batteries

MDPI

Review

High-Volume Battery Recycling: Technical Review of Challenges and Future Directions

Sheikh Rehman *, Maher Al-Greer *, Adam S. Burn, Michael Short and Xinjun Cui

School of Computing Engineering and Digital Technology (SCEDT), Teesside University, Middlesbrough TS1 3BX, UK; v8043657@tees.ac.uk (A.S.B.); m.short@tees.ac.uk (M.S.); x.cui@tees.ac.uk (X.C.)
* Correspondence: s.rehman@tees.ac.uk (S.R.); m.al-greer@tees.ac.uk (M.A.-G.)

Abstract: The growing demand for lithium-ion batteries (LIBs), driven by their use in portable electronics and electric vehicles (EVs), has led to an increasing volume of spent batteries. Effective end-of-life (EoL) management is crucial to mitigate environmental risks and prevent depletion of valuable raw materials like lithium (Li), cobalt (Co), nickel (Ni), and manganese (Mn). Sustainable, high-volume recycling and material recovery are key to establishing a circular economy in the battery industry. This paper investigates challenges and proposes innovative solutions for high-volume LIB recycling, focusing on automation for large-scale recycling. Key issues include managing variations in battery design, chemistry, and topology, as well as the availability of sustainable raw materials and low-carbon energy sources for the recycling process. The paper presents a comparative study of emerging recycling techniques, including EV battery sorting, dismantling, discharge, and material recovery. With the expected growth in battery volume by 2030 (1.4 million per year by 2040), automation will be essential for efficient waste processing. Understanding the underlying processes in battery recycling is crucial for enabling safe and effective recycling methods. Finally, the paper emphasizes the importance of sustainable LIB recycling in supporting the circular economy. Our proposals aim to overcome these challenges by advancing automation and improving material recovery techniques.

Keywords: EV battery recycling; IoT; automation; LIB chemistries; sorting; end of life (EoL); disassembly; digital twin

Academic Editors: Yaocai Bai and Panpan Xu

Received: 18 January 2025
Revised: 24 February 2025
Accepted: 26 February 2025
Published: 28 February 2025

Citation: Rehman, S.; Al-Greer, M.; Burn, A.S.; Short, M.; Cui, X. High-Volume Battery Recycling: Technical Review of Challenges and Future Directions. *Batteries* **2025**, *11*, 94. https://doi.org/10.3390/batteries11030094

1. Introduction

The automotive industry's traditional reliance on fossil fuels has contributed large greenhouse gas emissions in the last century, playing a significant role in driving climate change. Since 2015, nearly 200 countries have committed to taking action to address climate change and its impacts [1]. According to a recent European Union report, transport is the only sector where greenhouse gas emissions have increased significantly in Europe over the past three decades, rising by 33.5% between 1990 and 2019 [2]. Achieving climate neutrality by 2050 requires reducing the sector's fossil fuel dependency [3]. With tighter regulations on CO_2 emissions, the demand for EVs has surged recently. Both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are currently regarded as crucial routes to achieving future environmental impact standards and sustainable transport. Rechargeable LIBs have gained global attention since their commercialization by Sony in 1991 [4]. LIBs were initially developed for commercial use in portable consumer electronics. In recent years, their application has expanded significantly, particularly in EVs [5], due to their high current density, low self-discharge, long lifespan, and low environmental effect [6–8] and versatility across various applications, including portable electronics and EVs. To improve battery lifespan, reliability, safety, and performance, various battery chemistries haven been developed in recent years and are still currently under development [9]. As highlighted in [10] the global LIB market is expanding rapidly, with production capacity rising from 242 GWh in 2020 to 822 GWh in 2024 and projected to reach 991 GWh in 2025 and 2731 GWh by 2030. This represents an over 11-times surge in LIB capacity within just a decade. Sales of EVs have been rising at an exponential rate; more than 10 million passenger EVs were sold in 2022, and by 2025, sales are predicted to double [11]. As the production of EVs continues to rise, the number of retired LIBs from these vehicles also increases, albeit with a significant lag; this leads to a growing need to consider end of life and dismantling/decommissioning for huge numbers of LIBs in the coming years. In particular, efficient upcycling/second life, recycling, and disposal solutions are needed to manage this rising waste stream and potentially recover and revalorize any reusable materials [12]. Figure 1 illustrates the projected growth in EV battery production in the UK alongside the global market's EV battery capacity from 2020 to 2030. This projection highlights the increasing demand for EV batteries driven by the rise in electric vehicle adoption. The UK's production capacity is expected to expand significantly, supporting the country's commitment to becoming a leader in sustainable automotive solutions. Meanwhile, global production capacity is set to experience exponential growth, reflecting broader trends in electrification and efforts to reduce reliance on fossil fuels, making EVs a cornerstone of future transportation strategies.

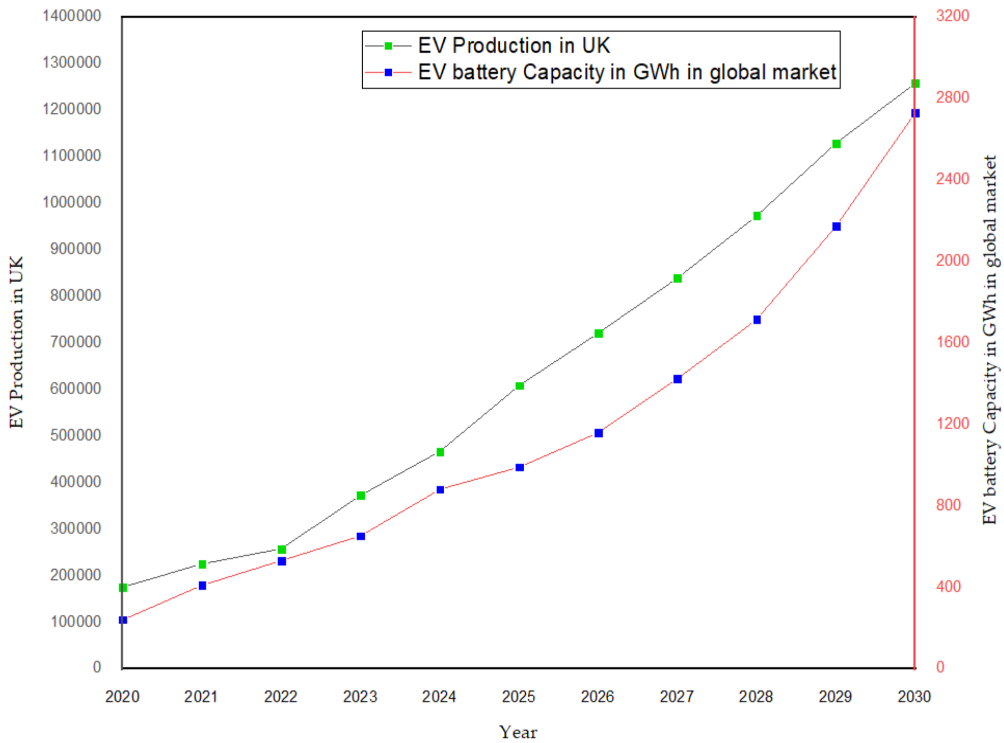

Figure 1. Projected EV production in the UK and EV battery capacity in Global Market from 2020 to 2030.

The growing demand for LIBs has increased the need for critical raw materials such as Li, Ni, and Co, which are concentrated in specific regions. For example, over 50% of cobalt is sourced from the Democratic Republic of Congo, and about 80% of lithium is controlled by Australia and Chile [13]. This uneven distribution raises concerns about supply chain stability, with geopolitical factors contributing to price volatility and potential monopolies [14]. To mitigate these risks, establishing a secondary supply of critical materials through the recycling of spent LIBs from EVs, stationary storage, and manufacturing waste is essential for sustainability [15]. Materials like copper (Cu) and aluminum that are easily recyclable are used to make packaging and covers. High-value metals like cobalt (5–20 weight percent), lithium (5–7 weight percent), and nickel (5–7 weight percent) are found in considerable amounts in spent lithium-ion batteries and are found in higher concentrations than in natural ores [16]. Thus, one of the best waste management solutions for discarded LIBs seems to be recycling processing [5,17]. Recycling techniques may reduce the need for raw material extraction, which involves high energy consumption and the production of CO_2 emissions, as certain elements will be recovered as high-quality outputs [18]. High-volume recycling of EoL batteries has become a major priority due to the rising number of EVs being produced, the growing number of spent batteries, and mounting environmental concerns. At the EoL stage, inadequate handling and recycling of batteries can significantly amplify environmental and health risks [19]. Table 1 illustrates the key components of the cell and their corresponding mass fractions, providing a detailed breakdown for reference.

Table 1. Typical Composition of a Commercial Lithium-Ion Battery Cell.

Battery Component	Materials	Mass (%)
Cathode	Lithium-based compounds (e.g., NMC, LFP, or LCO).	30–40
Anode	Primarily graphite, sometimes with small percentages of silicon additives for enhanced energy density.	20–25
Electrolyte	Composed of lithium salts (e.g., $LiPF_6$) dissolved in a mixture of organic solvents like EC, DMC, and DEC.	10–15
Separator	Made from thin polymeric films (e.g., polyethylene or polypropylene).	5
Current Collectors	Aluminum foil (for the cathode) and copper foil (for the anode).	10–15
Binder and Conductive Additives	Polyvinylidene fluoride (PVDF) is generally considered the standard binder for most LIB cathodes, a combination of carboxymethyl cellulose (CMC) and styrene-butadiene rubber (SBR) is typically used as the binder for anodes.	3–5
Casing	Aluminum or steel.	10–20

The study and deployment of LIBs are currently of tremendous scientific and technological interest, offering alternatives which can help reduce the number of fossil fuel-powered vehicles. Vehicle electrification is an emerging solution (among other things, such as potential weight reduction and improved powertrain performance) to reduce fossil fuel dependence and the environmental pollution caused by automobile emission [20]. As the market for LIBs grows, there is an increasing demand to recover and recycle spent LIBs [21]. Health and environmental risks associated with battery waste could affect society's ability to grow sustainably [22]. Therefore, developing efficient and sustainable recycling methods is key to reducing the environmental impact and promoting a circular economy. Recycling not only recovers valuable materials but also reduces the need for raw material extraction, which is energy-intensive and generates significant CO_2 emission [17,23,24]. Recycling opportunities are expected to emerge early, driven by the need to process manufacturing scrap from the battery production process. This scrap includes defective cells, modules, and excess electrode material. During initial scale-up and optimization, production scrap can reach 20–30%, dropping to 5–10% once stabilized [25]. In the 2020s, production scrap will be the main source of recyclable material [26], while, by the 2030s, EoL batteries will contribute significantly more, and by 2040, around 83% of recycled battery material is projected to come from EoL batteries [27]. Furthermore, a significant portion of EVs is written off annually by insurers due to the inability to assess or repair damaged battery packs, particularly after incidents such as vehicle collisions [28]. These compromised battery packs, often deemed unserviceable due to safety and performance risks, are classified as non-repairable and must undergo EoL processing for safe material recovery and recycling [29].

Repurposed LIBs can be a valuable source of future battery materials. By 2030, it is anticipated that more than 5 million metric tons of LIBs will reach the end of their operational lifespan [30]. The National Academy of Science and Engineering predicts that, by 2035, there will be 150 million used EV batteries, up from 50,000 in 2020. This highlights the significance of having a recycling infrastructure and established reuse procedures in place to handle the influx of spent batteries [31]. This projected surge necessitates the development of extensive recycling infrastructures to recover valuable materials and mitigate the environmental and health hazards posed by improperly managed toxic components. Ensuring sustainable battery management practices is crucial to preventing these burdens from being passed to future generations. Thus, the battery manufacturing industry must embrace a model that prioritizes social responsibility, environmental sustainability, economic feasibility, and innovative practices [32].

Removing the battery from the vehicle and discarding it is not the best option. In this case, the battery industry has two choices for dealing with the battery's EoL phase. Redirecting the battery to a second-life use circuit extends its usable life and provides alternate energy storage, lowering the environmental effect per kWh delivered. Transferring the battery to a recycling circuit, where important components, including critical raw materials, are reused to make new batteries, lowers the environmental effect of manufacturing [32]. The rapid deployment of EVs in the market, in combination with reuse and recycling, has the potential to create a circular economy [33]. Technologies for recycling must be versatile and adaptable to developing methods of manufacturing, especially those that process materials for future battery generations [34]. Figure 2 presents a schematic overview of the potential recycling pathways for LIBs.

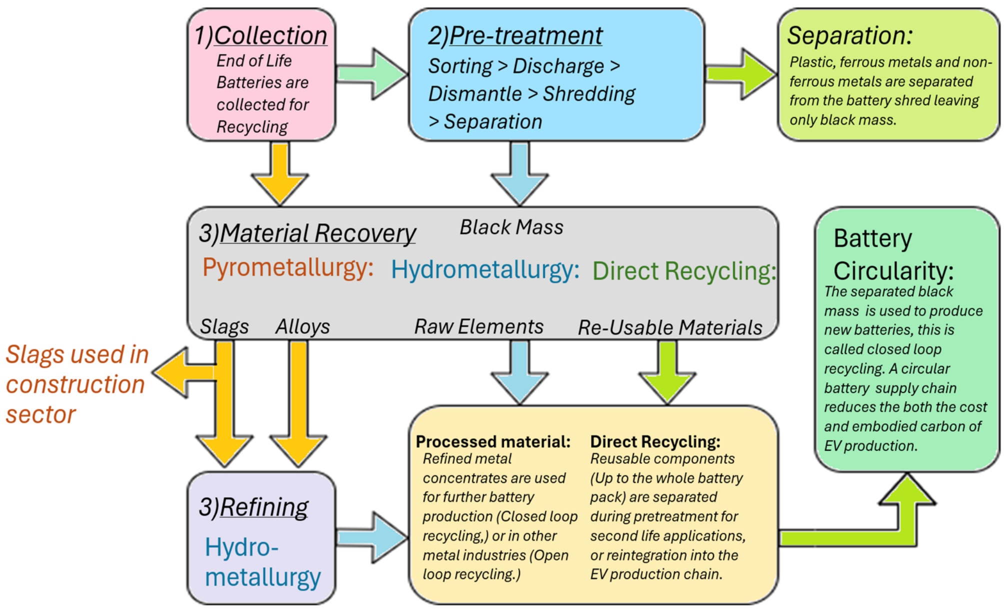

Figure 2. Schematic overview of possible recycling routes for LIBs.

Recycling lithium-ion batteries presents a variety of technical, economic, and environmental challenges that need to be addressed. Some of the key challenges are discussed below.

- Li, Co, Ni, Mn, and graphite are among the components that make up lithium-ion batteries. The recycling process is complicated and costly because each of these materials requires a different set of processes [35,36].
- The variety of battery formulations makes sorting difficulties according to their chemistry a crucial problem when it comes to recycling lithium-ion batteries. Distinct recycling procedures are needed for different battery chemistries, and incorrect sorting can result in lower material recovery, safety hazards, and inefficiencies [37].
- The wide variations in battery designs among manufacturers pose a challenge to the development of standardized recycling procedures. Automatic disassembly and recovery are made more difficult by this irregularity [38,39].
- If LIBs are handled improperly during manufacturing or transportation, they may experience thermal runaway, which can result in explosions or fires [40]. It is important to follow safety precautions when handling damaged or used batteries.
- Battery systems in electrically powered vehicles store energy in chemical form, with capacities ranging from 20 to 100 kWh and system voltages between 300 and 800 V [41,42]. The associated hazards become particularly critical when the battery is disconnected from its operational context, such as during dismantling or recycling procedures [43].
- There are significant regional differences in the laws regarding battery recycling. Large-scale recycling system development is hampered by a lack of international standards and a lack of enforcement of current laws [44,45].
- Recycling is intended to lessen environmental damage, however, the procedures themselves can be harmful and energy-intensive.

Each of the existing materials recovery process technologies, such as the direct recycling process, hydrometallurgical process, and pyrometallurgical process, has disadvantages [16,46]. Table 2 provides a detailed comparison of various EV battery recycling methods, each with its unique advantages and disadvantages.

Table 2. Comparison of the EV battery recycling methods [17,47–55].

Current Recycling Methods	Pros	Cons
Pyrometallurgical Process	High recycling rates Solvent free Simple operation	High energy consumption due to high temperatures Toxic gas generation May need other operations to effectively recover materials Li and Mn are not recovered
Hydrometallurgical Processes	High recycling rates High-purity product formation Wide variety of metals are recovered Low energy consumption	Complex process Usage of toxic reagents Long and costly operation Excess wastewater generation
Direct Recycling Process	Environmentally sustainable High specificity Low energy consumption High recovery rate Reduction in recovery costs	Does not allow for simultaneous processing of different cathode materials High operational and equipment costs Challenges associated with component heterogeneity

Table 3 presents a key challenges and advanced technologies involved in LIB recycling. These challenges include the complexity of battery chemistries, safety risks associated with dismantling, and the environmental impact of current recycling processes. Advanced technologies such as robotic disassembly, hydrometallurgical and direct recycling methods, and artificial intelligence (AI)-driven sorting systems are being explored to improve efficiency and sustainability. Ongoing research focuses on enhancing material recovery rates, reducing energy consumption, and developing cost-effective recycling solutions to support the circular economy for LIBs.

Table 3. LIB Recycling Challenges and Technologies.

Challenges in LIB Recycling	Technologies and Innovations	Future Directions
Collection and Sorting (Logistics, safety, battery identification).	Advanced Recycling Technologies (Low-emission pyrometallurgy, improved hydrometallurgy).	Sustainable Practices (Circular economy, eco-design of LIBs).
Discharge and Dismantling (High energy density, thermal runaway and fire hazards, toxic chemical exposure, labor-intensive process).	Automation and Robotics (Automated dismantling, robotic sorting).	Policy and Regulations (Standardization, safety protocols, global agreements).
Material Recovery Process (Pyrometallurgy, hydrometallurgy, direct recycling).	Direct Recycling Methods (Reuse of active materials with minimal processing).	Research and Development (Efficiency improvements, reducing emissions, maximizing recovery).
Technical Challenges (Battery chemistry variation).		
Economic Challenges (High costs, market demand fluctuations).		
Environmental and Safety Challenges (Hazardous waste, fire risks, emissions).		

This review paper provides an in-depth review of the high-volume recycling challenges related to LIBs, including the materials recovery procedure and current recycling technologies, and, based upon the results, offers advanced technical insights that set it apart from existing literature. Unlike many reviews that focus on specific aspects such as material recovery or environmental impacts, this paper takes a holistic approach by integrating the challenges associated with the entire lifecycle and recycling process, including LIB online tracking and condition monitoring, recycling decision support, material recovery, battery discharge management, and automated dismantling. A key distinguishing feature is the inclusion of practical technical data, such as datasets for battery sorting, control algorithms for battery discharge, and methodologies for robotic dismantling. These elements are often underexplored in other reviews, yet they are crucial for advancing the scalability and safety of recycling processes, as well as for data-oriented decision making in recycling processes. Additionally, the paper emphasizes the adoption of emerging technologies like automation, robotics, and artificial intelligence, addressing the critical need for efficient and scalable solutions in line with Industry 4.0 advancements. By bridging knowledge gaps, enabling industrial adoption, and providing actionable insights, this paper not only enhances academic understanding but also supports the transition of innovative recycling technologies from research to real-world applications. Its focus on practical data and future-oriented solutions makes it a significant resource for driving progress in sustainable LIB recycling, particularly in the context of the growing demand for electric vehicles.

The remainder of this article is structured as follows: Section 2 presents a comprehensive background review and an in-depth analysis of current developments in the field of EV battery recycling, in light of recent commitments to vehicle electrification. This section addresses several critical challenges, including the complexities involved in sorting EV batteries efficiently, managing the discharge of batteries during the scale-up production process, and the technical hurdles associated with dismantling batteries for recycling. These challenges are essential to overcome in order to support the growing demand for EVs and ensure sustainable battery lifecycles.

Section 3 explores the groundbreaking innovations reshaping the recycling of EoL EV batteries, focusing specifically on automation technologies and the advancement of sophisticated sorting and disassembly methods. The use of robots in dismantling EV batteries is a key area of innovation, providing significant improvements in safety, efficiency, and precision. Robotic systems can perform complex tasks such as the removal of battery modules, disassembling battery packs, and sorting materials, reducing the need for manual labor and mitigating risks associated with handling hazardous materials. This section also explores the recovery of critical materials from EoL EV batteries, such as lithium, cobalt, and nickel, which are essential for new battery production. Innovations in this area aim to increase recovery rates, reduce costs, and minimize environmental impact, contributing to a more sustainable and circular economy in the automotive industry.

2. Current Challenges and Developments

The growing demand for batteries and their use in a variety of industries, especially in various types of vehicles, are the results of the quick development of LIBs, which has improved manufacturing efficiency and decreased costs for manufacturers [17,56]. Reusing, recycling, and repurposing LIBs are essential to creating a sustainable battery economy that can meet demand for LIBs while reducing emissions that have an adverse effect on the climate [17,57]. The increasing demand for EVs worldwide due to the urgent need for greener transportation and reduced greenhouse gas emissions has made recycling LIBs more crucial than ever [58]. These batteries, which are essential to the operation of the majority of EVs, contain lithium, cobalt, and nickel in addition to other valuable and scarce minerals. Improper disposal of these batteries poses significant environmental risks [24]. Effective recycling reduces the carbon footprint of battery manufacturing and dependency on virgin resources [59]. It also makes it easier to recover necessary materials and reduces the risk of environmental contamination [60]. A more sustainable strategy to managing EV batteries is being made possible by recent advancements in recycling technologies, changing regulatory frameworks, and heightened industry stakeholder collaboration. Because of this, LIB recycling is a fundamental component of the circular economy and is necessary to promote environmental stewardship and the long-term sustainability of electric vehicles.

2.1. Challenges in Sorting EV Batteries

Sorting is the first step in recycling EV batteries, and it is a crucial but difficult procedure. Due to the large variety of battery chemistries, forms, and architectures that have been produced by the quick rate of innovation in EV battery technologies, separating batteries effectively for recycling has become increasingly difficult [14,32,61]. LIB packs are intricate assemblies consisting of multiple interconnected modules. Each module contains numerous cells, which can be of pouch, prismatic, or cylindrical types [62]. These cells are typically arranged in diverse parallel-series configurations to achieve the desired electrical output. Common techniques for joining within LIB cells, modules, and packs include welding, wire bonding, and mechanical fastening, ensuring structural integrity and electrical connectivity [63]. Diversity in chemistry, intricate battery designs, labor-intensive procedures, a lack of standardized labeling, and safety concerns are some of the issues that affect sorting accuracy, which in turn affects the safety, effectiveness, and economic viability of recycling processes [64,65].

The chemistry of the battery is a primary criterion in the sorting process and is often complemented by additional parameters such as state of health (SoH), remaining usable life (RUL), and state of charge (SoC). These parameters are crucial for determining the most appropriate recycling pathway for spent LIBs [61]. However, accurately estimating a battery's SoH is particularly challenging due to the variability in internal side reactions and external operating conditions [62]. Batteries must be properly sorted in order to be arranged in storage chambers based on their unique types and conditions, which lowers safety risks associated with damaged and unknown EoL batteries [66]. In this context, "unknown" EoL batteries refer to those with uncertain or undocumented characteristics, such as unidentified chemistry, unclear usage history, or undetermined state of health. These uncertainties make it difficult to assess their safety and recycling potential, increasing the risks of hazardous incidents such as thermal runaway or leakage. Proper identification and sorting of such batteries are essential to ensure safe handling, storage, and processing.

In Figure 3, a comprehensive framework for cloud-based battery tracking, classification, sorting, and recycling support is presented. A prototype implementation of such a framework is currently being developed at Teesside University. Testing, analysis, and experience reporting are part of planned future work [67].

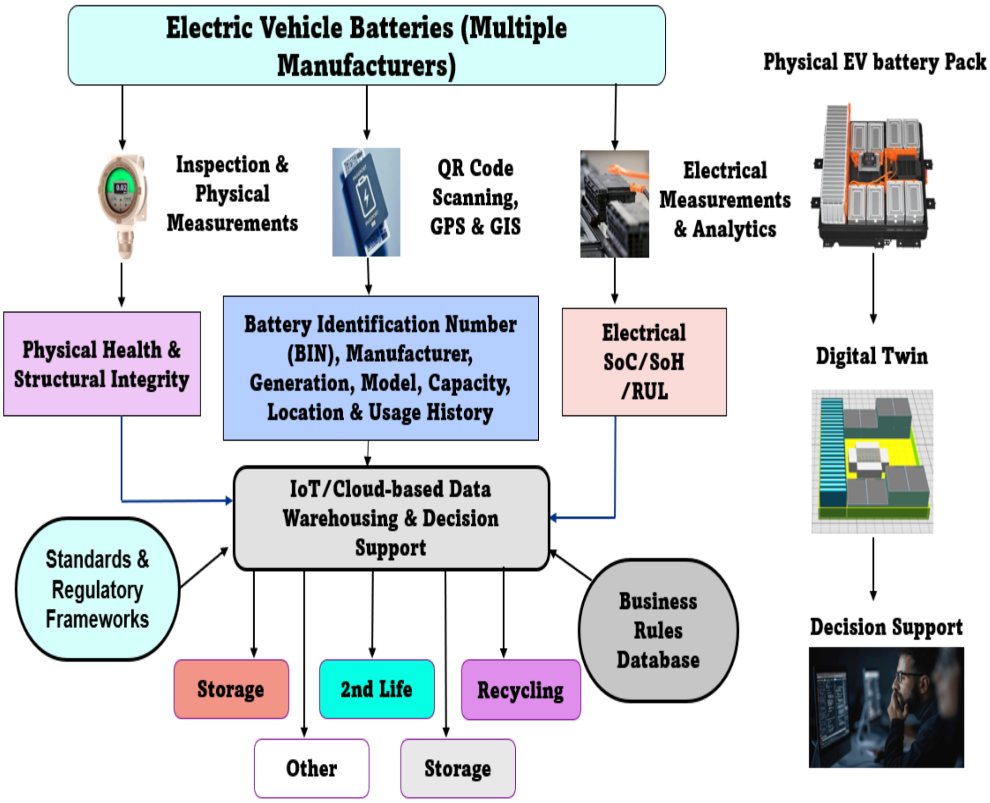

Figure 3. EV Battery Tracking, Classification, and Sorting Mechanisms.

2.1.1. Diversity in Chemistry and Compatibility Issues

EV batteries use a range of cathode chemistries, including lithium cobalt oxide (LCO), lithium nickel cobalt aluminum oxide (NCA), lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP), and lithium manganese oxide (LMO), with lithium titanate (LTO) being the exception as a common anode material [68–70]. Graphite is typically used as the anode material in many of these batteries. To maximize recovery and reduce contamination, each type requires a different approach to treatment. For example, NMC batteries are valued for their nickel and cobalt content, whereas LFP batteries have fewer high-value elements, which makes recovery using traditional techniques less profitable [71]. In the recycling process, mixing numerous chemistries can decrease the purity of recovered materials, making it more difficult to re-enter the battery supply chain and reducing profit [24,72,73]. Additionally, there are safety and handling standards for these chemicals; improper sorting increases the risk of fires, particularly when volatile chemicals are inadvertently mixed [74]. Table 4 compares various characteristics of the chemistries in terms of specific energy, cycle life, thermal runaway, nominal voltage, operating range, and applications.

Table 4. Different Li-ion batteries' chemistries.

Battery Chemistry	Specific Energy (Wh/kg)	Cycle Life	Thermal Runaway (°C)	Nominal Voltage/Cell (V)	Operating Range/Cell (V)	Applications
LCO	150–200	500–1000	150	3.60	3.0–4.2	Mobile phones, tablets, laptops, cameras
LMO	100–150	300–700	250	3.70	3.0–4.2	Power tools, medical devices, electric powertrains
NMC	150–220	1000–2000	210	3.70	3.6–4.0	E-bikes, medical devices, EVs, industrial
LFP	90–160	2000 and higher	270	3.20	2.0–3.65	Portable and stationary needing high load currents and endurance
NCA	200–260	500	150	3.70	3.0–4.2	Medical devices, industrial, electric powertrain (Tesla)
LTO	50–80	3000–7000	N/A	2.3	1.5–2.85	UPS, electric powertrain, solar-powered street lighting

2.1.2. Complexity of Battery Pack Design

Disassembling EV batteries presents significant challenges due to the wide variety of battery designs [75], the lack of detailed knowledge about each battery's condition, and the limited availability of comprehensive design information from original equipment manufacturers (OEMs). This complexity often necessitates adaptive strategies and specialized expertise to navigate unknown variables effectively [76]. To maximize battery performance and safety, manufacturers frequently create packs with distinctive electronics, cooling systems, module designs, and casing. Because of this diversity, specific disassembly methods are needed, which are time-consuming and need specific abilities and tools. For instance, some packs have welded joints or adhesive coatings that make it difficult to separate cells and modules using conventional disassembly techniques [38].

The complexity of battery pack design varies significantly across manufacturers, driven by differences in battery chemistry, cell configuration, thermal management strategies, and scalability. For example, Tesla uses cylindrical cells, such as the 18,650 and 2170 models, in its battery packs. These cells are arranged in large-scale configurations, with up to 7000 cells in models like the Model S, allowing for high energy density and efficient use of space. However, this design introduces significant complexity, as each cell requires individual monitoring for voltage balancing, temperature regulation, and charge/discharge optimization.

In contrast, the Nissan Leaf uses pouch cells, which are lighter and more flexible than prismatic cells, allowing for efficient packing and better optimization of space within the battery pack. The 48-module configuration in the Leaf's battery pack can range from 24 kWh to 62 kWh in the latest models, providing a balance between energy density and system simplicity. However, pouch cells have certain limitations, particularly in their thermal management, as they are more sensitive to temperature fluctuations.

The design complexity of EV battery packs is influenced by the choice of cell format, thermal management methods, and overall system integration. Tesla's cylindrical cells and advanced cooling systems are optimized for high energy density and long-range performance but require complex thermal and management solutions. In contrast, manufacturers like Nissan use cost-effective designs with pouch cells and simpler thermal strategies, which offer trade-offs in energy density and range. Each approach reflects the manufacturer's priorities, whether it is maximizing performance, minimizing costs, or balancing both.

2.1.3. Lack of Standardized Labeling and Identification Systems

The lack of standardized labeling for battery chemistries, structural designs, and manufacturer-specific data is a significant impediment to efficient sorting, and the absence of material labeling significantly impedes the quality of recycling processes [39]. Many battery packs lack unambiguous labeling indicating their composition or even manufacturer origin, which slows sorting and raises the chance of errors. Several initiatives have proposed universal labeling standards, such as the use of QR codes [77], with information on chemistry, capacity, and recycling instructions, however, acceptance has been uneven across sectors and countries. The review by Bai et al. [78] provides a comprehensive overview of the current state of research and introduces the concept of the Battery Identity Global Passport (BIGP). This concept aims to enhance the recyclability of LIBs by facilitating the separation of components. This can be achieved by identifiable markings, such as labels and QR codes, which simplify the sorting and processing of battery materials during recycling. Without a standardized strategy, recycling facilities are compelled to use human identification methods, which adds time and cost to the sorting process. Standardized labeling has the potential to increase sorting accuracy and efficiency by providing recyclers with crucial information for safe and optimized handling. European governments and battery industry businesses are working to enhance battery and accumulator regulations [79].

2.1.4. High-Cost, Labor-Intensive Processes

At present, disassembly is typically performed manually and is not non-destructive. Additionally, the absence of proper labeling for materials used in the batteries impedes the ability to conduct high-quality recycling [39]. Due to technological limitations, in automated systems, current sorting processes remain largely manual, resulting in high labor costs and limited throughput. These limitations arise from the complexity of accurately identifying diverse battery chemistries, the need for precision in handling delicate components, and the difficulty in scaling automation to accommodate various battery types. While advancements in robotic systems offer potential for improved precision and efficiency, their integration into sorting processes is still in the developmental phase, limiting the effectiveness of fully automated solutions in high-volume operations. The sophisticated construction of battery packs necessitates expert workers identifying chemistries, disassembling components, and sorting them by kind, a time-consuming and error-prone task. While robotic solutions and AI-powered sorting systems are being developed, they are still prohibitively expensive and not yet feasible for general usage. Advanced AI technologies capable of distinguishing battery kinds by visual or chemical fingerprints, for example, could speed up sorting, but the needed equipment and cost commitment make it difficult for many facilities to implement. Furthermore, human error in sorting might result in misclassification, lowering recycling efficiency and posing safety issues.

2.1.5. Safety Risks and Environmental Hazards

Sorting EV batteries involves several environmental and safety issues that need to be carefully handled. During handling, batteries may retain residual charge, which could result in short circuits or thermal runaways [80]. Thermal runaway in LIBs refers to a rapid, uncontrolled increase in temperature caused by a chain reaction of exothermic chemical processes within the battery. This phenomenon occurs when the internal temperature of the battery rises to a critical point, causing the materials inside such as the electrolyte, anode, and cathode to decompose and release more heat. As the temperature continues to rise, it accelerates the reaction, leading to potential fire, explosion, or permanent damage to the battery, posing serious safety risks [81].

The global commitment to decarbonizing the transportation sector has catalyzed significant growth in the EV market, which in turn drives an escalating demand for battery raw materials. As the world strives to meet net-zero emissions targets, the demand for key materials such as Li, Co, Ni, and graphite is expected to rise substantially. Specifically, between 2021 and 2050, the global demand for Li is projected to increase 26 times, Co 6 times, Ni 12 times, and graphite 9 times. This surge in demand underscores the critical need for sustainable sourcing and efficient recycling strategies to meet the future needs of the EV industry while addressing environmental concerns associated with raw material extraction [56].

Furthermore, several batteries have dangerous components like cobalt, lithium salts, and poisonous electrolytes that, if handled improperly, can cause fires or release hazardous compounds into the environment. Therefore, to reduce these dangers, sorting procedures must follow strict safety guidelines, such as fireproof enclosure and specialized handling equipment. Inadequate sorting and processing of batteries can result in groundwater and soil contamination, which presents long-term ecological risks [24]. The economic feasibility of battery recycling is thus further impacted by safety precautions, which increase the difficulty and expense of sorting.

2.1.6. Logistics and Infrastructure Limitations

In many regions, insufficient infrastructure for processing various battery types complicates sorting and increases logistical challenges. While transportation to recycling facilities has some environmental impact, it is minimal compared to the energy-intensive recycling processes. However, transporting spent EV batteries over long distances raises costs and emissions, especially when facilities are centralized. Additionally, many recycling centers lack equipment to handle diverse battery types, reducing efficiency and capacity. Recovered materials must eventually be transported to battery manufacturing plants, which could be located near recycling facilities, minimizing transport energy use. Developing regional sorting and recycling infrastructure could enhance efficiency, reduce emissions, and lower costs, but this requires significant investment and stakeholder collaboration [32].

2.2. Challenges in Discharge EV Batteries (Scaled-Up Production)

The disassembly of electric vehicle batteries is a pivotal step in the recovery, recycling, and reuse of valuable materials. However, this process is hindered by a lack of standardization, intricate design variations, and safety challenges posed by the uncertain and variable conditions of EoL batteries [82]. Scaling up the discharge of EV batteries presents numerous issues, the most significant of which is the large residual energy that EoL batteries retain, which increases the risk of short circuits, fires, and chemical reactions [83,84]. To ensure safety, specialized equipment and protocols are required, which are expensive and difficult to execute on a large scale. The lack of standardization among battery types complicates matters further, as each kind may require distinct discharge procedures, slowing the process and increasing labor expenses [85,86]. The discharge process is often time-consuming and requires a balance of speed and safety, since quick discharge can result in overheating, whilst sluggish discharge diminishes operational efficiency [87]. Furthermore, large-scale discharge facilities must meet severe environmental and regulatory requirements, manage hazardous waste, and employ experienced workers trained in high-voltage safety, all of which add to expenses [88]. Limited automation choices, as well as the challenging logistics of transporting and processing multiple batteries, impede scaling efforts and make it difficult to build efficient, safe, and economically sustainable EV battery discharge facilities.

2.3. Challenges in Dismantling EV Batteries

Dismantling EV batteries on a large scale is difficult due to their complicated and non-standard designs [89]. The manual dismantling process also presents safety hazards for workers [90,91]. Battery systems in passenger vehicles generally operate at voltage levels between 400 and 800 volts [92] which can cause severe injury if mishandled. Depending on the battery pack's condition, there may be an elevated risk of toxic electrolyte leakage [93] potentially leading to chemical burns or environmental contamination. Furthermore, the potential for thermal runaway remains a constant concern, particularly in damaged batteries [91,94]. Each manufacturer has a unique battery design, cell arrangement, and module structure, making it challenging to establish uniform dismantling techniques [72]. EoL batteries pose significant safety issues due to their high energy and dangerous contents, which can lead to fires and chemical exposure [95].

Dismantling is primarily manual and labor-intensive because existing robotic techniques are not fully ready to properly handle the vast range of battery designs. Scaling up is further complicated by environmental and legal limits, as the process must adhere to stringent handling and disposal regulations for dangerous chemicals such as heavy metals and electrolytes. Furthermore, diversity in battery conditions such as damage, degeneration, or leakage requires flexible handling techniques, which makes automated dismantling difficult to standardize. To manage huge volumes of batteries, parts, and materials, facilities need a huge area and logistics [96].

Manual recycling processes, while often more accessible due to lower initial capital investment, involve significant labor costs and are prone to inefficiencies associated with human intervention. Tasks such as disassembly, sorting, and material recovery are labor-intensive and time-consuming, leading to higher operational costs. Furthermore, manual processes may exhibit variability in throughput and material quality, which can affect the overall effectiveness of the recycling operation. In contrast, automated recycling systems, which involve robotic systems and advanced sorting technologies, require substantial initial investment in machinery and infrastructure. However, automation presents long-term cost advantages by reducing labor costs, improving throughput, and minimizing human error, which leads to more consistent and higher-quality material recovery. These systems are particularly well-suited for high-volume operations where continuous, large-scale recycling is required. Automated systems can significantly reduce the need for manual labor, increase operational efficiency, and optimize material recovery through precision processing.

The cost analysis should account for both the initial capital investment and ongoing operational costs such as energy consumption, maintenance, and system downtime. While automated systems have higher initial costs, their ability to operate continuously with minimal human intervention can lead to greater cost savings over time. Additionally, automated systems can provide more predictable and higher yields of recovered materials, improving the economic viability of recycling operations at scale. The comparison of manual versus automated processes highlights the trade-offs between flexibility, scalability, and cost efficiency and provides insight into selecting the most appropriate method for specific recycling applications and operational scales. Laura Lander et al. examined the impact of automation on the disassembly process by developing three scenarios: a fully manual dismantling process, a hybrid semi-automated workstation where a worker collaborates with a robot, and a fully automated system. Their analysis found that automation significantly reduces labor costs, cutting them by 97% per battery pack. Additionally, automation greatly enhances the annual disassembly capacity, which could positively influence the overall profitability of battery disassembly operations [97].

Figure 4 compares the battery pack architectures of three well-known EV models such as the Tesla Model S, BMW i3, and Nissan Leaf, each utilizing distinct cell formats: cylindrical, prismatic, and pouch cells, respectively. The differences in design directly impact the complexity of dismantling, separation of components, and material recovery efficiency during the recycling process.

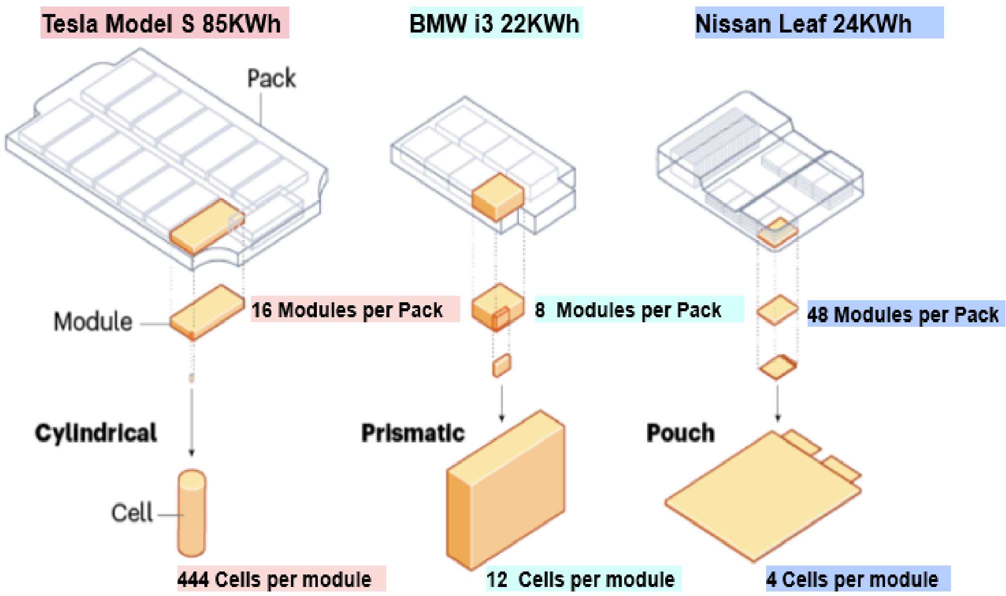

Figure 4. Challenges of different battery pack designs in EV battery recycling (use of cylindrical, prismatic, and pouch cells).

The Tesla Model S features cylindrical lithium-ion cells (initially 18,650 and later 21,700), densely packed within modules containing thousands of cells. While cylindrical cells offer high energy density and robust performance, their high cell count and complex module interconnections make disassembly labor-intensive. The series-parallel configuration increases the number of welds and interconnects, complicating automated disassembly. Additionally, Tesla employs an advanced liquid cooling system, which adds another layer of complexity in recycling, as the cooling channels and thermal interface materials must be carefully separated before processing the cells.

The BMW i3, utilizing prismatic lithium-ion cells, presents a different set of challenges. Prismatic cells offer a compact, rigid structure that improves space utilization and simplifies module integration. However, their enclosed metal casing requires additional steps to safely extract the active materials. Unlike cylindrical cells, prismatic modules are often glued or welded together, making separation more difficult. The presence of liquid cooling systems further complicates the recycling process, as specialized handling is required to prevent contamination and ensure the efficient recovery of valuable materials.

The Nissan Leaf, which uses pouch cells, introduces another layer of complexity. While pouch cells are lightweight and allow for flexible pack design, they are more susceptible to swelling and degradation over time, posing safety risks during handling. The soft polymer casing lacks structural rigidity, making automated dismantling difficult compared to prismatic or cylindrical cells. Additionally, Nissan relies primarily on air cooling, which reduces thermal management components but does not eliminate the challenge of safely separating individual pouch cells from the module enclosures.

Each of these battery pack architectures presents unique technical and economic challenges in the recycling process. The differences in cell design, module arrangement, cooling systems, and interconnects affect the feasibility of automated disassembly and the efficiency of recovering valuable materials such as lithium, cobalt, and nickel. Figure 4 highlights how cell type, pack structure, and cooling strategies influence the dismantling process, emphasizing the need for standardized battery designs or improved robotic disassembly techniques to enhance the sustainability of EV battery recycling.

Finally, the economics of dismantling are difficult; the high costs of labor, specialized equipment, and compliance can surpass the value of materials recovered, making large-scale operations economically unsustainable [98]. To tackle these obstacles, advancements in automation, improved design standardization, and efficient safety standards, as well as industry collaboration to ease dismantling and enable more sustainable battery recycling, are required.

2.4. Challenges in Critical Material Recovery

Recycling technologies for EV batteries face significant challenges, particularly in the recovery of critical materials like lithium, cobalt, and nickel. The current methods, such as pyrometallurgical, hydrometallurgical, and direct recycling, each come with limitations, including energy consumption, material loss, environmental risks, and chemical complexity. However, there are substantial opportunities for improvement through advancements in automation, new leaching methods, green chemistry, and direct recycling techniques [99]. As EV adoption continues to grow, it is crucial to develop more efficient, cost-effective, and environmentally friendly recycling technologies to meet the demand for critical materials while reducing the environmental impact of battery disposal. In Section 3.4.2, the three main recycling processes for recovering critical materials from EV batteries, pyrometallurgical, hydrometallurgical, and direct recycling, are discussed. Each process has its advantages and disadvantages, with pyrometallurgical methods being energy-intensive but effective for certain metals, hydrometallurgical methods offering more selective recovery with lower energy requirements but complex chemical handling, and direct recycling holding promise for preserving the integrity of materials while minimizing environmental impact. Additionally, we explore the significant opportunities for improving critical material recovery through innovations in automation, advanced leaching methods, and direct recycling improvements.

2.5. Technical and Economic Barriers to Large-Scale Implementation of Automation and AI in Battery Recycling

The potential for automation and AI to enhance the efficiency, safety, and material recovery in EV battery recycling is immense. However, several technical and economic challenges must be addressed to achieve large-scale implementation. These barriers hinder the widespread adoption of these technologies, despite their long-term promise. A key technical barrier is the compatibility and interoperability of data and interfaces. Variations in battery designs and chemistries make standardization difficult, complicating AI-driven automation. Similarly, battery heterogeneity poses challenges, as differences in size, composition, and SoH require adaptable AI algorithms and flexible robotic handling systems.

From an economic perspective, the high capital investment needed for AI-driven sorting and robotic disassembly systems limits adoption, particularly for smaller facilities. The regulatory landscape adds further complexity, with varying safety and environmental compliance requirements creating uncertainty for investors.

Safety concerns are another critical issue, as automated systems must handle high-voltage batteries while preventing risks such as thermal runaway and hazardous material leaks. Implementing advanced monitoring and fail-safe mechanisms increases costs and complexity. Additionally, the energy and carbon footprint of AI-driven recycling must be managed by integrating renewable energy sources and optimizing AI models for efficiency.

3. Innovations in EoL EV Battery Recycling

EoL EV battery recycling innovations are revolutionizing the sector by improving sustainability, efficiency, and material recovery [100]. With the use of advanced recycling processes, such as hydrometallurgical processes and direct recycling, vital materials like nickel, cobalt, and lithium can be recovered with minimal waste and energy. Sorting and processing are optimized through the use of AI and machine learning (ML), allowing for more accurate battery component identification and classification [101]. Furthermore, automated robotic technologies improve battery disassembly effectiveness and safety, and new chemical processes are being developed to recover components without producing dangerous by-products [82]. By reusing EV batteries for energy storage solutions, research into second-life uses is also essential to prolonging the batteries' lifespan. Together, these developments not only make battery recycling more economically feasible but they also help create a more circular economy by lowering dependency on virgin resources and lessening the negative effects on the environment.

3.1. Automation in Recycling

As EV demand rises, automation in EV battery recycling is becoming more and more vital to improving sustainability and operating efficiency. This innovative technique safely and efficiently disassembles battery packs by using advanced robotic tools, such as the ABB IRB 6700. AI-powered technologies and automated sorting lines also greatly improve the recovery and classification of precious materials, guaranteeing the best possible use of available resources. Using data analytics and predictive maintenance, these automated systems save downtime, optimize operations, and enhance safety by handling dangerous materials in regulated settings [102,103]. Moreover, traceability and regulatory compliance are guaranteed throughout the recycling process via integrated automated systems. Automation has the potential to transform EV battery recycling, making it more effective, efficient, and environmentally friendly, even while obstacles like high upfront costs and the need for skilled employees still exist. Automating the dismantling of batteries could lead to significant cost reductions. For example, the manual disassembly of EV battery packs from manufacturers like Renault, Nissan, Peugeot, Tesla, BAIC, and BYD ranges in cost from USD 47 to USD 197 per pack. This cost variation primarily arises from differences in the number of modules, screws, fasteners, and welded components [97]. Transitioning from manual to semi-automated or fully automated recycling could dramatically lower these costs. For instance, the recycling cost for a Nissan Leaf battery could decrease from USD 0.64 per kg to just USD 0.02 per kg [97]. Ongoing research into automation, alongside advancements in artificial intelligence, is progressing rapidly, aiming to enable the sorting of batteries based on visual characteristics such as size, color, and geometry [104].

There are a few challenges in automating the LIB disassembly process due to the absence of standardization among battery designs making it difficult to automate the disassembly of lithium-ion traction batteries, requiring robots to adapt to different configurations [76,105]. The wide variation in component geometries within battery packs, coupled with the complexity of differing battery pack designs, presents a major challenge for automating the disassembly process, even between EV battery packs from the same manufacturer [106]. Additionally, significant differences in component weights complicate the precise and efficient selection of appropriate disassembly tools and robotic platforms [39]. Another significant challenge arises from non-detachable connections, such as glued or welded joints, including thermal interface materials used to couple battery cells to cooling plates and adhesive seals between the housing cover and tray. Developing specialized tools and processes is essential to automate the separation of these components. Additionally, the limited accessibility of individual parts further complicates the design of an effective automation concept [104,107]. Another challenge is that hazardous materials and high-voltage components require complex sensors and control systems to limit toxic exposure and prevent fires, and safety hazards further hinder automation [93]. Furthermore, it is challenging for robots to disassemble batteries without damaging the strong adhesives and fasteners used in their production; this necessitates sophisticated manipulation techniques that raise the complexity and expense. Because of these issues, automation is not economically feasible for extensive recycling applications due to its high cost and technical demands. In industrial production, robots are usually programmed for repetitive tasks on fixed objects within structured environments. However, disassembling used EV batteries presents a more complex challenge, as it involves working with less predictable conditions that vary depending on the battery's state, type, and design. This requires robots to be adaptable to different battery configurations and conditions. To achieve this, higher-level control systems and advanced machine vision are necessary to accommodate the variability in processes and parameters [75].

Despite these difficulties, an automated disassembly solution that can successfully overcome the associated technological obstacles is desperately needed. These issues must be specifically addressed by creating specialized tools and sophisticated component detection techniques, as well as by structuring the disassembly system to consider the particular needs of battery disassembly. With the anticipated rapid increase in the number of electric vehicles on the road, the volume of battery returns at the end of their lifecycle will rise significantly. This highlights the critical need for process automation to ensure a cost-effective and efficient separation process in the future.

3.2. Advanced Sorting and Disassembly Techniques

Battery sorting presents a significant challenge and can become a costly component within the battery recycling process [108]. Currently, battery sorting relies heavily on manual labor, with technicians and staff performing many of the tasks. However, this process demands a deeper understanding of battery chemistries and SoH, which adds complexity [109]. Given the substantial energy stored in battery packs, they are not suitable for manual disassembly. Their intricate designs, numerous components, varying configurations, and different EoL conditions make automated disassembly the most viable solution. Automation is necessary to ensure safety, efficiency, and scalability in handling these complex systems [66]. The various battery designs, chemistries, sizes, electrical connections, and packaging formats present ongoing challenges to the development and implementation of automated disassembly solutions, despite the fact that researchers and industry players are actively exploring automated disassembly technologies to improve the efficiency and scalability of the recycling process [110].

Parameters such as size, weight, and magnetic properties are crucial for developing a basic approach to approximating battery chemistry [111]. However, the chemistries and internal structures of many batteries are either not disclosed or are obscured due to battery degradation. This makes the chemistry-based sorting process more challenging. To address this, recent studies propose integrating electrochemical models with deep learning and machine learning algorithms to better determine the electrochemical characteristics of the battery [112]. Recent advances of incorporating AI and machine learning in sorting processes provide innovative approaches to cope with the demanding situations of computerized disassembly [113]. Understanding the disassembly process through human worker monitoring and analysis can help in developing efficient automation strategies [114].

Figure 5 presents a conceptual flowchart of EV battery recycling based on their SoH and cathode chemistry. One effective solution to address the variability in battery designs is the creation of digital passports for EV batteries. These digital passports would be invaluable for automating processes such as testing and disassembly. They would store critical information, including component dimensions, 3D CAD models, the level of degradation in battery modules, and whether a module is damaged or still reusable. Additionally, sensor-based sorting technologies could be utilized to analyze cathode chemistry and assess the SoH of the battery, further enhancing the sorting and recycling process [66]. Additionally, AI and ML methodologies can significantly improve the dismantling process through advanced computer vision pipelines and sensor-based sorting technologies. When effectively implemented, these technologies can accelerate the process while reducing time, costs, and safety risks compared to manual methods. AI and ML enhance the accuracy and efficiency of sorting by enabling the recognition of battery components, such as screws and connectors, which allows robots to perform disassembly more effectively. Redwood Materials is an example of a company that has developed efficient methods for recycling lithium-ion batteries. They employ cutting-edge sorting systems, utilizing high-precision robots and advanced material recovery processes to optimize recycling efficiency.

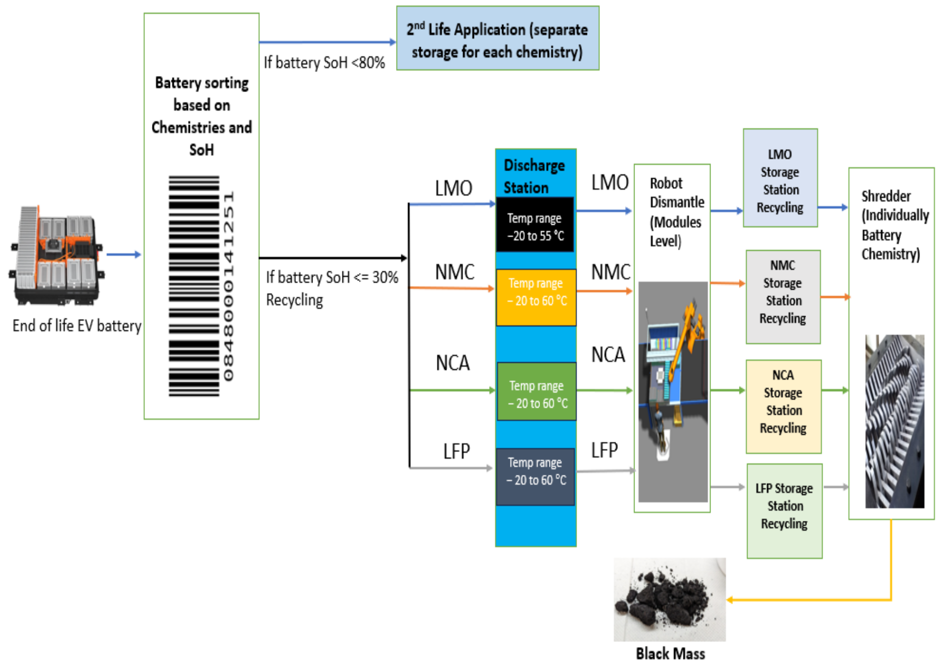

Figure 5. Proposed flowchart of EV battery recycling.

3.3. Integration of Artificial Intelligence/Machine Learning in Recycling Processes

The incorporation of AI and ML in the recycling of EV batteries has revolutionized the industry by significantly enhancing efficiency, sustainability, and resource recovery [115]. AI technologies leverage ML algorithms, sensors, and data analysis to automate the sorting and identification of various battery types based on their chemistry, size, and state of charge [116]. AI detection systems utilize advanced visual inspection technologies to evaluate material quality, identify defects, and ensure precise placement during recycling processes [117]. This automation not only minimizes human labor but also increases the accuracy and speed of sorting, ensuring that batteries are correctly categorized for appropriate processing [105]. Once sorted, AI optimizes the subsequent recycling processes, such as dismantling and material recovery, by continuously analyzing data and predicting the most effective methods for extracting valuable metals like lithium, cobalt, and nickel [118]. This results in improved resource utilization, reduced waste, and a more sustainable recycling process. Furthermore, AI plays a crucial role in the logistics of battery collection and transportation, analyzing data on collection routes and facility capacities to optimize the flow of materials. This optimization reduces transportation costs, lowers fuel consumption, and minimizes the environmental footprint of the recycling operations. By enabling higher recovery rates and reducing the need for new raw materials, AI contributes to the circular economy, helping to mitigate the environmental impacts of battery production and disposal. As AI technologies continue to evolve, their potential to further improve the sustainability of EV battery recycling becomes increasingly significant, driving both economic and environmental benefits [60].

3.4. Recovery of Critical Materials from EoL EV Batteries

Sustainability requires recovering crucial elements from EoL EV batteries because of the growing demand for EVs and the valuable metals they contain, including nickel, manganese, cobalt, and lithium [104]. Although the production of new batteries depends on these metals, their extraction from natural sources is expensive and harmful to the environment. Recycling and recovering these elements from EoL batteries can help save natural resources, lessen waste and environmental effect, and drastically reduce reliance on raw material mining. Battery packs are safely and methodically disassembled at the start of the recovery process, usually with the aid of sophisticated robotic devices. Because it expedites the disassembly process and reduces human exposure to hazardous chemicals, high-voltage systems, and other possible hazards, automation is essential in this situation [119]. In this phase, battery packs are disassembled into separate cells and modules, making it possible to efficiently access the vital components inside. Robotic systems with machine vision and sophisticated manipulation skills guarantee accurate handling of battery parts, lowering the possibility of contamination or damage and enhancing the process's overall safety and effectiveness [39]. After disassembly, separated battery cells undergo a series of chemical extraction processes to isolate and purify key metals [71]. The two most common methods are hydrometallurgy and pyrometallurgy [120–122]. Alongside these traditional approaches, direct recycling is gaining traction as an innovative technique for recovering essential materials from EoL EV batteries.

3.4.1. Mechanical Treatment of Spent LIBs

Mechanical treatment in EV battery recycling is a key procedure that involves physically separating spent batteries to recover valuable materials such as metals, plastics, and critical minerals. The process starts by discharging the batteries to eliminate any residual charge, minimizing the risk of fire or explosion. Once discharged, the batteries are dismantled to remove the outer casings and separate the individual modules or cells. This can be performed either manually or using robotic systems, which enhance both efficiency and safety [119].

The next phase involves shredding, where the battery cells are broken down into smaller pieces. This is followed by size reduction, achieved through milling or grinding, to create finer materials, especially when separating metals from other components. Various separation techniques, including magnetic separation for ferrous metals, eddy current separation for non-ferrous metals, and gravity separation based on density differences, help extract valuable materials such as aluminum, copper, and iron from plastics, ceramics, and other waste. Additionally, air classification is used to further separate lightweight materials.

The final product is black mass, a powder rich in Li, Co, Ni, and Mn, which is then processed through hydrometallurgical treatment to recover these valuable metals [123]. This mechanical treatment is a crucial step in the recycling process, offering an efficient and energy-conscious way to recover essential elements while minimizing the environmental risks linked to battery disposal [8].

3.4.2. Metallurgical Recycling

Mechanical techniques cannot separate black mass components due to the physical and chemical features of active materials, such as microscopic grain size. These processing steps can be accomplished through metallurgical techniques [124]. Pyrometallurgy is a high-temperature process [125,126] widely used to recover valuable metals such as Co, Ni, and Cu. In the pyrometallurgical process, which is a conventional method of recovering metal, various thermal processes, including roasting, sintering, smelting, and burning, are performed at regulated high temperatures in order to extract the metallic components from electronic waste [127]. The high-temperature smelting method is relatively simple and productive [128]. However, smelting processes typically result in low lithium recovery rates, requiring the addition of metal alloys to enhance the recovery process. This extra step increases both the complexity and cost of smelting, ultimately reducing its overall feasibility for large-scale metal recovery from LIBs [129] and high energy consumption has limited its further application [130].

The hydrometallurgical process is a chemical-based method for recycling EV batteries that uses selective precipitation and dissolution to extract important metals like nickel, cobalt, and lithium from EoL batteries [53,71]. The process of hydrometallurgy delivers a high recovery rate of over 98% for Cu, Ni, and Li [25]. Hydrometallurgy uses a sequence of aqueous (water-based) chemical processes and works at relatively low temperatures, in contrast to pyrometallurgy, which depends on high temperatures. This makes it a more environmentally friendly and energy-efficient technique to recycle EV batteries, particularly as it gives more control over the extraction of high-purity metals [131]. Following battery disassembly and shredding into "black mass", this substance is dissolved in an acidic solution including H_2SO_4 [132,133], HCl [133], and HNO_3 [134] in a process known as leaching [135,136] Metals can dissolve into ions as a result of the materials being broken down. After the metals have dissolved, high-purity metals are isolated for further usage using methods such as solvent extraction and precipitation [8,137]. Energy efficiency and accurate metal recovery are two benefits of hydrometallurgy [123]; nevertheless, controlling acidic waste and increasing recovery rates are still difficulties. Nevertheless, it is a productive method for creating battery-grade materials, enabling a closed-loop system in the electric vehicle sector.

The direct recycling of the active material is a third option, in addition to pyrometallurgy and hydrometallurgy [138]. This procedure was created to produce new LIBs by reusing the cathode active material from LIB recycling. Recovering electrode material from LIBs and then regenerating the recycled electrode material are the two main processes in the method [139]. Numerous studies have already shown success on a laboratory scale, but industrial application has not yet occurred. Figure 6 compares the costs and key environmental impacts associated with producing 1 kg of NMC111 from virgin raw materials and through three recycling methods, pyrometallurgical, hydrometallurgical, and direct recycling, at a large commercial scale (50,000 tons per year). The data reveal that direct recycling results in the lowest environmental and cost impacts across all categories [140].

New leaching methods, such as those involving green chemistry or ionic liquids, could offer environmentally friendly alternatives to traditional acid-based processes [129,141]. These methods can reduce the environmental impact of recycling and enhance the recovery of lithium and other rare materials with greater selectivity and fewer by-products. Electrochemical leaching is another emerging method that holds promise for recovering high-purity metals with lower energy requirements compared to traditional chemical leaching [142,143].

Moreover, the advancement of direct recycling techniques, such as electrochemical regeneration or material reconditioning, could minimize material loss and enhance the quality of recovered components [143]. By restoring battery components (such as graphite anodes and lithium cobalt oxide cathodes) to their original structure and functionality, direct recycling could provide a cost-effective and sustainable solution for the future of EV battery recycling. Research into better electrode regeneration techniques could enable the reuse of high-value materials while reducing the reliance on virgin mining for raw materials.

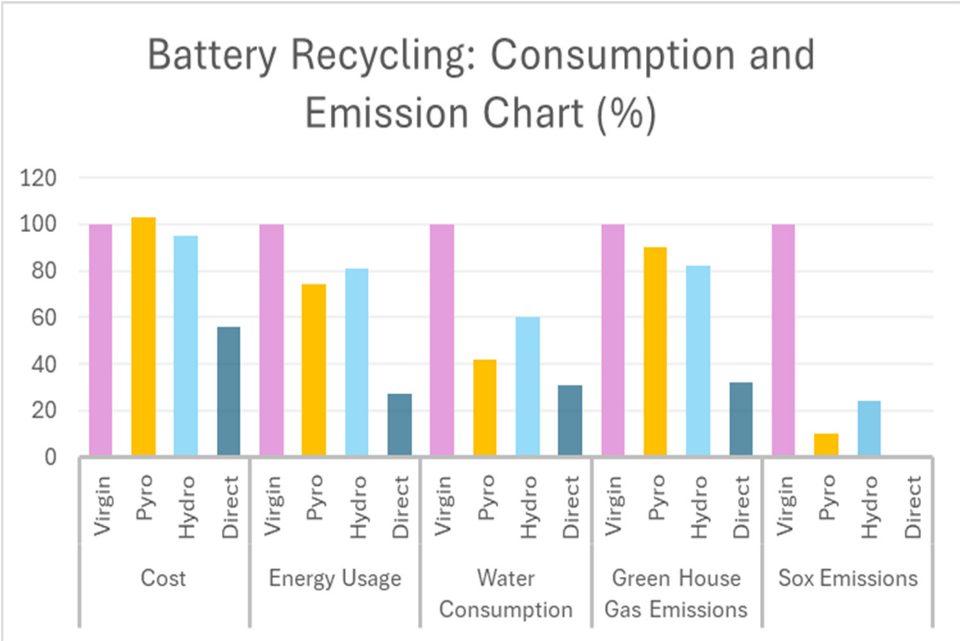

Figure 6. Cost and environmental impacts of producing 1 kg of NMC111 from virgin material and recycled using different methods [140].

As EV adoption continues to grow, there is a critical need to scale up recycling technologies to meet the demand for critical materials and reduce environmental waste. Investing in research and development for new recycling technologies is paramount, as is the creation of industry standards that facilitate the recycling of a broader range of battery types. Moreover, collaboration between automakers, recycling companies, and policymakers will be crucial to establish incentives, regulations, and infrastructure that promote the efficient recycling of batteries and the responsible recovery of critical materials.

4. Discussion

LIBs play a critical role in modern technology, powering applications ranging from portable consumer devices to EVs and large-scale energy storage systems. The rapid growth of EV adoption, driven by stricter decarbonization policies and CO_2 emission reduction targets, has intensified the need for affordable EVs and efficient strategies for managing end-of-life batteries.

Battery recycling has emerged as a sustainable and practical solution. Advanced methods allow for the recovery of valuable metals like Ni, Co, Mn, and Li and packaging materials such as aluminum and Cu, reducing dependence on raw material extraction. This not only conserves resources but also lowers energy consumption and environmental emissions. Additionally, efficient recycling processes significantly reduce the costs of new battery production, making EVs more economically viable. The reviewed literature highlights significant challenges in the current EV battery recycling processes, including the wide variation in battery chemistries, complex pack designs, and the absence of standardized labeling systems. These issues increase the complexity of dismantling and sorting operations, leading to higher costs, lower efficiency, and elevated environmental and safety risks. While advancements in robotic dismantling and material recovery technologies show promise, their scalability and efficiency are limited due to the lack of integration with standardized manufacturing and automated sorting systems. This underscores a critical research gap in achieving seamless automation and harmonization across the battery lifecycle, from production to end-of-life recycling.

A key observation is the lack of universal standards in battery pack design, which significantly hinders the efficiency of recycling operations. Proprietary designs and non-uniform configurations complicate automated disassembly. The implementation of standardized modular designs and digital labeling technologies, such as QR codes, could facilitate precise identification of battery chemistries and configurations, streamlining sorting and dismantling processes. Moreover, while robotic dismantling technologies have shown potential, they remain in the developmental phase and require further optimization to address the diverse designs and chemistries of battery packs effectively.

Another major gap identified is the absence of integrated data management systems for real-time tracking of battery chemistries and electrical parameters. Establishing comprehensive, database-driven sorting methodologies could significantly enhance the accuracy and efficiency of material recovery processes. Furthermore, leveraging advanced technologies such as digital twin models for process simulation and optimization could enable dynamic adaptation to varying battery designs, improving both safety and efficiency. Addressing these gaps through interdisciplinary research, policy support, and collaboration between manufacturers and recyclers is essential for conserving resources, reducing environmental impacts, and transitioning toward a sustainable circular economy for EV batteries.

Robotic battery dismantling represents a significant innovation in recycling workflows. Robots enhance precision and safety, reducing human exposure to hazardous materials while improving efficiency in disassembling complex battery packs. Currently, robotic dismantling is still in its early stages, requiring substantial advancements to enhance its speed, efficiency, and overall effectiveness. Optimizing this technology will allow for the rapid dismantling of entire battery packs, meeting the demands of large-scale recycling. By combining these advanced methods, robotic dismantling, data-driven sorting, and digital twin technology, battery recycling is evolving into a critical pillar of the circular economy. Continued innovation in these areas is essential for creating a robust and sustainable infrastructure to meet the growing demands of EV and energy storage industries.

Altilium, a UK-based clean technology innovator, is spearheading the global transition toward a zero-carbon energy future through its proprietary EcoCathode™ technology [67]. This advanced hydrometallurgical process represents a significant breakthrough in the recycling of EoL LIBs and production waste from gigafactories. Designed to maximize material recovery and minimize environmental impact, EcoCathode™ enables the efficient extraction of critical metals including lithium, nickel, cobalt, and manganese at high purity levels suitable for direct reuse in the manufacturing of new batteries.

Unlike conventional pyrometallurgical methods, which are energy-intensive and often result in the loss of valuable materials like lithium and manganese, Altilium's EcoCathode™ process leverages aqueous chemical extraction techniques to achieve superior recovery rates. Specifically, the process recovers over 95% of key metals from EV battery waste streams, preserving their quality for reintegration into the battery supply chain. This ensures a closed-loop recycling system that reduces dependency on raw material mining, which is both environmentally damaging and subject to volatile market conditions.

EcoCathode™ is engineered to address the dual challenges of sustainability and economic viability in battery recycling. The process achieves a 60% reduction in carbon emissions compared to traditional mining and refining of virgin raw materials, making it a more environmentally sustainable solution. Additionally, the process reduces material recovery costs by 20%, offering a competitive edge to manufacturers seeking to lower production expenses without compromising quality or performance [144].

The scalability of EcoCathode™ further enhances its industrial appeal. Its modular design and adaptability to different battery chemistries, including NMC and LFP, make it a versatile solution for the rapidly evolving energy storage market. By addressing key technical, environmental, and economic barriers, Altilium's EcoCathode™ technology provides a robust framework for establishing a circular economy within the battery industry, ensuring long-term sustainability and resilience in the transition to clean energy systems.

Altilium Clean Technology is partnering with leading UK automakers to establish a circular economy for EV battery recycling. Their advanced processes focus on maximizing material recovery, minimizing environmental impact, and enabling the reuse of critical metals in new battery production. Planned UK recycling facilities are expected to produce enough sustainable lithium annually to manufacture over 250,000 EV batteries, equivalent to powering more than 80% of the EVs sold in the UK in 2023, significantly reducing reliance on virgin material sourcing [145].

Through this review and observations, it is evident that improving EV battery recycling requires a combination of standardized manufacturing practices, technological innovation, and policy support. By addressing these challenges, the industry can significantly reduce waste, conserve critical resources, and make EVs more sustainable. Continued research and collaboration between stakeholders will be critical to achieving these goals, ensuring that the EV revolution aligns with environmental and economic sustainability.

5. Conclusions

This review has explored the critical challenges and emerging technologies in EV battery recycling, highlighting the urgent need for sustainable and efficient solutions. Key obstacles such as the diversity in battery chemistries, complex pack designs, the absence of standardized labeling systems, high operational costs, and safety risks continue to hinder progress in recycling processes. Additionally, inefficient collection networks, regulatory inconsistencies, and the environmental impact of current recycling methods further complicate large-scale implementation.

Despite these challenges, advancements in robotic dismantling, AI-driven sorting, and innovative material recovery techniques, such as hydrometallurgical and direct recycling methods, demonstrate significant potential in improving recycling efficiency. However, the lack of industry-wide standardization, limited integration of advanced digital tools, and insufficient economic incentives remain major barriers to widespread adoption.

EV battery recycling technologies encounter substantial challenges, particularly in the efficient recovery of critical materials such as lithium, cobalt, and nickel. Existing methods including pyrometallurgical, hydrometallurgical, and direct recycling each present limitations, such as high energy consumption, material losses, environmental concerns, and complex chemical processes. However, significant opportunities for enhancement exist through advancements in automation, innovative leaching techniques, green chemistry approaches, and improved direct recycling methods. These innovations have the potential to make recycling processes more efficient, cost-effective, and environmentally sustainable, ultimately contributing to a more circular and resource-efficient battery economy. Additionally, the safe handling of high-voltage battery packs remains a critical issue, as improper disassembly can pose significant safety risks, including electrical hazards, thermal runaway, and toxic electrolyte leakage. To mitigate these risks, deep discharge before dismantling has emerged as an essential safety step, reducing the likelihood of short circuits and uncontrolled energy release. Integrating automated deep discharge systems within the recycling process can enhance safety, streamline disassembly, and improve overall process efficiency.

Addressing these challenges is essential to improving the economic feasibility and environmental sustainability of battery recycling. Implementing standardized battery designs, enhancing EoL traceability through data-driven monitoring technologies, and advancing automation in dismantling and separation processes can greatly improve efficiency. Collaboration between policymakers, manufacturers, and researchers is crucial to developing harmonized regulatory frameworks that promote innovation in battery lifecycle management and resource conservation. Governments and industry stakeholders must work together to establish financial incentives, invest in research and development, and encourage closed-loop recycling systems to reduce dependence on virgin materials.

The digital twin model represents a transformative, technologically advanced approach to EV battery recycling. By integrating automation, real-time monitoring, and chemistry-specific processing, it addresses key challenges associated with resource recovery and sustainability. The model's ability to simulate and optimize the recycling process offers significant benefits, including improved safety, enhanced material recovery rates, and reduced environmental impact. Ultimately, this innovation contributes to a more sustainable and resource-efficient future for the EV industry.

6. Future Work

To overcome current limitations and drive progress in EV battery recycling, several future research and development directions must be pursued.

First, the development of standardized battery pack designs should be prioritized. Universal guidelines for modular, recycling-friendly pack designs, coupled with digital labeling systems such as barcodes/QR codes, can simplify sorting and dismantling processes. These measures will enable efficient identification of battery chemistries and configurations, reducing complexity during recycling.

Second, significant advancements in robotic dismantling systems are needed. Future efforts should focus on enhancing the speed, precision, and adaptability of robotic technologies to handle diverse battery pack structures. Incorporating machine learning and AI algorithms into robotic systems could further improve their ability to manage variability in design while ensuring safety and precision.

Third, the integration of digital twin technology offers immense potential for optimizing recycling operations. Digital twins can enable real-time simulation, monitoring, and predictive maintenance of recycling systems, increasing efficiency and scalability while reducing operational costs.

Additionally, the implementation of centralized, database-driven sorting systems can enhance material recovery rates. These systems should track battery chemistries, configurations, and lifecycle data, ensuring accurate sorting and efficient recovery of valuable materials. Concurrently, research must focus on developing eco-friendly and cost-effective recycling processes that minimize environmental impacts while achieving high recovery yields for critical materials.

Finally, strong policy and regulatory frameworks are essential to support these advancements. Regulations promoting circular economy practices, extended producer responsibility, and financial incentives for recycling-friendly designs can drive widespread adoption. Collaborative efforts between stakeholders are vital to achieving a sustainable battery recycling ecosystem.

By addressing these priorities, the EV battery industry can overcome existing challenges and establish a robust, resource-efficient recycling framework. These advancements will not only conserve critical materials but also mitigate environmental impacts, contributing to the global shift toward cleaner and more sustainable energy systems.

Author Contributions: Conceptualization, S.R. and M.A.-G.; formal analysis, S.R.; Investigation, S.R.; writing—original draft preparation, S.R.; writing—review and editing, S.R., A.S.B., M.S., M.A.-G. and X.C.; visualization, S.R. and A.S.B.; supervision, M.S., M.A.-G. and X.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Innovate UK under the Launchpad: Net Zero, CR&D Tees Valley, R2 Competition, Grant No. 10075111.

Data Availability Statement: Not applicable.

Acknowledgments: The work described in the paper was carried out in the context of the project entitled "Development of new, innovative technologies for electric vehicle battery recycling & low carbon minerals recovery in the Tees Valley" The authors are grateful for the support from the funder and industry partner. Preliminary versions of some of the material presented in this article were presented at the 29th International Conference on Automation and Computing [63,64] in August 2024.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

LIBs	Lithium-Ion Batteries
EoL	End of Life
EV	Electric Vehicle
Mn	Manganese
Co	Cobalt
Li	Lithium
Ni	Nickel
LCO	Lithium Cobalt Oxide
NCA	Lithium Nickel Cobalt Aluminum Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
LTO	Lithium Titanate
Cu	Copper
BEVs	Battery Electric Vehicles
PHEVs	Plug-In Hybrid Electric Vehicles
BIGP	Battery Identity Global Passport
AI	Artificial Intelligence
ML	Machine Learning
EC	Ethylene Carbonate
DMC	Dimethyl Carbonate
DEC	Diethyl Carbonate

References

1. Voituriez, T.; Morita, K.; Giordano, T.; Bakkour, N.; Shimizu, N. Financing the 2030 agenda for sustainable development. In *Governing Trough Goals: Sustainable Development Goals as Governance Innovation*; MIT: London, UK, 2017; Volume 16301, pp. 259–273. [CrossRef]
2. European Parliament. *CO_2 Emissions from Cars: Facts and Figures (Infographics)*; European Parliament: Strasbourg, France, 2023; pp. 1–6. Available online: https://www.europarl.europa.eu/news/en/headlines/society/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics (accessed on 28 December 2024).
3. Hung, C.R.; Völler, S.; Agez, M.; Majeau-Bettez, G.; Strømman, A.H. Regionalized climate footprints of battery electric vehicles in Europe. *J. Clean. Prod.* **2021**, *322*, 129052. [CrossRef]
4. Service, R.F. Lithium-ion battery development takes Nobel. *Science* **2019**, *366*, 292. [CrossRef]

5. Biswal, B.K.; Zhang, B.; Thi Minh Tran, P.; Zhang, J.; Balasubramanian, R. Recycling of spent lithium-ion batteries for a sustainable future: Recent advancements. *Chem. Soc. Rev.* **2024**, *53*, 5552–5592. [CrossRef] [PubMed]
6. Cognet, M.; Condomines, J.; Cambedouzou, J.; Madhavi, S.; Carboni, M.; Meyer, D. An original recycling method for Li-ion batteries through large scale production of Metal Organic Frameworks. *J. Hazard. Mater.* **2020**, *385*, 121603. [CrossRef] [PubMed]
7. Cui, Z.; Wang, L.; Li, Q.; Wang, K. A comprehensive review on the state of charge estimation for lithium-ion battery based on neural network. *Int. J. Energy Res.* **2022**, *46*, 5423–5440. [CrossRef]
8. Windisch-Kern, S.; Gerold, E.; Nigl, T.; Jandric, A.; Altendorfer, M.; Rutrecht, B.; Scherhaufer, S.; Raupenstrauch, H.; Pomberger, R.; Antrekowitsch, H.; et al. Recycling chains for lithium-ion batteries: A critical examination of current challenges, opportunities and process dependencies. *Waste Manag.* **2022**, *138*, 125–139. [CrossRef] [PubMed]
9. Sheikh, M.; Rashid, M.; Rehman, S. Robust testing requirements for Li-ion battery performance analysis. *Renew. Energy Gener. Appl.* **2024**, *43*, 197–204. [CrossRef]
10. Estimated Capacity of Lithium-Ion Batteries Placed on the Global Market in 2020 with Forecast for 2021 Through 2030 (in Gigawatt Hours). Available online: https://www.statista.com/statistics/1246914/capacity-of-lithium-ion-batteries-placed-on-the-global-market/ (accessed on 12 December 2024).
11. International Energy Agency. Global EV Outlook 2023: Catching up with Climate Ambitions. 2023. Available online: www.iea.org (accessed on 22 December 2024).
12. Pražanová, A.; Knap, V.; Stroe, D.-I. Literature Review, Recycling of Lithium-Ion Batteries from Electric Vehicles, Part II: Environmental and Economic Perspective. *Energies* **2022**, *15*, 7356. [CrossRef]
13. Zeng, A.; Chen, W.; Rasmussen, K.D.; Zhu, X.; Lundhaug, M.; Müller, D.B.; Tan, J.; Keiding, J.K.; Liu, L.; Dai, T.; et al. Battery technology and recycling alone will not save the electric mobility transition from future cobalt shortages. *Nat. Commun.* **2022**, *13*, 1341. [CrossRef]
14. Chen, M.; Ma, X.; Chen, B.; Arsenault, R.; Karlson, P.; Simon, N.; Wang, Y. Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries. *Joule* **2019**, *3*, 2622–2646. [CrossRef]
15. Yu, X.; Li, W.; Gupta, V.; Gao, H.; Tran, D.; Sarwar, S.; Chen, Z. Current Challenges in Efficient Lithium-Ion Batteries' Recycling: A Perspective. *Glob. Chall.* **2022**, *6*, 2200099. [CrossRef]
16. Wang, Y.; An, N.; Wen, L.; Wang, L.; Jiang, X.; Hou, F.; Yin, Y.; Liang, J. Recent progress on the recycling technology of Li-ion batteries. *J. Energy Chem.* **2020**, *55*, 391–419. [CrossRef]
17. Zanoletti, A.; Carena, E.; Ferrara, C.; Bontempi, E. A Review of Lithium-Ion Battery Recycling: Technologies, Sustainability, and Open Issues. *Batteries* **2024**, *10*, 38. [CrossRef]
18. EuRIC AISBL. Metal Recycling Factsheet. In *Recycling: Bridging Circular Economy & Cilmate Policy*; EuRIC AISBL: Schaerbeek, Belgium, 2020; p. 8. Available online: https://circulareconomy.europa.eu/platform/en/knowledge/metal-recycling-factsheet-euric (accessed on 15 January 2025).
19. Nie, Y.; Wang, Y.; Li, L.; Liao, H. Literature Review on Power Battery Echelon Reuse and Recycling from a Circular Economy Perspective. *Int. J. Environ. Res. Public Health* **2023**, *20*, 4346. [CrossRef] [PubMed]
20. Rashid, M.; Sheikh, M.; Rehman, S. Li-ion batteries life cycle from electric vehicles to energy storage. *Renew. Energy Gener. Appl.* **2024**, *43*, 223–229. [CrossRef]
21. Carey, N. JLR, Altilium to Test EV Batteries Made with Recycled Materials. Available online: https://www.reuters.com/business/autos-transportation/jlr-altilium-test-ev-batteries-made-with-recycled-materials-2024-09-26/?utm_source=chatgpt.com (accessed on 22 December 2024).
22. Available online: https://pubs.acs.org/doi/10.1021/es400614y (accessed on 9 December 2024).
23. Marchese, D.; Giosuè, C.; Staffolani, A.; Conti, M.; Orcioni, S.; Soavi, F.; Cavalletti, M.; Stipa, P. An Overview of the Sustainable Recycling Processes Used for Lithium-Ion Batteries. *Batteries* **2024**, *10*, 27. [CrossRef]
24. Mrozik, W.; Rajaeifar, M.A.; Heidrich, O.; Christensen, P. Environmental impacts, pollution sources and pathways of spent lithium-ion batteries. *Energy Environ. Sci.* **2021**, *14*, 6099–6121. [CrossRef]
25. Leong, J. *Developing a UK Lithium-Ion Battery Recycling Industry*; Faraday Institution: Didcot, UK, 2024; pp. 1–16.
26. Battery Production Scrap to Be Main Source of Recyclable Material This Decade. Available online: https://source.benchmarkminerals.com/article/battery-production-scrap-to-be-main-source-of-recyclable-material-this-decade (accessed on 9 December 2024).
27. Fleischmann, J.; Hanicke, M.; Horetsky, E.; Ibrahim, D.; Jautelat, S.; Linder, M.; Schaufuss, P.; Torscht, L.; van de Rijt, A. *Battery 2030: Resilient, Sustainable, and Circular*; McKinsey & Company: New York, NY, USA, 2023; pp. 1–18.
28. Nick Carey, S.M.; Lienert, P. Insight: Scratched EV Battery? Your Insurer May Have to Junk the Whole Car. Available online: https://www.reuters.com/business/autos-transportation/scratched-ev-battery-your-insurer-may-have-junk-whole-car-2023-03-20/ (accessed on 10 December 2024).
29. Staff, C. Electric Car Battery Recycling: What Happens to the Dead Batteries? Available online: https://www.carwow.co.uk/blog/ev-battery-recycling-what-happens-to-dead-batteries#gref (accessed on 9 December 2024).

30. Propulsion Quebec. *Developing a Promising Sector for Quebec's Economy Lithium-Ion Battery Sector*; Propulsion Quebec: Montreal, QC, Canada, 2019.
31. Circular Economy Initiative. *Germany Resource-Efficient Battery Life Cycles-Driving Electric Mobility with the Circular Economy*; The National Academy of Science and Engineering: Munich, Germany, 2020.
32. Beaudet, A.; Larouche, F.; Amouzegar, K.; Bouchard, P.; Zaghib, K. Key challenges and opportunities for recycling electric vehicle battery materials. *Sustainability* **2020**, *12*, 5837. [CrossRef]
33. Kotak, Y.; Fernández, C.M.; Casals, L.C.; Kotak, B.S.; Koch, D.; Geisbauer, C.; Trilla, L.; Gómez-Núñez, A.; Schweiger, H.G. End of electric vehicle batteries: Reuse vs. recycle. *Energies* **2021**, *14*, 2217. [CrossRef]
34. Fan, E.; Li, L.; Wang, Z.; Lin, J.; Huang, Y.; Yao, Y.; Chen, R.; Wu, F. Sustainable Recycling Technology for Li-Ion Batteries and Beyond: Challenges and Future Prospects. *Chem. Rev.* **2020**, *120*, 7020–7063. [CrossRef]
35. Toro, L.; Moscardini, E.; Baldassari, L.; Forte, F.; Falcone, I.; Coletta, J.; Toro, L. A Systematic Review of Battery Recycling Technologies: Advances, Challenges, and Future Prospects. *Energies* **2023**, *16*, 6571. [CrossRef]
36. Sojka, R.; Pan, Q.; Billmann, L. *Comparative Study of Li-Ion Battery Recycling Processes*; ACCUREC Recycling GmbH: Krefeld, Germany, 2020; pp. 1–54.
37. Li, P.; Luo, S.; Lin, Y.; Xiao, J.; Xia, X.; Liu, X.; Wang, L.; He, X. Fundamentals of the recycling of spent lithium-ion batteries. *Chem. Soc. Rev.* **2024**, *53*, 11967–12013. [CrossRef]
38. Klohs, D.; Offermanns, C.; Heimes, H.; Kampker, A. Automated Battery Disassembly—Examination of the Product- and Process-Related Challenges for Automotive Traction Batteries. *Recycling* **2023**, *8*, 89. [CrossRef]
39. Zorn, M.; Ionescu, C.; Klohs, D.; Zähl, K.; Kisseler, N.; Daldrup, A.; Hams, S.; Zheng, Y.; Offermanns, C.; Flamme, S.; et al. An Approach for Automated Disassembly of Lithium-Ion Battery Packs and High-Quality Recycling Using Computer Vision, Labeling, and Material Characterization. *Recycling* **2022**, *7*, 48. [CrossRef]
40. Chen, Z.; Yildizbasi, A.; Wang, Y.; Sarkis, J. Safety Concerns for the Management of End-of-Life Lithium-Ion Batteries. *Glob. Chall.* **2022**, *6*, 2200049. [CrossRef] [PubMed]
41. Kwade, A.; Haselrieder, W.; Leithoff, R.; Modlinger, A.; Dietrich, F.; Droeder, K. Current status and challenges for automotive battery production technologies. *Nat. Energy* **2018**, *3*, 290–300. [CrossRef]
42. Iclodean, C.; Varga, B.; Burnete, N.; Cimerdean, D.; Jurchiş, B. Comparison of Different Battery Types for Electric Vehicles. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *252*, 012058. [CrossRef]
43. Kwade, A.; Diekmann, J. *Recycling of Lithium-Ion Batteries*, 1st ed.; Springer: Cham, Switzerland, 2018. [CrossRef]
44. Velázquez-Martínez, O.; Valio, J.; Santasalo-Aarnio, A.; Reuter, M.; Serna-Guerrero, R. A critical review of lithium-ion battery recycling processes from a circular economy perspective. *Batteries* **2019**, *5*, 68. [CrossRef]
45. Islam, M.T.; Iyer-Raniga, U. Lithium-Ion Battery Recycling in the Circular Economy: A Review. *Recycling* **2022**, *7*, 33. [CrossRef]
46. He, B.; Zheng, H.; Tang, K.; Xi, P.; Li, M.; Wei, L.; Guan, Q. A Comprehensive Review of Lithium-Ion Battery (LiB) Recycling Technologies and Industrial Market Trend Insights. *Recycling* **2024**, *9*, 9. [CrossRef]
47. Shi, G.; Cheng, J.; Wang, J.; Zhang, S.; Shao, X.; Chen, X.; Li, X.; Xin, B. A comprehensive review of full recycling and utilization of cathode and anode as well as electrolyte from spent lithium-ion batteries. *J. Energy Storage* **2023**, *72*, 108486. [CrossRef]
48. Mossali, E.; Picone, N.; Gentilini, L.; Rodrìguez, O.; Pérez, J.M.; Colledani, M. Lithium-ion batteries towards circular economy: A literature review of opportunities and issues of recycling treatments. *J. Environ. Manag.* **2020**, *264*, 110500. [CrossRef] [PubMed]
49. Zeng, G.; Yao, J.; Liu, C.; Luo, X.; Ji, H.; Mi, X.; Deng, C. Simultaneous Recycling of Critical Metals and Aluminum Foil from Waste $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$Cathode via Ethylene Glycol-Citric Acid System. *ACS Sustain. Chem. Eng.* **2021**, *9*, 16133–16142. [CrossRef]
50. Botelho Junior, A.B.; Stopic, S.; Friedrich, B.; Tenório, J.A.S.; Espinosa, D.C.R. Cobalt recovery from li-ion battery recycling: A critical review. *Metals* **2021**, *11*, 1999. [CrossRef]
51. Zhou, L.F.; Yang, D.; Du, T.; Gong, H.; Luo, W. Bin The Current Process for the Recycling of Spent Lithium Ion Batteries. *Front. Chem.* **2020**, *8*, 578044. [CrossRef] [PubMed]
52. Nkuna, R.; Ijoma, G.N.; Matambo, T.S.; Chimwani, N. Accessing Metals from Low-Grade Ores and the Environmental Impact Considerations: A Review of the Perspectives of Conventional versus Bioleaching Strategies. *Minerals* **2022**, *12*, 506. [CrossRef]
53. Paul, S.; Shrotriya, P. Efficient Recycling Processes for Lithium-Ion Batteries. *Materials* **2025**, *18*, 613. [CrossRef] [PubMed]
54. Asadi Dalini, E.; Karimi, G.; Zandevakili, S.; Goodarzi, M. A Review on Environmental, Economic and Hydrometallurgical Processes of Recycling Spent Lithium-ion Batteries. *Miner. Process. Extr. Metall. Rev.* **2020**, *42*, 451–472. [CrossRef]
55. Barbosa de Mattos, D.F.; Duda, S.; Petranikova, M. Recycling of Lithium Iron Phosphate ($LiFePO_4$) Batteries from the End Product Quality Perspective. *Batteries* **2025**, *11*, 33. [CrossRef]
56. Jannesar Niri, A.; Poelzer, G.A.; Zhang, S.E.; Rosenkranz, J.; Pettersson, M.; Ghorbani, Y. Sustainability challenges throughout the electric vehicle battery value chain. *Renew. Sustain. Energy Rev.* **2024**, *191*, 114176. [CrossRef]
57. Ahmed, S.; Hasan, F.; Kabir, S.S.; Khan, A.S. Sustainable Management of Spent Lithium-Ion Batteries: The Role of Reverse Logistics in the Automotive Sector. *Eng. Proc.* **2024**, *76*, 61. [CrossRef]

58. Llamas-Orozco, J.A.; Meng, F.; Walker, G.S.; Abdul-Manan, A.F.N.; MacLean, H.L.; Posen, I.D.; McKechnie, J. Estimating the environmental impacts of global lithium-ion battery supply chain: A temporal, geographical, and technological perspective. *PNAS Nexus* **2023**, *2*, pgad361. [CrossRef] [PubMed]
59. Breiter, A.; Linder, M.; Schuldt, T.; Siccardo, G.; Vekic, N. *202303_McKinsey_Battery Recycling Takes the Driver's Seat*; McKinsey Co.: New York, NY, USA, 2023.
60. Chigbu, B.I. Advancing sustainable development through circular economy and skill development in EV lithium-ion battery recycling: A comprehensive review. *Front. Sustain.* **2024**, *5*, 1409498. [CrossRef]
61. Doose, S.; Mayer, J.K.; Michalowski, P.; Kwade, A. Challenges in ecofriendly battery recycling and closed material cycles: A perspective on future lithium battery generations. *Metals* **2021**, *11*, 291. [CrossRef]
62. Kerem Eren, M.; Aras, K.; Gucukoglu, T.; Erhan, K.; Ipek, E. Effects of Cell and Module Configuration on BatterySystem in Electric Vehicles. *Int. J. Eng. Technol.* **2018**, *4*, 143–152.
63. Cai, W.; Kang, B.; Hu, S.J.; Li, J.; Zhou, S.; Han, Y.; Wiley, J. Analysis of Li-Ion Battery Joining Technologies. 2017. Available online: http://cii-resource.com/cet/fbc-05-04/Presentations/BMF/Cai_Wayne.pdf (accessed on 15 November 2024).
64. Patel, A.N.; Lander, L.; Ahuja, J.; Bulman, J.; Lum, J.K.H.; Pople, J.O.D.; Hales, A.; Patel, Y.; Edge, J.S. Lithium-ion battery second life: Pathways, challenges and outlook. *Front. Chem.* **2024**, *12*, 1358417. [CrossRef]
65. Harper, G.D.J.; Kendrick, E.; Anderson, P.A.; Mrozik, W.; Christensen, P.; Lambert, S.; Greenwood, D.; Das, P.K.; Ahmeid, M.; Milojevic, Z.; et al. Roadmap for a sustainable circular economy in lithium-ion and future battery technologies. *J. Phys. Energy* **2023**, *5*, 021501. [CrossRef]
66. Rehman, S.; Short, M.; Savage, R.; Cui, X.; Maher, A.-G.; Emandi, B.; Burn, A. A Review of the EoL EV Batteries Sorting and Disassembly Challenges. In Proceedings of the 2024 29th International Conference on Automation and Computing (ICAC), Sunderland, UK, 28–30 August 2024; pp. 1–6. [CrossRef]
67. Short, M.; Rehman, S.; Cui, X.; Maher, A.-G.; Savage, R.; Emandi, B.; Burn, A. Technologies for EoL EV Batteries Recycling: Assessment and Proposals. In Proceedings of the 2024 29th International Conference on Automation and Computing (ICAC), Sunderland, UK, 28–30 August 2024; pp. 1–6. [CrossRef]
68. Houache, M.S.E.; Yim, C.H.; Karkar, Z.; Abu-Lebdeh, Y. On the Current and Future Outlook of Battery Chemistries for Electric Vehicles—Mini Review. *Batteries* **2022**, *8*, 70. [CrossRef]
69. Marie, J.-J. Developments in Lithium-Ion Battery Cathodes. *Faraday Insights* **2023**, *18*, 1–12.
70. BU-205: Types of Lithium-Ion. Available online: https://batteryuniversity.com/article/bu-205-types-of-lithium-ion#google_vignette (accessed on 30 October 2024).
71. Davis, K.; Demopoulos, G.P. Hydrometallurgical recycling technologies for NMC Li-ion battery cathodes: Current industrial practice and new R&D trends. *RSC Sustain.* **2023**, *1*, 1932–1951. [CrossRef]
72. Thompson, D.L.; Hartley, J.M.; Lambert, S.M.; Shiref, M.; Harper, G.D.J.; Kendrick, E.; Anderson, P.; Ryder, K.S.; Gaines, L.; Abbott, A.P. The importance of design in lithium ion battery recycling-a critical review. *Green Chem.* **2020**, *22*, 7585–7603. [CrossRef]
73. Vegh, G.; Madikere Raghunatha Reddy, A.K.; Li, X.; Deng, S.; Amine, K.; Zaghib, K. North America's Potential for an Environmentally Sustainable Nickel, Manganese, and Cobalt Battery Value Chain. *Batteries* **2024**, *10*, 377. [CrossRef]
74. Christopher, J.; Doughty, D. Lithium Ion Battery Safety Guidance. In *The Electrochemical Society Interface*; MIT: London, UK, 2017; pp. 1–18. Available online: https://www.semanticscholar.org/paper/Lithium-Ion-Battery-Safety-Orendorff-Doughty/5100e14290d969b0b968d770fb6b9891b13b9073 (accessed on 9 December 2024).
75. Kaarlela, T.; Villagrossi, E.; Rastegarpanah, A.; San-Miguel-Tello, A.; Pitkäaho, T. Robotised disassembly of electric vehicle batteries: A systematic literature review. *J. Manuf. Syst.* **2024**, *74*, 901–921. [CrossRef]
76. Rastegarpanah, A.; Mineo, C.; Contreras, C.A.; Aflakian, A.; Paragliola, G.; Stolkin, R. Electric Vehicle Battery Disassembly Using Interfacing Toolbox for Robotic Arms. *Batteries* **2024**, *10*, 147. [CrossRef]
77. Wilkins, B.D.; October, J.K. Lithium-Ion Battery Manufacturers and Recycling. 2023, pp. 1–5. Available online: https://atlaspolicy.com/wp-content/uploads/2024/01/Summit-Lithium-Ion-Batteries-and-Recycling.pdf (accessed on 9 December 2024).
78. Bai, Y.; Muralidharan, N.; Sun, Y.K.; Passerini, S.; Stanley Whittingham, M.; Belharouak, I. Energy and environmental aspects in recycling lithium-ion batteries: Concept of Battery Identity Global Passport. *Mater. Today* **2020**, *41*, 304–315. [CrossRef]
79. Giosuè, C.; Marchese, D.; Cavalletti, M.; Isidori, R.; Conti, M.; Orcioni, S.; Ruello, M.L.; Stipa, P. 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* **2021**, *13*, 11154. [CrossRef]
80. Zhu, J.; Mathews, I.; Ren, D.; Li, W.; Cogswell, D.; Xing, B.; Sedlatschek, T.; Kantareddy, S.N.R.; Yi, M.; Gao, T.; et al. End-of-life or second-life options for retired electric vehicle batteries. *Cell Rep. Phys. Sci.* **2021**, *2*, 100537. [CrossRef]
81. Rehman, S.; Sheikh, M.; Elmarakbi, A. Thermal and Electrical failure analysis of lithium-ion battery after crash. In Proceedings of the 2nd International Electrical Engineering Conference (IEEC 2017), Karachi, Pakistan, 19–20 May 2017; p. 9.
82. Hathaway, J.; Shaarawy, A.; Akdeniz, C.; Aflakian, A.; Stolkin, R.; Rastegarpanah, A. Towards reuse and recycling of lithium-ion batteries: Tele-robotics for disassembly of electric vehicle batteries. *Front. Robot. AI* **2023**, *10*, 1179296. [CrossRef]

83. Yang, F.; Xie, Y.; Deng, Y.; Yuan, C. Predictive modeling of battery degradation and greenhouse gas emissions from U.S. state-level electric vehicle operation. *Nat. Commun.* **2018**, *9*, 2429. [CrossRef] [PubMed]
84. Guo, J.; Yang, J.; Cao, W.; Serrano, C. Evaluation of EV battery degradation under different charging strategies and V2G schemes. In Proceedings of the 8th Renewable Power Generation Conference (RPG 2019), Shanghai, China, 24–25 October 2019.
85. Wu, S.; Kaden, N.; Dröder, K. A Systematic Review on Lithium-Ion Battery Disassembly Processes for Efficient Recycling. *Batteries* **2023**, *9*, 297. [CrossRef]
86. Bhar, M.; Ghosh, S.; Krishnamurthy, S.; Kaliprasad, Y.; Martha, S.K. A review on spent lithium-ion battery recycling: From collection to black mass recovery. *RSC Sustain.* **2023**, *1*, 1150–1167. [CrossRef]
87. Zhang, K.; Wang, L.; Xu, C.; Wu, H.; Huang, D.; Jin, K.; Xu, X. Study on Thermal Runaway Risk Prevention of Lithium-Ion Battery with Composite Phase Change Materials. *Fire* **2023**, *6*, 208. [CrossRef]
88. Hoskinson, C. Lithium Battery Recycling Regulatory Status and Frequently Asked Questions. 2023; pp. 1–12. Available online: https://rcrapublic.epa.gov/files/14957.pdf (accessed on 17 November 2024).
89. Baazouzi, S.; Rist, F.P.; Weeber, M.; Birke, K.P. Optimization of disassembly strategies for electric vehicle batteries. *Batteries* **2021**, *7*, 74. [CrossRef]
90. Klohs, D.; Frieges, M.; Gorsch, J.; Ellmann, P.; Heimes, H.H. Product and Process Data Structure for Automated Battery Disassembly. *Recycling* **2025**, *10*, 25. [CrossRef]
91. Jia, Y.; Liu, B.; Hong, Z.; Yin, S.; Finegan, D.P.; Xu, J. Safety issues of defective lithium-ion batteries: Identification and risk evaluation. *J. Mater. Chem. A* **2020**, *8*, 12472–12484. [CrossRef]
92. Aghabali, I.; Bauman, J.; Kollmeyer, P.J.; Wang, Y.; Bilgin, B.; Emadi, A. 800-V Electric Vehicle Powertrains: Review and Analysis of Benefits, Challenges, and Future Trends. *IEEE Trans. Transp. Electrif.* **2021**, *7*, 927–948. [CrossRef]
93. Beghi, M.; Braghin, F.; Roveda, L. Enhancing Disassembly Practices for Electric Vehicle Battery Packs: A Narrative Comprehensive Review. *Designs* **2023**, *7*, 109. [CrossRef]
94. Gerlitz, E.; Greifenstein, M.; Kaiser, J.P.; Mayer, D.; Lanza, G.; Fleischer, J. Systematic Identification of Hazardous States and Approach for Condition Monitoring in the Context of Li-ion Battery Disassembly. *Procedia CIRP* **2022**, *107*, 308–313. [CrossRef]
95. O'Connor, P.; Wise, P. An Analysis of Lithium-Ion Battery Fires in Waste Management and Recycling. 2021; p. 7. Available online: https://www.epa.gov/system/files/documents/2021-08/lithium-ion-battery-report-update-7.01_508.pdf (accessed on 2 January 2025).
96. Qu, M.; Pham, D.T.; Altumi, F.; Gbadebo, A.; Hartono, N.; Jiang, K.; Kerin, M.; Lan, F.; Micheli, M.; Xu, S.; et al. Robotic Disassembly Platform for Disassembly of a Plug-In Hybrid Electric Vehicle Battery: A Case Study. *Automation* **2024**, *5*, 50–67. [CrossRef]
97. Lander, L.; Tagnon, C.; Nguyen-Tien, V.; Kendrick, E.; Elliott, R.J.R.; Abbott, A.P.; Edge, J.S.; Offer, G.J. Breaking it down: A techno-economic assessment of the impact of battery pack design on disassembly costs. *Appl. Energy* **2023**, *331*, 120437. [CrossRef]
98. Tankou, A.; Bieker, G.; Hall, D. *Scaling Up Reuse and Recycling of Electric Vehicle Batteries: Assessing Challenges and Policy Approaches*; International Council on Clean Transportation: Washington, DC, USA, 2023; Available online: www.theicct.orgcommunications@theicct.org (accessed on 2 January 2025).
99. Sederholm, J.G.; Li, L.; Liu, Z.; Lan, K.W.; Cho, E.J.; Gurumukhi, Y.; Dipto, M.J.; Ahmari, A.; Yu, J.; Haynes, M.; et al. Emerging Trends and Future Opportunities for Battery Recycling. *ACS Energy Lett.* **2024**, *10*, 107–119. [CrossRef]
100. Gaines, L. Lithium-ion battery recycling processes: Research towards a sustainable course. *Sustain. Mater. Technol.* **2018**, *17*, e00068. [CrossRef]
101. Pregowska, A.; Osial, M.; Urbańska, W. The Application of Artificial Intelligence in the Effective Battery Life Cycle in the Closed Circular Economy Model—A Perspective. *Recycling* **2022**, *7*, 81. [CrossRef]
102. Ucar, A.; Karakose, M.; Kırımça, N. Artificial Intelligence for Predictive Maintenance Applications: Key components, trustworthiness, and future trends. *Appl. Sci.* **2024**, *14*, 898. [CrossRef]
103. Fioravanti, R.; Kumar, K.; Nakata, S.; Chalamala, B.; Preger, Y. Predictive-Maintenance Practices. *IEEE Power Energy Mag.* **2020**, *18*, 86–97. [CrossRef]
104. Harper, G.; Sommerville, R.; Kendrick, E.; Driscoll, L.; Slater, P.; Stolkin, R.; Walton, A.; Christensen, P.; Heidrich, O.; Lambert, S.; et al. Recycling lithium-ion batteries from electric vehicles There are amendments to this paper. *Nature* **2019**, *575*, 75–86. [CrossRef]
105. Erdogan, C.; Contreras, C.A.; Stolkin, R.; Rastegarpanah, A. Multi-Robot Task Planning for Efficient Battery Disassembly in Electric Vehicles. *Robotics* **2024**, *13*, 75. [CrossRef]
106. Zang, Y.; Wang, Y. Robotic disassembly of electric vehicle batteries: An overview. In Proceedings of the 2022 27th International Conference on Automation and Computing (ICAC), Bristol, UK, 1–3 September 2022; pp. 1–3. [CrossRef]
107. Gerlitz, E.; Greifenstein, M.; Hofmann, J.; Fleischer, J. Analysis of the Variety of Lithium-Ion Battery Modules and the Challenges for an Agile Automated Disassembly System. *Procedia CIRP* **2020**, *96*, 175–180. [CrossRef]

108. Sorting, X. From Innovation to Implementation: X-Ray Sorting Advancing Battery Sorting Through Pioneering a Breakthrough in Battery Overcoming Limitations with Smart X-Ray Revolutionizing Battery Sorting with. Available online: https://www.linevsystems.com/wp-content/uploads/2022/08/case-study-batteray.pdf (accessed on 21 November 2024).
109. Dineva, A. Evaluation of Advances in Battery Health Prediction for Electric Vehicles from Traditional Linear Filters to Latest Machine Learning Approaches. *Batteries* **2024**, *10*, 356. [CrossRef]
110. Hellmuth, J.F.; DiFilippo, N.M.; Jouaneh, M.K. Assessment of the automation potential of electric vehicle battery disassembly. *J. Manuf. Syst.* **2021**, *59*, 398–412. [CrossRef]
111. Wang, Y.; Tan, J.; Liu, Z.; Ditta, A. Lithium-ion battery screening by k-means with DBSCAN for denoising. *Comput. Mater. Contin.* **2020**, *65*, 2111–2122. [CrossRef]
112. Kampker, A.; Wessel, S.; Fiedler, F.; Maltoni, F. Battery pack remanufacturing process up to cell level with sorting and repurposing of battery cells. *J. Remanufacturing* **2021**, *11*, 1–23. [CrossRef]
113. Meng, K.; Xu, G.; Peng, X.; Youcef-Toumi, K.; Li, J. Intelligent disassembly of electric-vehicle batteries: A forward-looking overview. *Resour. Conserv. Recycl.* **2022**, *182*, 106207. [CrossRef]
114. Rosenberg, S.; Huster, S.; Baazouzi, S.; Glöser-Chahoud, S.; Al Assadi, A.; Schultmann, F. Field Study and Multimethod Analysis of an EV Battery System Disassembly. *Energies* **2022**, *15*, 5324. [CrossRef]
115. Jose, S.A.; Cook, C.A.D.; Palacios, J.; Seo, H.; Ramirez, C.E.T.; Wu, J.; Menezes, P.L. *Recent Advancements in Artificial Intelligence*; Innovations in Sustainable Technologies and Computing; Springer: Berlin/Heidelberg, Germany, 2024; Available online: http://link.springer.com/book/10.1007/978-981-97-1111-6 (accessed on 9 December 2024).
116. Lombardo, T.; Duquesnoy, M.; El-Bouysidy, H.; Årén, F.; Gallo-Bueno, A.; Jørgensen, P.B.; Bhowmik, A.; Demortière, A.; Ayerbe, E.; Alcaide, F.; et al. Artificial Intelligence Applied to Battery Research: Hype or Reality? *Chem. Rev.* **2022**, *122*, 10899–10969. [CrossRef] [PubMed]
117. Ariwala, P. What Is AI Visual Inspection for Defect Detection? A Deep Dive. Available online: https://marutitech.com/ai-visual-inspection-for-defect-detection/ (accessed on 21 December 2024).
118. Daniel, R. How AI Is Revolutionizing Lithium-Ion Battery Recycling at Oscorp Energy. Available online: https://www.oscorpenergy.com.au/post/how-ai-is-revolutionizing-lithium-ion-battery-recycling-at-oscorp-energy?utm_source=chatgpt.com (accessed on 5 November 2024).
119. Kay, I.; Farhad, S.; Mahajan, A.; Esmaeeli, R.; Hashemi, S.R. Robotic Disassembly of Electric Vehicles' Battery Modules for Recycling. *Energies* **2022**, *15*, 4856. [CrossRef]
120. Makuza, B.; Tian, Q.; Guo, X.; Chattopadhyay, K.; Yu, D. Pyrometallurgical options for recycling spent lithium-ion batteries: A comprehensive review. *J. Power Sources* **2021**, *491*, 229622. [CrossRef]
121. Pindar, S.; Dhawan, N. Recycling of mixed discarded lithium-ion batteries via microwave processing route. *Sustain. Mater. Technol.* **2020**, *25*, e00157. [CrossRef]
122. Mayyas, A.; Steward, D.; Mann, M. The case for recycling: Overview and challenges in the material supply chain for automotive li-ion batteries. *Sustain. Mater. Technol.* **2019**, *19*, e00087. [CrossRef]
123. Ciez, R.E.; Whitacre, J.F. Examining different recycling processes for lithium-ion batteries. *Nat. Sustain.* **2019**, *2*, 148–156. [CrossRef]
124. Petzold, M.; Flamme, S. Recycling Strategies for Spent Consumer Lithium-Ion Batteries. *Metals* **2024**, *14*, 151. [CrossRef]
125. Ma, Y.; Qiu, K. Recovery of lead from lead paste in spent lead acid battery by hydrometallurgical desulfurization and vacuum thermal reduction. *Waste Manag.* **2015**, *40*, 151–156. [CrossRef] [PubMed]
126. Sheng, O.; Jin, C.; Ding, X.; Liu, T.; Wan, Y.; Liu, Y.; Nai, J.; Wang, Y.; Liu, C.; Tao, X. A Decade of Progress on Solid-State Electrolytes for Secondary Batteries: Advances and Contributions. *Adv. Funct. Mater.* **2021**, *31*, 2100891. [CrossRef]
127. Kumari, R.; Samadder, S.R. A critical review of the pre-processing and metals recovery methods from e-wastes. *J. Environ. Manag.* **2022**, *320*, 115887. [CrossRef] [PubMed]
128. Assefi, M.; Maroufi, S.; Yamauchi, Y.; Sahajwalla, V. Pyrometallurgical recycling of Li-ion, Ni–Cd and Ni–MH batteries: A minireview. *Curr. Opin. Green Sustain. Chem.* **2020**, *24*, 26–31. [CrossRef]
129. Dar, A.A.; Chen, Z.; Zhang, G.; Hu, J.; Zaghib, K.; Deng, S.; Wang, X.; Haghighat, F.; Mulligan, C.N.; An, C.; et al. Sustainable Extraction of Critical Minerals from Waste Batteries: A Green Solvent Approach in Resource Recovery. *Batteries* **2025**, *11*, 51. [CrossRef]
130. Yu, W.; Guo, Y.; Shang, Z.; Zhang, Y.; Xu, S. A review on comprehensive recycling of spent power lithium-ion battery in China. *eTransportation* **2022**, *11*, 100155. [CrossRef]
131. Ali, A.; Manzan, M.; Adjoumane, A. Hydrometallurgy for EV Batteries. 2022. Available online: https://sdgs.un.org/sites/default/files/2022-05/2.4.8-18-Ali-Hydrometallurgy%20for%20EV%20batteries.pdf (accessed on 18 December 2024).
132. Kang, J.; Senanayake, G.; Sohn, J.; Shin, S.M. Recovery of cobalt sulfate from spent lithium ion batteries by reductive leaching and solvent extraction with Cyanex 272. *Hydrometallurgy* **2010**, *100*, 168–171. [CrossRef]

133. Chen, X.; Guo, C.; Ma, H.; Li, J.; Zhou, T.; Cao, L.; Kang, D. Organic reductants based leaching: A sustainable process for the recovery of valuable metals from spent lithium ion batteries. *Waste Manag.* **2018**, *75*, 459–468. [CrossRef] [PubMed]
134. Nayl, A.A.; Elkhashab, R.A.; Badawy, S.M.; El-Khateeb, M.A. Acid leaching of mixed spent Li-ion batteries. *Arab. J. Chem.* **2017**, *10*, S3632–S3639. [CrossRef]
135. Ants, M. Extraction Process of Black Mass from Lithium-Ion Batteries. Available online: https://batxenergies.com/extraction-process-of-black-mass-from-lithium-ion-batteries/ (accessed on 6 January 2025).
136. Jung, J.C.Y.; Sui, P.C.; Zhang, J. A review of recycling spent lithium-ion battery cathode materials using hydrometallurgical treatments. *J. Energy Storage* **2021**, *35*, 102217. [CrossRef]
137. Baum, Z.J.; Bird, R.E.; Yu, X.; Ma, J. Lithium-Ion Battery Recycling–Overview of Techniques and Trends. *ACS Energy Lett.* **2022**, *7*, 712–719. [CrossRef]
138. Larouche, F.; Tedjar, F.; Amouzegar, K.; Houlachi, G.; Bouchard, P.; Demopoulos, G.P.; Zaghib, K. Progress and status of hydrometallurgical and direct recycling of Li-Ion batteries and beyond. *Materials* **2020**, *13*, 801. [CrossRef] [PubMed]
139. Zhan, R.; Payne, T.; Leftwich, T.; Perrine, K.; Pan, L. De-agglomeration of cathode composites for direct recycling of Li-ion batteries. *Waste Manag.* **2020**, *105*, 39–48. [CrossRef] [PubMed]
140. Gaines, L.; Dai, Q.; Vaughey, J.T.; Gillard, S. Direct recycling R&D at the recell center. *Recycling* **2021**, *6*, 31. [CrossRef]
141. Shi, H.; Luo, Y.; Yin, C.; Ou, L. Review of the application of ionic liquid systems in achieving green and sustainable recycling of spent lithium-ion batteries. *Green Chem.* **2024**, *26*, 8100–8122. [CrossRef]
142. Arnold, S.; Ruthes, J.G.A.; Kim, C.; Presser, V. Electrochemical recycling of lithium-ion batteries: Advancements and future directions. *EcoMat* **2024**, *6*, e12494. [CrossRef]
143. Yang, L.; Gao, Z.; Liu, T.; Huang, M.; Liu, G.; Feng, Y.; Shao, P.; Luo, X. Direct Electrochemical Leaching Method for High-Purity Lithium Recovery from Spent Lithium Batteries. *Environ. Sci. Technol.* **2023**, *57*, 4591–4597. [CrossRef] [PubMed]
144. Process. Available online: https://altilium.tech/process/ (accessed on 10 November 2024).
145. Altilium in Numbers: Meeting the Demand for Sustainable Lithium. Available online: https://altilium.tech/2024/06/25/altilium-in-numbers-meeting-the-demand-for-sustainable-lithium/ (accessed on 10 December 2024).