active materials. In contrast, Marshall et al. [83] disassembled lithium-ion cells in a fume cupboard without using an inert gas environment. They focused on extracting and separating cell components by employing an ultrasonic bath with an oxalic acid solution, which resulted in an almost 100 % effective separation rate for the cathodes and anodes.

Wu et al. [84] proposed a physical separation strategy aimed at recovering cathodic active materials. Their method involved dismantling the cells, separating the cathode foils, and applying subsequent processes such as thermal treatment, mechanical vibration, and shredding, achieving an impressive separation rate of 85 % for the cathode materials. Bi et al. [10] developed a procedure for disassembling and crushing lithium-ion batteries. Following manual disassembly, the separated electrodes underwent thermal treatment, were crushed, and separated via an eddy current. This method achieved a recovery rate exceeding 92 %.

While disassembling individual cells allows for efficient component separation, safety considerations are paramount. Spent cells must be discharged before disassembly to eliminate any remaining electrical potential, which poses a risk of hazards. However, this discharge procedure requires more time and expenditure on specialist equipment. Furthermore, it offers an economic benefit that exceeds other direct separation methods by 32.22 %, demonstrating greater efficacy than traditional pyrometallurgy and hydrometallurgy.

3.4. *Automatic dismantling: Technological advances in disassembly*

Recent research has focused on automating the disassembly of Li-ion batteries, which differs from traditional dismantling techniques. This change is critical because traditional dismantling methods, like manual methods pose significant risks, require extensive labour, and result in higher costs. Automating the disassembly process provides numerous advantages, including improved safety, increased efficiency, and lower operational costs. This sophisticated gripper removes the cells and assesses their state to ensure the dismantling process is carried out safely.

A prototype of a gripper system has recently been developed [85]. This device can disassemble battery cells while detecting their voltage and internal resistance measurements. During their inquiry, Hellmuth and his colleagues investigated the possibility of reusing the battery from an Audi Q5 Hybrid within the context of automated procedures. Through their investigation of the disassembly capabilities of the batteries found in the 2017 Chevrolet Bolt BEV and the Audi Q5 HEV, they got valuable insights into the feasibility of automating the disassembly process for various battery types [86].

In recent years, considerable improvements have been made in automated disassembly technology, which has resulted in substantial improvements in both the effectiveness and the overall safety of recycling lithium-ion batteries. Within the scope of these enhancements is the use of computer vision and other approaches for the characterization of materials. When these technologies are used, not only does the process of disassembly become more efficient, but it also guarantees the efficient recovery of vital resources while simultaneously reducing the threats to the environment.

Since many battery packs and modules include screws, the use of gripper systems and robotic arms has been recognized as an effective and risk-free approach for disassembling lithium-ion batteries. Unscrewing is an essential component of this automated process because of the ubiquitous presence of screws in these battery packs and modules. Wegner et al. [87] dismantled the Audi Q5 Hybrid battery into cells and used a camera system to detect screws. They designed an unscrewing tool attached to a robotic arm, which worked in a workstation where humans handled complicated tasks, like removing glued components.

At the same time, robots took care of more straightforward tasks like loosening screws. Research by Garg et al. [88] and Zhou et al. [89] showed that using robots for unscrewing can significantly reduce disassembly time. They created a framework for safer and more efficient disassembly of battery modules with cylindrical cells, combining a battery information system, a robot-based disassembly system, and a battery classification system. Their results indicated that robotic unscrewing saved 55 % of the time, and overall, robotic disassembly cut the disassembly time by 80–90 %.

However, during the planning phase, it's not always necessary to synthesize and modify the specialized tools and prototypes. Instead, the design of an automated disassembly system can be represented using a 3D model, which allows for performance simulations without needing physical prototypes. Fleischer et al. [2] introduced a flexible robot-based disassembly station with movement mechanisms and end effectors. Rastegarpanah et al. [90] studied a semi-automatic disassembly system that used a mobile robot to sort components in messy environments, achieving at least an 82 % success rate in simulations.

Instead of building tools, some research identifies essential characteristics for effective automated disassembly implementation. These frameworks aid in assessing automation's feasibility and potential benefits by considering factors such as safety, time, cost, design, and uncertainty. For instance, Yin et al. [91] introduced a collaborative human-robot system to mitigate uncertainties associated with the disassembly process, including structural characteristics and connecting techniques.

Blankemeyer et al. [92] investigated automated disassembly and devised a feasible configuration for a disassembly station that addressed safety, uncertainty, and design concerns. Tan et al. [93] proposed a hybrid disassembly station that utilizes bespoke tools and modified robotic limbs to expedite disassembly, resulting in a five-step reduction for equivalent battery pack designs. The development of effective automated disassembly systems is significantly impeded by the diverse configurations of LIBs from various manufacturers and researchers. This complexity includes creative tool selection, ingenious workplace arrangements, and other critical factors.

4. Challenges in LIBs dismantling and recycling

As represented in Figure10, comparing mechanical dismantling and chemical and thermal treatments techniques can give important insights into the most effective and ecologically friendly ways to recycle lithium-ion batteries. Recent research has been performed to increase the efficiency, sustainability, and cost-effectiveness of lithium-ion battery recycling using mechanical, thermal and chemical procedures. By improving these techniques, the industry may recover critical materials while reducing the environmental impact of resource extraction and battery disposal.

Moreover, translating these concepts into practical applications through concrete experiments, particularly in the concept of dismantling approach, remains challenging. Despite the initial interest in automated disassembly, its real-world implementation has been limited. The first notable attempt at automating LIBs disassembly occurred in 2018, led by Gerber et al. [82]. They developed a human-robot collaboration station that built upon earlier concepts, emphasizing ergonomic and safety aspects. A cost-effective robotic arm was equipped with a screwdriver to loosen connections within battery packs and modules, as represented in Fig. 11.

Disassembly tests conducted with this demonstrator confirmed the feasibility of semi-automated disassembly at the module level, leading to a workstation design that enhances flexibility, productivity, and safety. Some experiments employed dummy samples instead of actual battery modules or cells to mitigate safety risks. Kay et al. demonstrated the use of industrial robots for battery disassembly under human supervision. Their experiments with dummy modules and cells revealed that the time required for automated opening could be reduced by 50 % [94]. The introduction of robots not only enhances safety but also significantly decreases disassembly time compared to manual methods. Their findings indicated that human-robot collaboration is an optimal approach for disassembling battery packs, with robots efficiently cutting through battery modules and allowing operators to sort components and remove connectors swiftly.

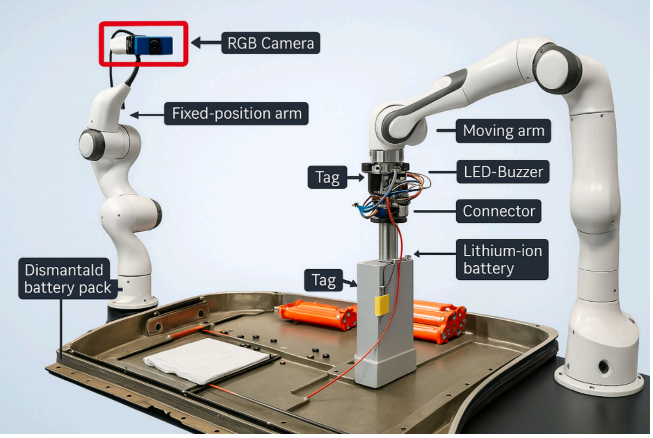

Fig. 11. Robotic arm developed for the automatic dismantling process [82].

Efforts to automate the disassembly of entire battery packs have also been explored. Zorn et al. [94] proposed a computer vision workflow aimed at automating the sorting of various components during disassembly. They suggested an identification system providing relevant information about the battery pack, such as cathode chemistry, to improve sorting operations and facilitate high-quality recycling. Additionally, they evaluated sensor-based sorting technologies for the peripheral components of the battery pack.

While much of the existing research has concentrated on the pack or module level, Kay et al. [85] also introduced methods and tools for the automated opening of dummy cells without further investigating electrode separation. Systematic research in this area has been limited. Li et al. [86] conducted the only comprehensive studies focused on automated mechanical separation methods for end-of-life pouch cells with z-folded electrode structures. Their verification experiments with dummy cells demonstrated the potential for automatically separating and extracting the main components of pouch LIBs. Notably, their work included the integration of online sensors into the electrode separation process, simplifying subsequent material extraction and processing for the direct recycling of LIBs.

5. Future perspectives and recommendations

Dismantling represents the first and most critical step in the recycling of LIBs, significantly influencing the overall environmental impact of electric vehicles and portable electronic devices. Given the growing urgency of the global energy transition, increasing environmental concerns, and the necessity of the resource sustainability, the development of safe, efficient, and environmentally responsible dismantling technologies is expected to become a central focus in future research and industrial practices. Advancements in this area will be essential for establishing a circular economy for LIBs and ensuring the long-term viability of battery-powered technologies.

Among the dismantling methods described, manual dismantling is effective for small-scale applications; however, it can be time-consuming, risky, and not suitable for larger-scale applications. In contrast, automated dismantling that employs robots and AI can significantly reduce the required time, human exposure to toxic materials, increase efficiency, and lower costs. Future systems are expected to utilize vision-based tools and advanced techniques, such as machine learning algorithms, to accurately identify battery components and optimize disassembly strategies. This approach will enhance the recovery efficiency of valuable parts while minimizing damage to materials.

In the future, updated systems and methodologies must focus on reducing waste and energy consumption to promote more sustainable dismantling and recycling practices. Improved AI-assisted automated dismantling process, followed by low-temperature and efficient chemical treatments using green solvents and biodegradable reagents can help achieve this goal. These advanced alternatives have the potential to replace the lengthy, hazardous, and inefficient manual dismantling methods currently in use, which are often followed by treatment with strong acids and toxic chemicals during the recycling process. Furthermore, greater emphasis should be placed on implementing zero liquid discharge (ZLD) strategies to minimize secondary pollution and enhance the overall environmental sustainability of LIB recycling.

In parallel, the standardization of battery design is expected to play a crucial role in advancing dismantling practices. Designing batteries with disassembly in mind can significantly improve safety, efficiency, and speed during the dismantling process. Moreover, standardized designs would facilitate the development of automated dismantling technologies tailored to consistent battery formats. This approach may include reducing the number of screws, adopting modular architectures, and clearly labelling components to enable easier identification by robots and separation.

In terms of regulation, stronger laws are needed to support sustainable dismantling approach. Governments can introduce extended producer responsibility rules that require battery makers to consider dismantling during product design. At the same time, funding programs can support industries working on automation and eco-friendly dismantling and recycling technologies.

Enhancing public awareness and improving collection programs are also essential, particularly for batteries used in consumer electronics. A significant number of batteries are not recycled simply because they are not returned at the end of their life cycle. Establishing more accessible and efficient collection networks, alongside public education initiatives that emphasize the environmental and economic importance of battery recycling, can substantially increase recovery rates and support a more sustainable recycling ecosystem.

In the long term, combining sustainable dismantling, smart automation, and eco-friendly recycling methods will create a cleaner and more efficient battery recycling system. This will reduce the need to mine raw materials and using the primary resources, cut greenhouse gas emissions, and support the transition to a circular economy. Future research should prioritize the systematic evaluation of these methods, progressing from laboratory-scale experiments to pilot-scale trials, and ultimately to industrial-scale implementation. Ensuring the cost-effectiveness and scalability of these approaches will be essential for their widespread global adoption.

6. Conclusion

LIBs are widely used in electric vehicles, consumer electronics, and energy storage systems due to their high energy density and long lifespan. As their global usage increases, the need for efficient and safe recycling becomes critical to recover valuable materials and reduce environmental risks. This review presented a comprehensive overview of existing dismantling approaches, recognized as the most critical step in the recycling of LIBs, including manual, mechanical, and automated methods. It also examined subsequent recycling processes involving thermal and chemical treatments and assessed the role of each approach within the overall recycling framework.

Manual and mechanical dismantling methods contribute to material recovery but are constrained by labour intensity, safety risks, and potential material losses. In contrast, automated dismantling, leveraging robotics and intelligent systems, shows significant promise in overcoming these limitations by improving safety, reducing human involvement, and increasing processing speed. In the subsequent recycling stages, thermal and chemical processes achieve high recovery efficiencies. However, they are often associated with substantial energy consumption and environmental emissions.

This review contributes to the field by compiling and comparing dismantling and recycling strategies in a single, comprehensive resource, supported by well-organized visuals to enhance clarity and understanding. The authors offer future perspectives and recommendations based on the current state of the literature, which aim to deepen insight into this critical topic amid the ongoing energy transition and growing environmental concerns. These perspectives are intended to support researchers, policymakers, and industry stakeholders in identifying knowledge gaps and advancing effective solutions for end-of-life management of lithium-ion batteries.

Moving forward, advancements in automation, regulatory support, and improved battery designs for disassembly will be essential to scale up recycling efforts. Adopting these technologies will not only reduce environmental impact but also support the shift toward a sustainable circular economy for the battery sector.

CRediT authorship contribution statement

Touseef Younas: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Hossein Shalchian:** Visualization, Validation. **Misbah Ullah:** Visualization. **Francesco Vegliò:** Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Valentina Innocenzi:** Validation, Supervision, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has been funded by the European Union - NextGenerationEU under the Italian Ministry of University and Research (MUR) National Innovation Ecosystem grant ECS00000041 - VITALITY - CUP E13C22001060006".

"VITALITY - Innovation, digitalisation and sustainability for the diffused economy in Central Italy (Ecosistema di Innovazione, Digitalizzazione e Sostenibilità per l'Economia Diffusa nell'Italia Centrale)".

Data availability

Data will be made available on request.

References

[1] Z. Wu, M. Wang, J. Zheng, X. Sun, M. Zhao, X. Wang, Life cycle greenhouse gas emission reduction potential of battery electric vehicle, J. Clean. Prod. 190 (2018) 462–470.

[2] J. Fleischer, E. Gerlitz, S. Rieβ, S. Coutandin, J. Hofmann, Concepts and requirements for flexible disassembly systems for drive train components of electric vehicles, Procedia CIRP 98 (2021) 577–582.

[3] J. Guo, X. Li, X. Xing, Z. Shao, Recycling, Regeneration, and Reutilization of Cathode Materials of Spent LiNixCoyMn (1-xy) O2 Batteries, J. Environ. Chem. Eng. (2024) 114740.

[4] Y. Zhao, et al., Precise separation of spent lithium-ion cells in water without discharging for recycling, Energy Storage Mater. 45 (2022) 1092–1099.

[5] C. Giosuè, et al., An exploratory study of the policies and legislative perspectives on the end-of-life of lithium-ion batteries from the perspective of producer obligation, Sustainability 13 (20) (2021) 11154.

[6] W. Ding, et al., A green cycle strategy for selective leach and recovery of critical metals from spent lithium-ion batteries: experimental and new mechanistic insights, J. Hazard. Mater. 488 (5 May 2025) 137368.

[7] A. Bhagaskara, et al., Recycling of nickel metal from spent nickel-manganese-cobalt (NMC) cathode batteries using H3PO4–H2C2O4 solution combination as an efficient leaching agent, Case Stud. Chem. Environ. Eng. 10 (2024) 100844.

[8] G.D.J. Harper, et al., Roadmap for a sustainable circular economy in lithium-ion and future battery technologies, J. Phys. Energy 5 (2) (2023), https://doi.org/10.1088/2515-7655/acaa57.

[9] J. Marshall, D. Gastol, R. Sommerville, B. Middleton, V. Goodship, E. Kendrick, Disassembly of Li ion cells—characterization and safety considerations of a recycling scheme, Metals (Basel) 10 (6) (Jun. 2020) 1–22, https://doi.org/10.3390/met10060773.

[10] H. Bi, H. Zhu, L. Zu, Y. Gao, S. Gao, Z. Wu, Eddy current separation for recovering aluminium and lithium-iron phosphate components of spent lithium-iron phosphate batteries, Waste Manag. Res. 37 (12) (2019) 1217–1228.

[11] K. Meng, G. Xu, X. Peng, K. Youcef-Toumi, J. Li, Intelligent disassembly of electric-vehicle batteries: a forward-looking overview, Resour. Conserv. Recycl. 182 (2022) 106207.

[12] J. Xiao, C. Jiang, B. Wang, A review on dynamic recycling of electric vehicle battery: Disassembly and echelon utilization, Batteries 9 (1) (2023) 57.

[13] G. Zhang, Z. Du, Y. He, H. Wang, W. Xie, T. Zhang, A sustainable process for the recovery of anode and cathode materials derived from spent lithium-ion batteries, Sustainability 11 (8) (2019) 2363.

[14] L.P. Yao, Q. Zeng, T. Qi, J. Li, An environmentally friendly discharge technology to pretreat spent lithium-ion batteries, J. Clean. Prod. 245 (2020) 118820.

[15] Y. Li, J. Yang, J. Song, Electromagnetic effects model and design of energy systems for lithium batteries with gradient structure in sustainable energy electric vehicles, Renew. Sust. Energ. Rev. 52 (2015) 842–851.

[16] M.A. Hannan, M.M. Hoque, A. Hussain, Y. Yusof, P.J. Ker, State-of-the-art and energy management system of lithium-ion batteries in electric vehicle applications: Issues and recommendations, Ieee Access 6 (2018) 19362–19378.

[17] M. Alfaro-Algaba, F.J. Ramirez, Techno-economic and environmental disassembly planning of lithium-ion electric vehicle battery packs for remanufacturing, Resour. Conserv. Recycl. 154 (Mar. 2020), https://doi.org/10.1016/j.resconrec.2019.104461.

[18] A.M. Andwari, A. Pesiridis, S. Rajoo, R. Martinez-Botas, V. Esfahanian, A review of Battery Electric Vehicle technology and readiness levels, Renew. Sust. Energy Rev. 78 (2017) 414–430.

[19] Y.A. Hassan, H. Hu, Current status of polymer nanocomposite dielectrics for high-temperature applications, Compos. Part A Appl. Sci. Manuf. 138 (2020) 106064.

[20] D. Yu, Z. Huang, B. Makuza, X. Guo, Q. Tian, Pretreatment options for the recycling of spent lithium-ion batteries: A comprehensive review, Elsevier Ltd. (Nov. 01, 2021), https://doi.org/10.1016/j.mineng.2021.107218.

[21] R. Muon, "European Commission and the use of scientific knowledge: an empirical study on sustainable battery regulation of the EU Green Deal".

[22] J.Y. Lee, A.K. Ramasamy, K.H. Ong, R. Verayiah, H. Mokhlis, M. Marsadek, Energy storage systems: a review of its progress and outlook, potential benefits, barriers and solutions within the Malaysian distribution network, J. Energy Storage 72 (2023) 108360.

[23] R. Bird, Z.J. Baum, X. Yu, J. Ma, The regulatory environment for lithium-ion battery recycling, ACS Publications, 2022.

[24] L. Mathieu, C. Mattea, From Dirty Oil to Clean Batteries: Batteries Vs Oil: A Systematic Comparison of Material Requirements, Transport & Environment, 2021.

[25] J. To, The EU-CEAP impacts on developing countries: An analysis of the plastic packaging, electric vehicles and batteries sectors, no. 12/2022. IDOS Discussion Paper, 2022.

[26] H. Zhou, W. Li, R. Langdon, P.J. Singh, P. Wang, Exploring the circular economy future of lithium-ion batteries in australia through comprehensive dynamic material flow analysis, Resour. Conserv. Recycl. 220 (2025) 108377.

[27] S. Hansen, et al., A structured approach for the compliance analysis of battery systems with regard to the new EU Battery Regulation, Resour. Conserv. Recycl. 209 (2024) 107752.

[28] Q. Hoarau, E. Lorang, An assessment of the European regulation on battery recycling for electric vehicles, Energy Policy 162 (2022) 112770.

[29] V. Rizos, P. Urban, Barriers and policy challenges in developing circularity approaches in the EU battery sector: An assessment, Resour. Conserv. Recycl. 209 (2024) 107800.

[30] V. Halleux, New EU regulatory framework for batteries: Setting sustainability requirements, 2021.

[31] W. Mrozik, M.A. Rajaeifar, O. Heidrich, P. Christensen, Environmental impacts, pollution sources and pathways of spent lithium-ion batteries, Energy Environ. Sci. 14 (12) (2021) 6099–6121.

[32] L. Dawson, J. Ahuja, R. Lee, Steering extended producer responsibility for electric vehicle batteries, Environ. Law Rev. 23 (2) (2021) 128–143.

[33] T. A. HendricNs, J. Campbell, D. Williams, R. Koon-Koon, and T. Wynter, "The Paradox of Going Green: Unintended Consequences and Environmental Challenges," in The CAS23–2023 Conference on The Sustainability and Development Initiatives of the Caribbean, p. 360.

[34] C. Whittaker, Putting the Ban Back Together: A Critical Look at California Restaurant Association v. Berkeley, Env't L. Rep. 54 (2024) 10325.

[35] N. Buddenbaum Pereira, O. Eisen, Exploring Insights for Innovation Management Strategies: A Study on Electric Vehicle Driver Needs at Energy and Service Stations, 2024.

[36] Z. Tong, M. Wang, Z. Bai, H. Li, N. Wang, Advances in lithium-ion battery recycling: Strategies, pathways, and technologies, ChemPhysMater 4 (1) (2025) 30–47.

[37] H. Li, H. Qiu, M. Ranneberg, H. Lucas, T. Graupner, B. Friedrich, M. Fischlschweiger, Enhancing lithium recycling efficiency in Pyrometallurgical processing through thermodynamic-based optimization and design of spent lithium-Ion battery slag compositions, ACS Sustain. Resour. Manag. 1 (6) (2024) 1170–1184.

[38] A. Liu, G. Hu, Y. Wu, F. Guo, Life cycle environmental impacts of pyrometallurgical and hydrometallurgical recovery processes for spent lithium-ion batteries: present and future perspectives, Clean Techn. Environ. Policy 26 (2) (2024) 381–400.

[39] Y. Dong, et al., Trends of sustainable recycling technology for lithium-ion batteries: Metal recovery from conventional metallurgical processes to innovative direct recycling, MetalMat 1 (1) (2024) e5.

[40] J. Wang, et al., Toward Direct Regeneration of Spent Lithium-Ion Batteries: A Next-Generation Recycling Method, Chem. Rev. 124 (5) (2024) 2839–2887.

[41] B.K. Biswal, B. Zhang, P.T.M. Tran, J. Zhang, R. Balasubramanian, Recycling of spent lithium-ion batteries for a sustainable future: recent advancements, Chem. Soc. Rev. 53 (11) (2024) 5552–5592.

[42] L. Brückner, J. Frank, T. Elwert, Industrial recycling of lithium-ion batteries—A critical review of metallurgical process routes, Metals (Basel) 10 (8) (2020) 1107.

[43] L.B. Diaz, et al., Meta-review of fire safety of lithium-ion batteries: Industry challenges and research contributions, J. Electrochem. Soc. 167 (9) (2020) 090559.

[44] M. BUKVIĆ, B. STOJANOVIĆ, L. IVANOVIĆ, S. MILOJEVIĆ, RECYCLING OF THE HYBRID AND ELECTRIC VEHICLES, Acta Tech. Corviniensis–Bull. Eng. 10 (3) (2017).

[45] W.J. Tan, C.M.M. Chin, A. Garg, L. Gao, A hybrid disassembly framework for disassembly of electric vehicle batteries, Int. J. Energy Res. 45 (5) (2021) 8073–8082.

[46] G. Yang, Y. Cao, G. Zhan, Q. Zeng, Q. Chen, Research on the layout of battery pack for plug-in hybrid vehicle, in: IOP Conference Series: Earth and Environmental Science, IOP Publishing Ltd, Jul. 2021, https://doi.org/10.1088/1755-1315/804/3/032041.

[47] O. Velázquez-Martínez, J. Valio, A. Santasalo-Aarnio, M. Reuter, R. Serna-Guerrero, A critical review of lithium-ion battery recycling processes from a circular economy perspective, Batteries 5 (4) (2019) 68.

[48] L. Li, P. Zheng, T. Yang, R. Sturges, M.W. Ellis, Z. Li, Disassembly automation for recycling end-of-life lithium-ion pouch cells, Jom 71 (2019) 4457–4464.

[49] S. Wu, N. Kaden, K. Dröder, A systematic review on lithium-ion battery disassembly processes for efficient recycling, Batteries (2023), https://doi.org/10.3390/batteries9060297.

[50] M. Rettenmeier, M. Möller, A. Sauer, Disassembly technologies of end-of-life automotive battery packs as the cornerstone for a circular battery value chain: A process-oriented analysis, Resour. Conserv. Recycl. 209 (Oct. 2024), https://doi.org/10.1016/j.resconrec.2024.107786.

[51] N.R. Haddaway, A.M. Collins, D. Coughlin, S. Kirk, The role of Google Scholar in evidence reviews and its applicability to grey literature searching, PLoS One 10 (9) (2015) e0138237.

[52] Q. Ke, P. Zhang, L. Zhang, S. Song, Electric vehicle battery disassembly sequence planning based on frame-subgroup structure combined with genetic algorithm, Front. Mech. Eng. 6 (2020) 576642.

[53] L. Gentilini, E. Mossali, A. Angius, M. Colledani, A safety oriented decision support tool for the remanufacturing and recycling of post-use H&EVs Lithium-Ion batteries, Procedia CIRP 90 (2020) 73–78.

[54] M. Choux, E. Marti Bigorra, I. Tyapin, Task planner for robotic disassembly of electric vehicle battery pack, Metals 11 (3) (2021) 387.

[55] K. Wegener, S. Andrew, A. Raatz, K. Dröder, C. Herrmann, Disassembly of electric vehicle batteries using the example of the Audi Q5 hybrid system, Procedia CIRP 23 (2014) 155–160.

[56] N. Akhmetov, A. Manakhov, A.S. Al-Qasim, Li-ion battery cathode recycling: An emerging response to growing metal demand and accumulating battery waste, Electronics 12 (5) (2023) 1152.

[57] D.L. Thompson, et al., The importance of design in lithium ion battery recycling–a critical review, Green Chem. 22 (22) (2020) 7585–7603.

[58] F. Cerdas, et al., "Disassembly planning and assessment of automation potentials for lithium-ion batteries," Recycling of Lithium-Ion Batteries: The LithoRec Way, 2018, pp. 83–97.

[59] S. Rosenberg, S. Huster, S. Baazouzi, S. Glöser-Chahoud, A. Al Assadi, F. Schultmann, Field study and multimethod analysis of an EV battery system disassembly, Energies (Basel) 15 (15) (2022) 5324.

[60] H. Rallo, G. Benveniste, I. Gestoso, B. Amante, Economic analysis of the disassembling activities to the reuse of electric vehicles Li-ion batteries, Resour. Conserv. Recycl. 159 (2020) 104785.

[62] D.M. Werner, T. Mütze, U.A. Peuker, Influence of cell opening methods on electrolyte removal during processing in lithium-ion battery recycling, Metals 12 (4) (2022) 663.

[63] S. Rohr, S. Wagner, M. Baumann, S. Müller, M. Lienkamp, A techno-economic analysis of end of life value chains for lithium-ion batteries from electric vehicles, in: 2017 Twelfth International Conference on Ecological Vehicles and Renewable Energies (EVER), IEEE, 2017, pp. 1–14.

[64] S. Kim, et al., A comprehensive review on the pretreatment process in lithium-ion battery recycling, J. Clean. Prod. 294 (2021) 126329.

[65] S.M. Shin, N.H. Kim, J.S. Sohn, D.H. Yang, Y.H. Kim, Development of a metal recovery process from Li-ion battery wastes, Hydrometallurgy 79 (3–4) (2005) 172–181.

[66] M. López, et al., E-waste dismantling as a source of personal exposure and environmental release of fine and ultrafine particles, Sci. Total Environ. 833 (2022) 154871.

[67] J. Shaw-Stewart, et al., Aqueous solution discharge of cylindrical lithium-ion cells, Sustain. Mater. Technol. 22 (2019) e00110.

[68] R. Golmohammadzadeh, F. Faraji, F. Rashchi, Recovery of lithium and cobalt from spent lithium ion batteries (LIBs) using organic acids as leaching reagents: A review, Resour. Conserv. Recycl. 136 (2018) 418–435.

[69] G. Harper, et al., Recycling lithium-ion batteries from electric vehicles, Nature 575 (7781) (2019) 75–86.

[70] A. Manthiram, X. Yu, S. Wang, Lithium battery chemistries enabled by solid-state electrolytes, Nat. Rev. Mater. 2 (4) (2017) 1–16.

[71] T. Greenhalgh, C. Jackson, S. Shaw, T. Janamian, Achieving research impact through co-creation in community-based health services: literature review and case study, Milbank Q. 94 (2) (2016) 392–429.

[72] H.-I. Kim, J.-S. Sohn, S.-K. Kim, D.-H. Yang, S. Byun, Development of Technology for Recycling Large-Capacity Lithium-Ion Batteries for EV, ESS, in: REWAS 2022: Developing Tomorrow’s Technical Cycles (Volume I), Springer, 2022, pp. 173–180.

[73] M.P. Dos Santos, et al., A technology for recycling lithium-ion batteries promoting the circular economy: The RecycLib, Resour. Conserv. Recycl. 175 (2021) 105863.

[74] J. Marshall, D. Gastol, R. Sommerville, B. Middleton, V. Goodship, E. Kendrick, Disassembly of Li ion cells—characterization and safety considerations of a recycling scheme, Metals (Basel) 10 (6) (2020) 773.

[75] Z. Wu, H. Zhu, H. Bi, P. He, S. Gao, Recycling of electrode materials from spent lithium-ion power batteries via thermal and mechanical treatments, Waste Manag. Res. 39 (4) (2021) 607–619.

[76] K. Wegener, W.H. Chen, F. Dietrich, K. Dröder, S. Kara, Robot assisted disassembly for the recycling of electric vehicle batteries, Procedia CIRP 29 (2015) 716–721.

[77] A. Garg, L. Zhou, J. Zheng, L. Gao, Qualitative framework based on intelligent robotics for safe and efficient disassembly of battery modules for recycling purposes, in: IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2020, p. 012159.

[78] L. Zhou, A. Garg, J. Zheng, L. Gao, K. Oh, Battery pack recycling challenges for the year 2030: Recommended solutions based on intelligent robotics for safe and efficient disassembly, residual energy detection, and secondary utilization, Energy Storage 3 (3) (2021) e190.

[79] A. Rastegarpanah, H.C. Gonzalez, R. Stolkin, Semi-autonomous behaviour tree-based framework for sorting electric vehicle batteries components, Robotics 10 (2) (2021) 82.

[80] H. Yin, J. Xiao, G. Wang, Human-robot collaboration re-manufacturing for uncertain disassembly in retired battery recycling, in: 2022 5th World Conference on Mechanical Engineering and Intelligent Manufacturing (WCMEIM), IEEE, 2022, pp. 595–598.

[81] S. Blankemeyer, D. Wiens, T. Wiese, A. Raatz, S. Kara, Investigation of the potential for an automated disassembly process of BEV batteries, Procedia CIRP 98 (2021) 559–564.

[82] R. Gerbers, K. Wegener, F. Dietrich, K. Dröder, “Safe, flexible and productive human-robot-collaboration for disassembly of lithium-ion batteries,” Recycling of lithium-ion batteries: the lithorec way, 2018, pp. 99–126.

[83] M. Zorn, et al., An Approach for Automated Disassembly of Lithium-Ion Battery Packs and High-Quality Recycling Using Computer Vision, Labeling, and Material Characterization, Recycling 7 (4) (2022), https://doi.org/10.3390/recycling7040048.

[84] M. Zorn, et al., An approach for automated disassembly of lithium-ion battery packs and high-quality recycling using computer vision, labeling, and material characterization, Recycling 7 (4) (2022) 48.

[85] I. Kay, S. Farhad, A. Mahajan, R. Esmaeeli, S.R. Hashemi, Robotic disassembly of electric vehicles’ battery modules for recycling, Energies (Basel) 15 (13) (2022) 4856.

[86] L. Li, M. Maftouni, Z.J. Kong, Z. Li, An automated recycling process of end-of-life lithium-ion batteries enhanced by online sensing and machine learning techniques, in: REWAS 2022: Developing Tomorrow’s Technical Cycles (Volume I), Springer, 2022, pp. 475–486.

[87] K. Wegener, W.H. Chen, F. Dietrich, K. Dröder, S. Kara, Robot Assisted Disassembly for the Recycling of Electric Vehicle Batteries, Procedia CIRP 29 (2015) 716–721.

[88] A. Garg, L. Zhou, J. Zheng, L. Gao, Qualitative Framework Based on Intelligent Robotics for Safe and Efficient Disassembly of Battery Modules for Recycling Purposes, in: Proceedings of the IOP Conference Series: Earth and Environmental Science 463, IOP Publishing, 2020 012159.

[89] L. Zhou, A. Garg, J. Zheng, L. Gao, K. Oh, Efficient Disassembly, Residual Energy Detection, and Secondary Utilization, Energy Storage 3 (2021) e190.

[90] A. Rastegarpanah, H.C. Gonzalez, R. Stolkin, Semi-Autonomous Behaviour Tree-Based Framework for Sorting Electric Vehicle Batteries Components, Robotics 10 (2021) 82.

[91] H. Yin, J. Xiao, G. Wang, Human-Robot Collaboration Re-Manufacturing for Uncertain Disassembly in Retired Battery Recycling, in: Proceedings of the 2022 5th World Conference on Mechanical Engineering and Intelligent Manufacturing (WCMEIM), IEEE, 2022, pp. 595–598.

[92] S. Blankemeyer, D. Wiens, T. Wiese, A. Raatz, S. Kara, Investigation of the Potential for an Automated Disassembly Process of BEV Batteries, Procedia CIRP 98 (2021) 559–564.

[93] W.J. Tan, C.M.M. Chin, A. Garg, L. Gao, A Hybrid Disassembly Framework for Disassembly of Electric Vehicle Batteries, Int. J. Energy Res. 45 (2021) 8073–8082.

[94] M. Zorn, C. Ionescu, D. Klohs, K. Zähl, N. Kisseler, A. Daldrup, S. Hams, Y. Zheng, C. Offermanns, S. Flamme, et al., An Approach for Automated Disassembly of Lithium-Ion Battery Packs and High-Quality Recycling Using Computer Vision, Labeling, and Material Characterization, Recycling 7 (2022), https://doi.org/10.3390/recycling7040048.