Review

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Progress, Challenges and Opportunities of Recycling Electric Vehicle Batteries: A Systematic Review Article

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Progress, Challenges and Opportunities of Recycling Electric Vehicle Batteries: A Systematic Review Article

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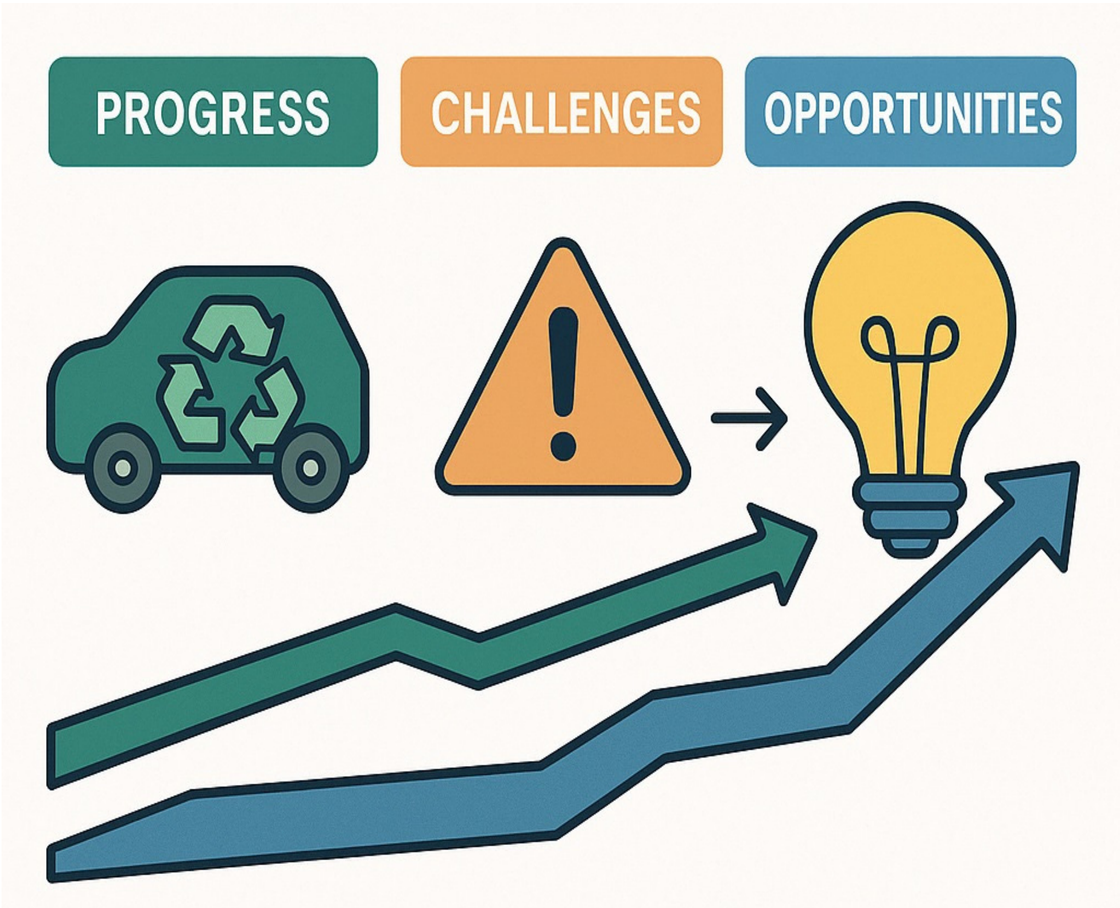
Graphical abstract



Abstract: Objective: To review progress of the recycling of electric vehicle batteries and prospects of it. **Design**: Review based on PRISMA 2020. **Data sources**: Scientific publications indexed in major databases such as Scopus, Web of Science, and ScienceDirect were searched for relevant studies published between 2020 and April 15, 2025. **Inclusion criteria**: Studies were included if they were published in English between 2020 and April 15, 2025, and focused on the recycling of electric vehicle batteries. Eligible studies specifically addressed (i) recycling methods, technologies, and material recovery processes for EV batteries; (ii) the impact of recycled battery systems on power generation processes and grid stability; and (iii) assessments of materials used in battery manufacturing, including efficiency and recyclability. Review articles and meta-analyses were excluded to ensure the inclusion of only original research data. **Data extraction**: One researcher independently screened all articles and extracted relevant data. A second researcher validated the accuracy of extracted data. The data were then organized and analyzed based on reported quantitative and qualitative indicators related to recycling methods, material recovery rates, environmental impact, and system-level energy benefits. **Results**: The review identified significant advancements in battery recycling technologies,

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particularly in hydrometallurgical and direct recycling methods. Material recovery rates for critical metals such as Li, Co, and Ni are improving, with implications for resource efficiency. Furthermore, recycled batteries show potential in stabilizing power grids through second-life applications in BESS. **Conclusion**: EV battery recycling represents a pivotal strategy in addressing raw material scarcity, reducing environmental burdens, and enhancing energy resilience. However, policy harmonization, technological scaling, and economic incentives remain key challenges for widespread implementation.

Keywords: BEV; EV batteries; recycling; lithium-ion battery; circular economy; sustainable material recovery; end-of-life management; policy and regulatory frameworks

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1. Introduction

The rapid global adoption of electric vehicles (EVs) is a cornerstone of the transition toward sustainable transportation and net-zero carbon emissions [1]. With EVs projected to account for over 60% of new car sales by 2040 [2], the demand for lithium-ion batteries (LIBs) has surged, leading to an unprecedented accumulation of end-of-life (EoL) battery waste. While EVs significantly reduce greenhouse gas emissions during operation, the environmental footprint of their batteries-spanning resource extraction, manufacturing, and disposal-poses a critical sustainability challenge [3]. Efficient recycling of EV batteries is thus imperative to close the material loop, mitigate resource scarcity, and minimize ecological harm.

LIBs, the dominant energy storage technology in EVs, rely on critical materials such as lithium, cobalt, nickel, and graphite. The extraction of these materials is often associated with severe environmental degradation, geopolitical tensions, and human rights concerns, particularly in cobalt-rich regions like the Democratic Republic of Congo [4]. Furthermore, the linear economy model-where spent batteries are discarded in landfills-results in toxic leakage and wasted valuable resources. Recycling presents a circular economy solution, reducing reliance on virgin mining and cutting lifecycle emissions by up to 50% [5,6].

Despite these benefits, The current recycling rate is less than 5% of LIBs globally. Key barriers include technological limitations, economic viability gaps, regulatory fragmentation, and logistical complexities in battery collection and transportation. Addressing these challenges requires a systematic evaluation of existing recycling methods, emerging innovations, and policy frameworks to scale sustainable practices [4,6].

1.1. Technological Progress in Battery Recycling

Modern recycling techniques can be broadly classified into pyrometallurgy, hydrometallurgy, and direct recycling. Pyrometallurgical processes, which involve high-temperature smelting, are commercially mature but energy-intensive and inefficient in recovering lithium [7]. Hydrometallurgy, employing chemical leaching, offers higher material recovery rates (>95% for cobalt and nickel) but generates hazardous waste. Direct recycling, an emerging approach, refurbishes cathode materials without full breakdown, preserving their electrochemical properties and reducing energy use [8].

Recent advancements include solvent-based separation, bioleaching, and electrochemical methods that enhance efficiency and sustainability [9]. However, the heterogeneity of battery chemistries (e.g., NMC, LFP) complicates universal recycling solutions, necessitating adaptable technologies [10].

1.1.1. Background and Motivation

The global push toward decarbonization and the reduction of greenhouse gas (GHG) emissions has led to a significant shift in the transportation sector, most notably through the rise of electric

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vehicles (EVs). Governments, industries, and consumers alike have embraced EVs as a cleaner alternative to internal combustion engine vehicles, driven by technological advancements in battery storage, stringent environmental regulations, and rising awareness of climate change. As a result, the EV market has seen exponential growth. According to the International Energy Agency (IEA), the number of electric cars on the road surpassed 26 million in 2022, with projections indicating continued expansion over the coming decades [11,12].

However, this shift is accompanied by a new set of challenges. Central among them is the issue of how to sustainably manage the growing volume of end-of-life (EoL) EV batteries. Lithium-ion batteries (LIBs), which are the dominant energy storage solution for EVs, have a limited lifespan and eventually become inefficient for vehicular use. As EV adoption increases, so does the volume of batteries requiring disposal, reuse, or recycling. The environmental implications of improperly managed EoL batteries, which contain hazardous substances and valuable metals, are significant. Recycling these batteries is therefore not just an environmental imperative but also an economic opportunity [12-14].

1.1.2. Composition and Structure of EV Batteries

A clear understanding of the structural and chemical makeup of electric vehicle (EV) batteries is crucial for designing efficient recycling processes. These batteries are generally composed of four main parts: the cathode, anode, electrolyte, and separator. Cathodes are rich in critical metals like lithium, cobalt, nickel, and manganese, whereas anodes typically consist of graphite. The electrolyte often comprises a lithium salt in an organic solvent, and the separator serves to keep the cathode and anode from coming into direct contact.

Battery composition varies depending on the specific chemistry used, with common types including lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP), and lithium cobalt oxide (LCO). Each type presents distinct implications for recyclability and material recovery. For instance, NMC batteries are favored for their high energy density but are more complex to recycle due to cobalt content. In contrast, LFP batteries are known for their safety and lower production costs but contain fewer high-value materials, making their recycling less economically attractive [15-17].

1.1.3. Environmental and Economic Importance of Battery Recycling

Recycling EV batteries addresses several key environmental and economic concerns. First, it prevents the accumulation of hazardous waste in landfills, where the potential for leaching toxic substances poses a threat to soil and groundwater quality. Second, recycling reduces the need for primary raw material extraction, which is associated with environmental degradation, high energy consumption, and socio-political risks. For instance, cobalt mining in the Democratic Republic of Congo has drawn criticism due to its environmental and ethical concerns.

From an economic perspective, battery recycling can support the development of a circular economy by recovering valuable metals that can be reintroduced into the production cycle. This not only reduces the demand for virgin materials but also stabilizes supply chains and lowers production costs. As demand for EVs increases, the global supply of critical battery materials will come under pressure, making recycling an essential strategy for resource conservation and market stability [16-19].

1.1.4. Overview of Recycling Methods

There are three main categories of recycling methods for EV batteries: pyrometallurgical, hydrometallurgical, and direct recycling. Each has distinct advantages and drawbacks, and the choice of method often depends on factors such as battery chemistry, available infrastructure, and environmental regulations.

- **Pyrometallurgy** involves high-temperature processing to extract metals from battery materials. It is a mature and widely used method that can handle a variety of battery chemistries but tends

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to be energy-intensive and may result in the loss of certain elements, such as lithium and aluminum [20,21].

- **Hydrometallurgy** uses aqueous chemistry, typically involving acid leaching, to selectively extract metals. This method offers higher recovery efficiency for certain metals and is less energy-intensive than pyrometallurgy. However, it produces liquid waste that requires careful management [22,23].
- **Direct Recycling**, also known as physical or mechanical recycling, aims to preserve the integrity of battery components, such as the cathode, for reuse. Although still in the developmental stage, direct recycling has the potential to reduce energy consumption and maintain the functional value of recovered materials [24,25].

1.1.5. Challenges and Barriers to Effective Recycling

Despite technological advancements, several barriers hinder the effective implementation of EV battery recycling at scale. One major issue is the lack of standardized battery designs, which complicates the disassembly and sorting processes. Additionally, battery packs are often sealed and integrated with complex electronics, making manual or automated dismantling labor-intensive and costly.

Another significant challenge is the absence of a comprehensive collection and logistics network for used batteries. In many regions, consumers and service providers lack clear guidance on how to dispose of or return EoL batteries. Regulatory frameworks are still evolving, and enforcement remains inconsistent, leading to a fragmented recycling ecosystem.

Economic feasibility also plays a crucial role. While some metals, such as cobalt and nickel, offer high recovery value, others like lithium and manganese are less economically attractive to reclaim. The fluctuating prices of raw materials further complicate investment decisions in recycling infrastructure [16,26,27].

1.1.6. Policy and Regulatory Landscape

Governments and international bodies have begun to address the need for regulation in battery recycling. The European Union's Battery Regulation, for instance, mandates minimum recycling efficiencies and material recovery targets for battery producers. It also promotes eco-design principles, such as design for disassembly, and the development of battery passports to track lifecycle information.

In the United States, policy efforts are more fragmented but are gaining momentum through initiatives like the Battery Recycling Prize and support from the Department of Energy. China, a leader in battery production, has also implemented regulations requiring producers to take responsibility for battery take-back and recycling.

These regulations are crucial for establishing a consistent and enforceable framework that encourages investment in recycling technologies and infrastructure. They also help create a level playing field for market participants and ensure environmental and safety standards are met [28,29].

1.1.7. Objectives and Scope of the Review

This review paper aims to provide a comprehensive analysis of the current state of EV battery recycling, highlighting technological advancements, economic considerations, and regulatory frameworks. The paper will explore the lifecycle of EV batteries, evaluate the strengths and limitations of existing recycling methods, and identify research gaps and future directions. Special attention will be given to the integration of recycling within a circular economy model, the role of stakeholders in the recycling value chain, and the potential for innovation through second-life applications and digital tracking systems.

By synthesizing insights from recent literature, industry practices, and policy developments, this paper seeks to inform researchers, policymakers, and practitioners on the pathways toward

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sustainable and efficient battery recycling systems that support the broader transition to clean energy and mobility.

1.2. Battery Lifecycle and End-of-Life Scenarios

The lifecycle of an electric vehicle (EV) battery extends far beyond its operational service in mobility, encompassing complex stages of production, utilization, degradation, and eventual repurposing or recycling. While LIBs typically retain 70–80% of their initial capacity after 8–10 years of vehicular use (Neubauer et al., 2015), their performance degradation necessitates strategic end-of-life (EoL) management to maximize resource efficiency. Potential EoL pathways include second-life applications (e.g., stationary energy storage), direct material recycling, or, in poorly regulated markets, landfilling-each carrying distinct environmental and economic implications. This section analyzes the technical, logistical, and regulatory determinants of these scenarios, emphasizing the critical role of lifecycle planning in achieving a sustainable circular economy for battery materials [30-32].

1.2.1. Overview of Battery Lifecycle

An EV battery typically undergoes several stages during its operational life. These include raw material extraction, manufacturing, first-use in vehicles, second-life applications, and eventual recycling or disposal. Understanding these stages is crucial to identifying intervention points where sustainability measures, such as reuse or material recovery, can be most effectively implemented.

1.2.2. Degradation and End-of-Life Characteristics

Battery degradation is a natural process resulting from repeated charge-discharge cycles, high temperatures, and other operational stresses. Over time, battery capacity decreases, and its ability to deliver sufficient power declines. When a battery's state of health (SoH) drops below approximately 70–80%, it is generally considered no longer viable for vehicular use, marking its transition to the EoL phase [32,33].

1.2.3. Second-Life Applications

Before recycling, EoL EV batteries can be repurposed for second-life applications, such as stationary energy storage for renewable energy integration, backup power systems, or grid support services. These applications capitalize on the residual capacity of EV batteries and extend their useful life, delaying environmental impacts and improving overall resource efficiency. However, standardization, safety testing, and performance assurance remain barriers to widespread implementation [31,33].

1.2.4. Collection and Sorting

Effective recycling depends heavily on efficient collection and sorting mechanisms. Currently, many countries lack a streamlined system for collecting EoL EV batteries, which results in missed recovery opportunities and environmental risks. Advanced identification and tracking technologies-such as battery identification codes and digital battery passports-are being explored to facilitate better management and traceability of used batteries [33,34].

1.2.5. Logistics and Transportation

Transporting EoL batteries to recycling facilities poses logistical and safety challenges. Lithium-ion batteries are classified as hazardous materials, requiring compliance with stringent regulations for storage, packaging, and transportation. Innovations such as modular packaging systems and real-time monitoring can enhance safety and reduce logistical complexity [31-34].

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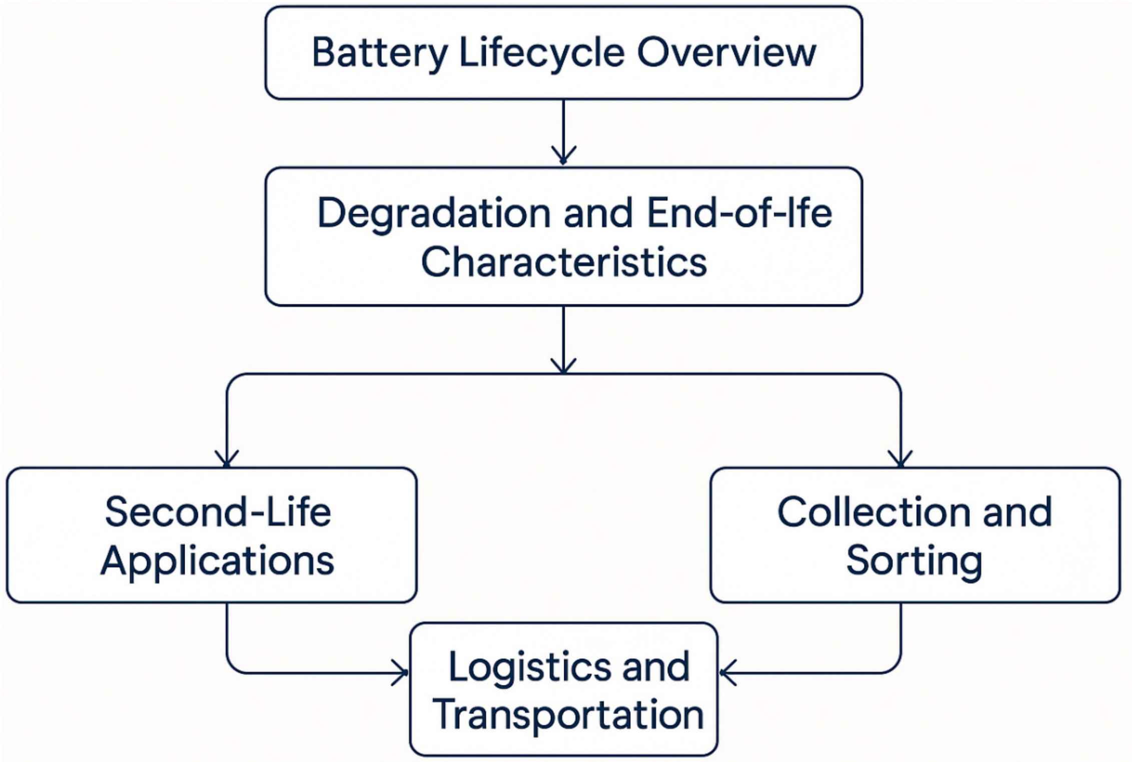

Figure 1. Battery Lifecycle and End-of-Life Scenarios.

1.3. Technological Advances in Recycling Processes

The recycling of electric vehicle (EV) batteries has undergone significant technological evolution in recent years, driven by the urgent need for sustainable material recovery and the growing volume of end-of-life lithium-ion batteries (LIBs). Conventional methods such as pyrometallurgy and hydrometallurgy, while effective for certain metals, face limitations in energy efficiency, material recovery rates, and environmental impact. In response, cutting-edge advancements-including direct recycling, solvent-assisted separation, and bioleaching-are reshaping the recycling landscape by improving selectivity, reducing energy consumption, and enabling higher purity material regeneration. Furthermore, innovations in automation, artificial intelligence (AI)-driven sorting, and closed-loop hydrometallurgical processes are enhancing scalability and economic viability. This section critically examines these emerging technologies, their comparative advantages, and their potential to overcome the existing barriers in large-scale battery recycling [35].

1.3.1. Pyrometallurgical Recycling in Practice

Several commercial recycling plants utilize pyrometallurgical techniques, particularly for processing mixed battery streams. The process involves shredding batteries followed by smelting in a high-temperature furnace. Metals like cobalt, nickel, and copper are recovered, but lithium and aluminum are typically lost in slag. Emerging improvements aim to lower energy use and recover more materials from the slag phase [36,37].

1.3.2. Hydrometallurgical Developments

Hydrometallurgy is gaining traction due to its higher selectivity and recovery rates. Recent research has focused on developing environmentally benign leaching agents, reducing chemical consumption, and integrating closed-loop systems to manage effluents. Startups and industrial players are piloting scalable processes to recover lithium, cobalt, and nickel with minimal environmental footprint [38,39].

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1.3.3. Direct Recycling and Closed-Loop Systems

Direct recycling processes aim to retain the structure and chemistry of active materials for immediate reuse. Key steps include battery disassembly, material separation, re-lithiation, and quality testing. Though still in the lab and pilot stages, direct recycling offers a promising path to sustainable and low-energy battery recovery [40].

1.3.4. Automation and Robotics

Automation is increasingly being integrated into battery recycling operations to reduce human exposure to hazardous materials and improve efficiency. Robotic disassembly systems, AI-based sorting mechanisms, and automated diagnostic tools are being developed to handle diverse battery formats and compositions [41].

1.3.5. Life Cycle Assessment (LCA) of Recycling Techniques

LCA studies compare the environmental impacts of different recycling technologies. Results generally show that hydrometallurgical and direct recycling methods offer lower GHG emissions and energy use compared to pyrometallurgy. However, regional differences in electricity mix, regulatory context, and plant scale can influence these outcomes significantly [30,33].

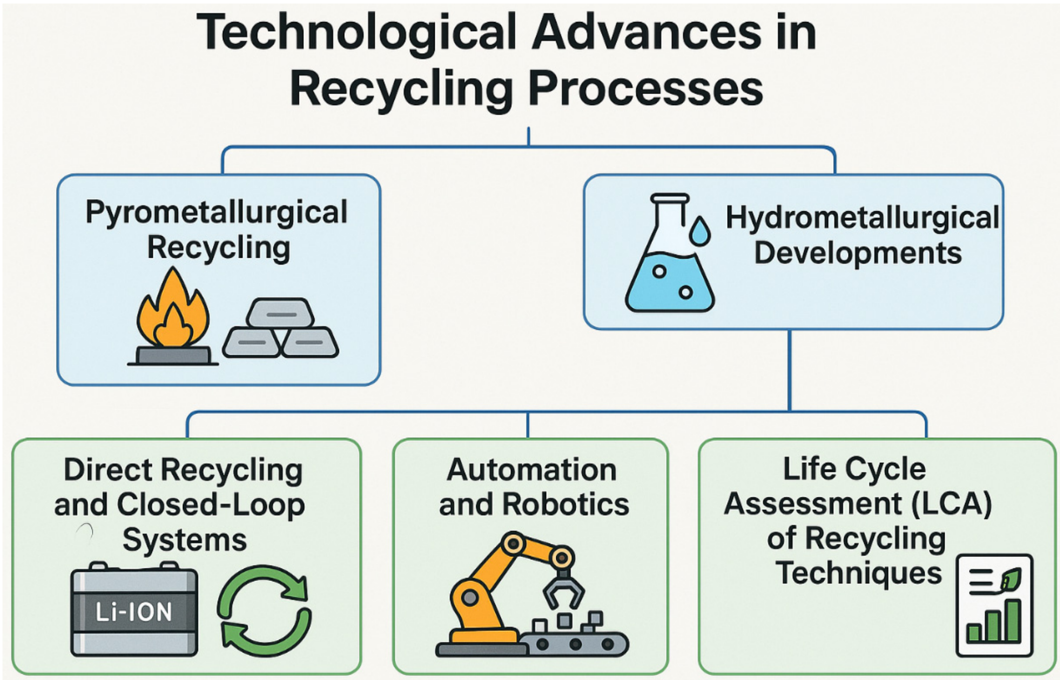

Figure 2. Technological Advances in Recycling Processes.

1.3.6. Global Battery Recycling Market Growth (2015–2025)

The global battery recycling market has expanded substantially over the past decade. In 2016, the market was valued at approximately \$8.74 billion, and by 2025, it is projected to reach \$21.04 billion, reflecting a compound annual growth rate (CAGR) of 10.4% [42].

Focusing specifically on lithium-ion batteries, which are prevalent in EVs and portable electronics, the recycling market was estimated at \$3.54 billion in 2023. This segment is expected to grow at a CAGR of 21%, reaching nearly \$24 billion by 2033 [43].

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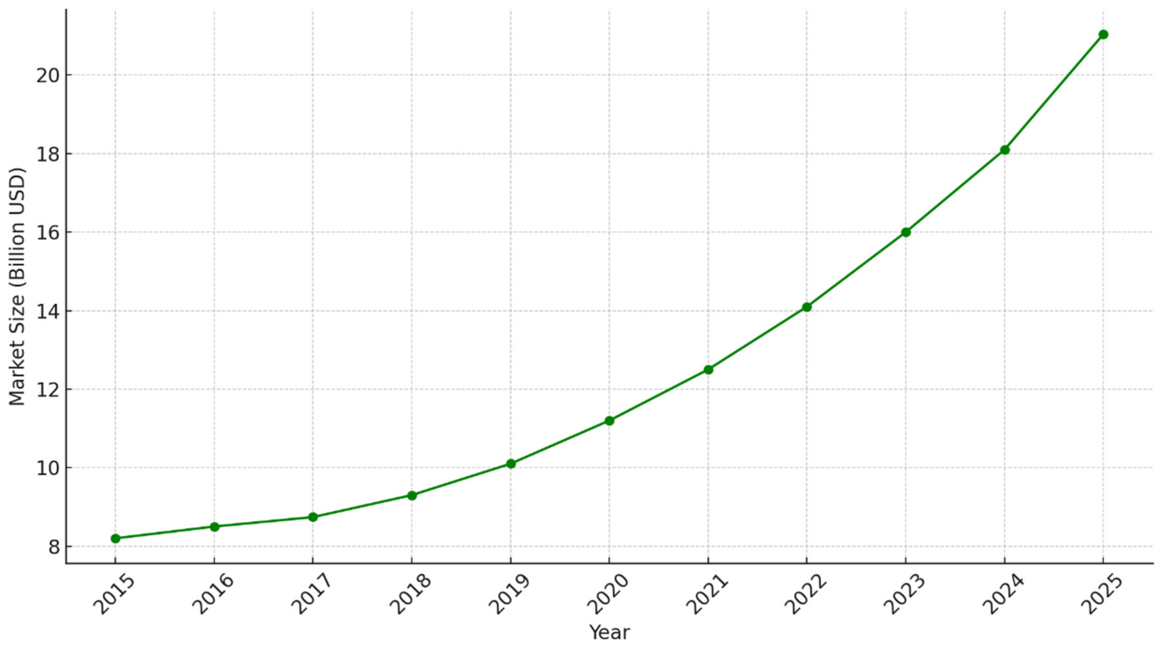

Figure 3. Global battery recycling market trend (2015 – 2025).

2. Methodology

Based on the Prisma 2020 checklist [44], the present systematic review was conducted by extracting studies from three scientific databases: Web of Science, SCOPUS, and Pub-Med. Published studies from the last 6 years from 2020 to 15 April 2025 were restricted and categorized based on Boolean combinations. These 6 years were dedicated to assessing recent achievements and developments in the field of recycling of vehicle batteries. By adopting the keywords BEV, EV Batteries, Recycling, Lithium-ion Battery, Circular Economy, Sustainable Material Recovery, End-of-Life Management, Policy and Regulatory Frameworks, 16% of the found studies were selected (312 papers). Then, the titles and abstracts of the articles were independently reviewed by two researchers (HS, FDM). In cases of inconsistency, discussions were held until agreement was reached. Then, the titles and abstracts were screened. After this first selection process, the researcher (FDM) independently screened the full-text articles for inclusion. In case of disagreement, consensus was reached by discussion on inclusion or exclusion, and a second researcher (HS) was consulted if necessary. Finally, the selected articles were studied for in-depth review and examination of the results (23 papers).

3. Results

According to the PRISMA method used in this study, the search identified 1916 articles (Figure 4). First, reviews, meta-analyses (88) and duplicates (34) were excluded. After that, an independent researcher (FDM) provided further screening based on the relevance of each study's title and abstract to the objectives of the current review. In case of doubt, a second independent researcher (HS) was involved. Finally, 1482 records were excluded. The remaining 312 studies were analyzed in more depth with respect to the introduction, methodology and results sections. Finally, 284 were excluded due to their lack of relevance to research on EV battery recycling and usually related to the scenario-based policy scenarios envisaged. Finally, 23 studies were included in the review.

23 studies in this review reported on EV battery recycling from 13 countries (Figure 5). Two studies were reported from Finland, seven from China, two from Brazil, three from the United States, one each from Germany and France, and one each from India and Sweden, four from East Asia, and two from the United Kingdom (Figure 5). A total of 23 studies were reported from 26 regions, of which eight were from the European Union, three from North America, two from South America, and 12 from Asia (some studies reported from more than one region).

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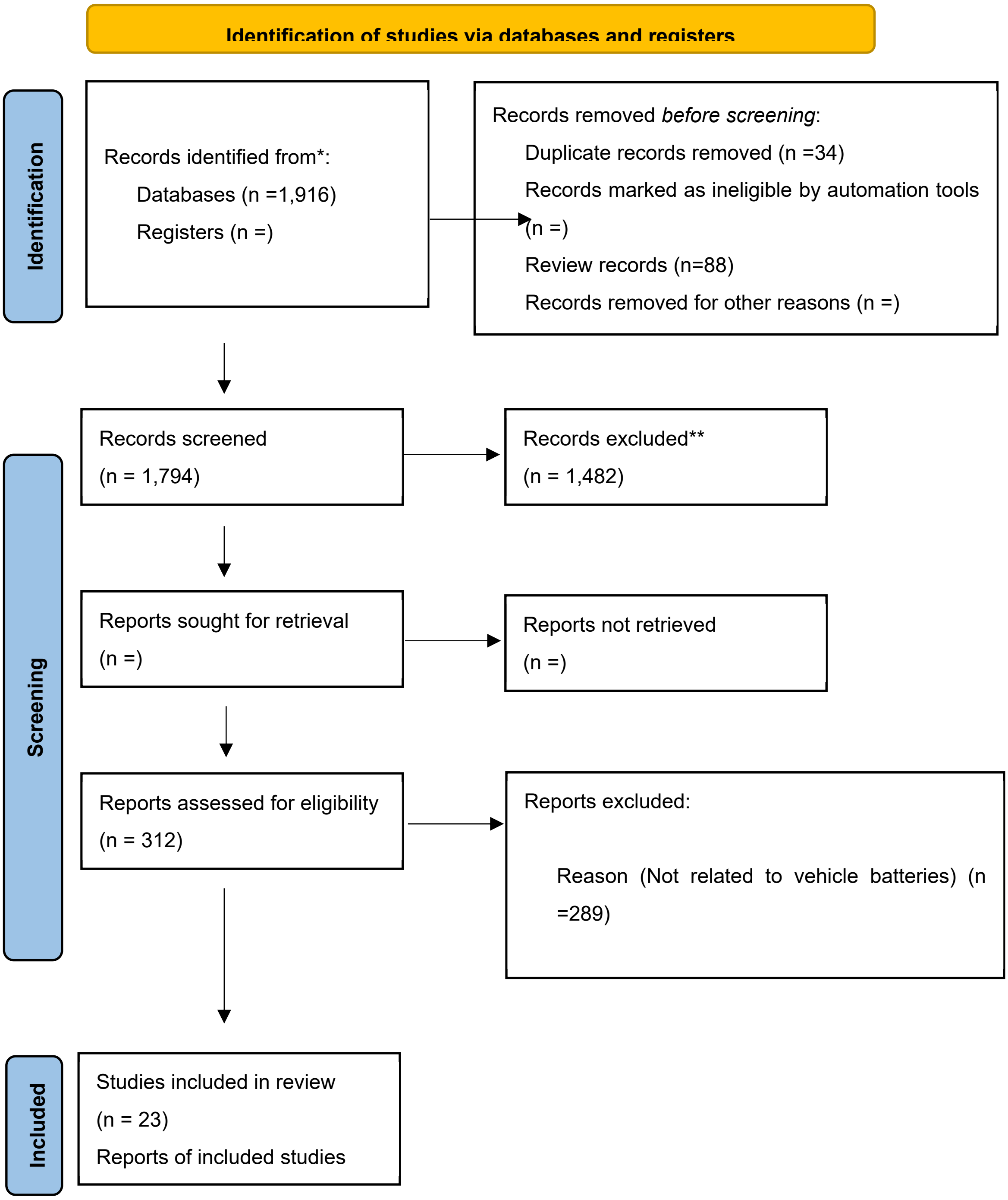

Figure 4. Flow diagram of the selection process of the studies included in the review.

After selecting the studies to be reviewed in this review, the results are summarized in Table 1. This table lists the studies' titles, objectives, and achievements. Table 2 also lists the parameters of the studies that are reported related to the structure of electric vehicle batteries, such as capacity, energy, voltage, current intensity, weight, and number of cells. These data have also been examined in terms of economics and optimization, and the minimum and maximum state of charge data as well as recycling costs have been provided. The results presented in the articles used in this review are also given in Figure 6. The graphs relate to the comparison of battery mass (6.a), state of charge (6.b), voltage and current (6.c), battery capacity (6.d), charging time (6.e), and recycling rate (6.f).

Table 1. Overview of the research selected in this review in terms of title, key focus, algorithm, and key funding.

Ref	Title	country	Methodology	Main Focus	Key funding	Year
[45]	The distribution of valuable metals in gasification of metal-containing residues from mechanical recycling of end-of-life vehicles and electronic waste	Finland	Experimental	Recycling of metal-containing wastes such as end-of-life vehicles (ELV)	The gasification abled to remove the organic matter efficiently and liberate metals.	2025
[46]	Deloitte China, and CAS. *Lithium-Ion Battery Recycling: Market & Innovation Trends for A Green Future*	China	Simulation	The future of recycling of Li-ion Batteries in China	-	2025
[47]	CAN Interface Insights for Electric Vehicle Battery Recycling	Finland	Simulation	Controller Area Network Interface Insights for Electric Vehicle Battery Recycling	-	2024
[48]	Design of Recycling Processes for NCA-Type Li-Ion Batteries from Electric Vehicles toward the Circular Economy	Brazil	Experimental	Hydrometallurgical recycling process of NCA cylindrical batteries	92% of Li, 80% of Ni, and 85% of Co can be recovered in hydrometallurgical processing	2024
[49]	Life cycle assessment of secondary use and physical recycling of lithium-ion batteries retired from electric vehicles in China	China	Experimental	LCA of secondary use and physical recycling of lithium-ion batteries	Secondary use has the greatest impact on assessment results in dynamic situations.	2024
[50]	Optimizing the Supply Chain for Recycling Electric Vehicle NMC Batteries	Indonesia	Simulation	Optimizing the Supply Chain for Recycling EV Batteries	-	2024
[51]	A system dynamics model for end-of-life management of electric vehicle batteries in the US: Comparing the cost, carbon, and material requirements of remanufacturing and recycling	USA	Simulation	End-of-life management of electric vehicle batteries	Remanufacturing can reduce the carbon footprint of the EV battery life cycle.	2024
[52]	Charting the electric vehicle battery reuse and recycling network in North America	USA	Simulation	Electric vehicle battery reuse and recycling network in North America	EV and EV battery EoL is market-driven system, relying on profitability.	2024

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[53]	Multi-objective combinatorial optimization analysis of the recycling of retired new energy electric vehicle power batteries in a sustainable dynamic reverse logistics network	China	Simulation	Explore the layout of the sustainable reverse logistics network for batteries recycling	The dynamic reverse logistics network is superior to its static counterpart	2023
[54]	Optimization of the Electrochemical Discharge of Spent Li-Ion Batteries from Electric Vehicles for Direct Recycling	Korea	Experimental	Optimization of the Electrochemical Discharge of Spent Li-Ion Batteries	The process will be suitable for the direct recycling of spent LIBs	2023
[55]	Dynamic estimation of end-of-life electric vehicle batteries in the EU-27 considering reuse, remanufacturing and recycling options	Germany - France	Simulation	Dynamic estimation of end-of-life electric vehicle batteries	The recycled metals could meet 5.2–11.3% of the demand for EU Battery Directive	2023
[56]	Scaling up reuse and recycling of electric vehicle batteries: Assessing challenges and policy approaches	India	Experimental	Challenges and policy approaches	-	2023
[57]	Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts	USA	Simulation	Electric vehicle lithium-ion battery recycled content standards for the US	Recycling US EV retirements domestically is more expensive than recycling in China	2022
[58]	Economic Aspects for Recycling of Used Lithium-Ion Batteries from Electric Vehicles	Brazil	Simulation	Factors that influence the economic feasibility of disposing of batteries	A business model is created for recycling LIBs in Brazil	2022
[59]	Uncovering the in-use metal stocks and implied recycling potential in electric vehicle batteries considering cascaded use: a case study of China	China	-	Recycling potential in electric vehicle batteries	Increasing recycling potential by 2030	2021
[60]	Potential impact of the end-of-life batteries recycling of electric vehicles on lithium demand in China: 2010–2050	China	Simulation	Potential impact of batteries recycling on lithium demand in China	The recovered lithium could meet 60% of the lithium demand for LIBs produced by 2050.	2021
[61]	Innovative recycling of organic binders from electric vehicle lithium-ion batteries by supercritical carbon dioxide extraction	Sweden	Experimental	Innovative recycling of organic binders	Recovered PVDF remained the same surficial chemical properties as the raw sample.	2021

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[62]	The role of nickel recycling from nickel-bearing batteries on alleviating demand-supply gap in China's industry of new energy vehicles	China	Simulation	Nickel recycling from nickel-bearing batteries	Recovered nickel is likely to play vital role for closing nickel loop in the industry of NEVs in China.	2021
[63]	On the influence of second use, future battery technologies, and battery lifetime on the maximum recycled content of future electric vehicle batteries in Europe	Belgium	Simulation	A novel forecasting model is developed to include second-use of vehicle batteries.	Cobalt content of recycled EV batteries may fulfil 91% of Europe’s 2040 EV demand.	2021
[64]	Financial viability of electric vehicle lithium-ion battery recycling	UK-Belgium-USA-South Korea-China	Simulation	Comprehensive techno-economic cost model for electric vehicle battery recycling	Economies of scale and battery materials are decisive for recycling profits	2021
[65]	Economic analysis of lithium-ion batteries recycled from electric vehicles for secondary use in power load peak shaving in China	China	-	A novel cost-benefit modelfor battery energy storage system of recycled Li-ion batteries	-	2020
[66]	Cell equalizer for recycling batteries from hybrid electric vehicles	Japan	Experimental	Cell equalizer for recycling	-	2020
[67]	Beyond the EVent horizon: Battery waste, recycling, and sustainability in the United Kingdom electric vehicle transition	UK	Simulation	Recycling, and sustainability in the United Kingdom electric vehicle	Sustainable recycling solutions will require sustainable business models.	2020

Table 2. Overview of the research on the recycling of EV batteries optimization objectives and parameters.

Ref	Battery type	EV / HEV	Energy	Voltage (V)	Current (A)	Peak current (A)	Capacity (Ah)	Mass (kg)	Number of Cells	Min SOC (%)	Max SOC (%)	Process. time (min)	Charge time (min)	Temp. (C)	pH	Rec. Li (%)	Rec. Ni (%)	Rec. Co (%)	Rec. cost
[45]	-	-	-	-	-	-	-	150 - 400	-	-	-	-	-	415 - 885	-	-	-	-	-

[46]	Li-ion (NMC)	EV	65	400	150	300	162.5	450	96	20	90	120	45	25	7	95	90	85	1,000 $/ton
[47]	Li-ion	HEV	430 Wh	48	75	250	9.8	17.5	16	8	82	-	110	23 - 65	-	-	-	-	-
[48]	Li-ion	EV	-	-	-	-	-	-	-	-	-	30 - 180	-	25 - 90	1-3.5	91.6	80.3	85	-
[49]	Li-ion	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
[50]	NMC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	128,000 IDR/kg
[51]	$LiCoO_2$ (LCO)	EV	0.175 kWh/kg	-	-	-	-	-	-	-	-	-	-	-	-	95	95	95	-
	LiMn2O4 (LMO)	EV	0.125 kWh/kg	-	-	-	-	-	-	-	-	-	-	-	-				-
	LiF_2PO_4 (LFP)	EV	0.105 kWh/kg	-	-	-	-	-	-	-	-	-	-	-	-				-
	NMC 111	EV	0.185 kWh/kg	-	-	-	-	-	-	-	-	-	-	-	-				-
	NMC 622	EV	0.185 kWh/kg	-	-	-	-	-	-	-	-	-	-	-	-				-
	NMC 811	EV	0.185 kWh/kg	-	-	-	-	-	-	-	-	-	-	-	-				-
	$LiNiCoAlO_2$ (NCA)	EV	0.3 kWh/kg	-	-	-	-	-	-	-	-	-	-	-	-				-
[53]	NiMH	HEV	40	300	120	240	133.3	350	80	30	90	90	35	25	6.8	75	65	55	800 $/ton
[54]	SM_3 ZEs	EV	35.9 kWh	360	-	-	74	-	192	-	-	24 (h)	-	40	-	-	-	-	-
[55]	NCA	EV / HEV	8.6 - 72 kWh	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	LMO			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	LFP			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	NMC 811			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	NMC 622			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	NMC 111			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	NMC 955			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	NMC 532			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
[56]	Li-ion (LFP)	EV	50	350	140	280	142.9	400	90	10	100	100	40	30	6.5	80	70	60	900 $/ton

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[57]	Li-ion (NCA)	EV	70	420	160	320	166.7	480	100	15	95	130	50	35	7.2	92	88	83	1,100 $/ton
[58]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	33.79 $/kWh
	NMC	EV	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
[59]	LFP	EV	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	LMO	EV	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	LFP-G	EV	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-
	NMC-G	EV	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-
[60]	NCA-G	EV	-	-	-	-	-	-	-	-	-	-	-	-	-	49-60	-	-	-
	Li-S	EV	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-
	Li-Air	EV	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-
[61]	ALB	EV	-	-	-	-	-	-	-	-	-	4 - 17	-	-	-	97.5	-	-	-
	NCA		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	NCM 111		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
[62]	NCM 523	EV / HEV	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	NCM 622		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	NCM 811		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Li-Iron Phosphate		-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-
	LMO		-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-
[63]	LMO blend	EV / HEV	-	-	-	-	44 - 60	-	-	-	-	-	-	-	-	-	-	-	-
	NMC 111		-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-
	NMC 532		-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-
	NMC 622		-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-

	NMC 811		-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-
	Li-Ni-Co-AlO3		-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-
	Advanced and beyond li-ion		-	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-
[64]	NCA	EV / HEV	24 - 93 kWh	-	-	-	-	295 - 1,009	192 - 10,368	-	-	-	-	-	-	90	98	98	10.55 - 21.9 $/kWh
	NMC 622			-	-	-	-			-	-	-	-	-	-				3.51-14.86 $/kWh
	NMC 811			-	-	-	-			-	-	-	-	-	-				1.43-12.77 $/kWh
	LFP			-	-	-	-			-	-	-	-	-	-				0-10.77 $/kWh
	LMO			-	-	-	-			-	-	-	-	-	-				0-9.15 $/kWh
[65]	Li-ion	EV	-	3.2	0.5	-	50	-	-	-	-	-	-	-	-	-	-	-	0.45 CNY/Wh
[66]	NiMH	HEV	-	14.37	1.8	2.2	3.3	-	-	80	100	110	90	-	-	-	-	-	-
[67]	Li-ion (LTO)	HEV	45	360	130	260	125	370	85	25	85	110	42	28	6.9	78	68	58	950 $/ton

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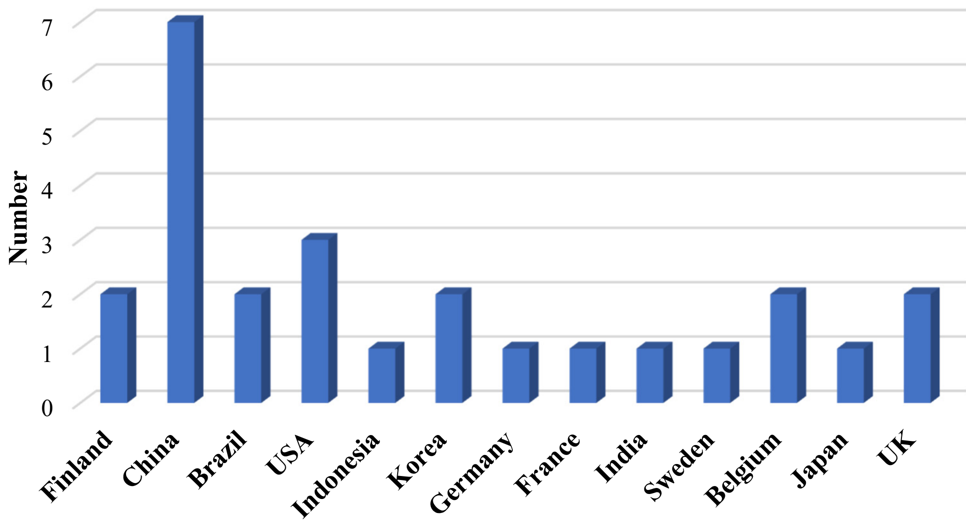
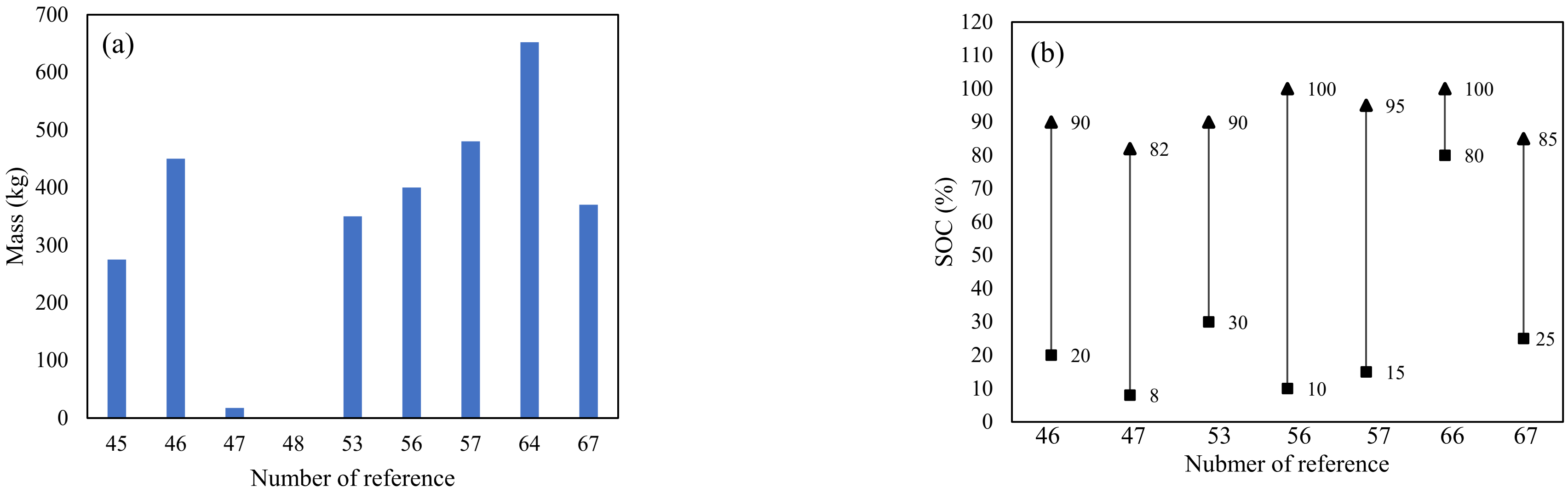


Figure 5. The number of geographical areas related to the included studies.



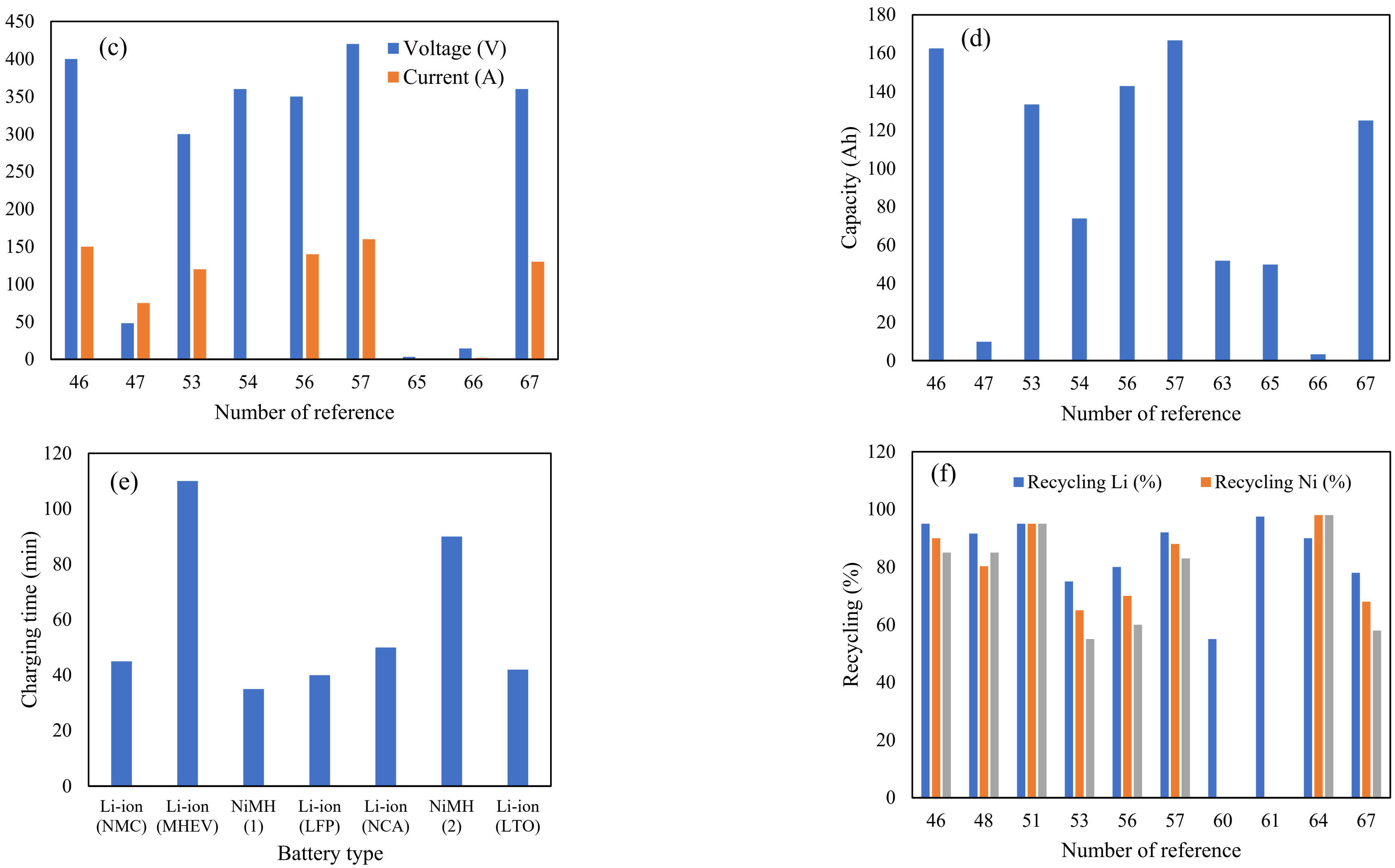


Figure 6. Comparison the important parameters includes: a) Battery mass, b) State of charge, c) voltage and current, d) Battery capacity, e) Charging time, and f) Recycling rate.

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Some studies have reported the chemical elements present in the structure of batteries. Some of these elements are specified in the battery description and some in the battery recycling. These elements are reported in Table 3, separated by reference number. Also, the reported amount of each element is given separately in Table 4.

In more detailed studies, the cost of the elements used in the battery structure has been reported separately in three studies, which can be seen in Table 5.

Table 3. Reported elements in battery structure or recycling.

Ref	C	H	N	O	Al	Cu	Fe	Sn	Zn	Ag	Au	Pd	Dy	Nd	Li	Ni	Co	Mn
[45]	*	*	*		*	*	*	*	*	*	*	*	*	*				
[47]	*			*	*										*	*	*	
[48]	*				*	*									*	*	*	*
[49]																*	*	*
[50]					*	*	*								*	*	*	*
[51]						*									*	*	*	*
[53]						*									*	*	*	
[54]					*	*	*								*	*	*	*
[55]					*	*	*								*	*	*	*
[58]					*	*	*								*	*	*	*
[59]					*										*	*	*	*
[60]	*														*	*	*	*
[61]	*				*	*	*								*	*	*	*
[62]		*		*			*									*		
[63]	*				*	*	*								*	*	*	*

Table 4. The contribution of each element in the battery structure.

Ref	C (%)	Al (%)	Cu (%)	Fe (%)	Ag (%)	Au (%)	Pd (%)	Li (%)	Ni (%)	Co (%)	Mn (%)
[45]	-	3	4.4	18.2	0.001	-	-	-	-	-	-
	-	1.5	21.6	6.1	0.06	0.0151	24.3	-	-	-	-
	-	1.1	6	0.14	0.01	0.393	71.9	-	-	-	-
[48]	1.6	36.6	-	-	-	-	-	4.2	30.3	5.2	-
[49]	22.44	8.76	9.83	-	-	-	-	-	5.74	2.3	3.22
[50]	-	-	-	-	-	-	-	-	22	22	20
[51]	-	0.304 (kg/kWh)	0.426 (kg/kWh)	0.963 (kg/kWh)	-	-	-	0.119 (kg/kWh)	0.071 (kg/kWh)	0.01 (kg/kWh)	-
	-	0.075 (kg/kWh)	0.075 (kg/kWh)	1.105 (kg/kWh)	-	-	-	0.104 (kg/kWh)	-	-	1.37 (kg/kWh)
	-	0.457 (kg/kWh)	0.571 (kg/kWh)	2.53 (kg/kWh)	-	-	-	0.084	-	-	-

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								(kg/kWh)			
	-	0.263 (kg/kWh)	0.390 (kg/kWh)	0.866 (kg/kWh)	-	-	-	0.139 (kg/kWh)	0.367 (kg/kWh)	0.394 (kg/kWh)	0.392 (kg/kWh)
	-	0.263 (kg/kWh)	0.390 (kg/kWh)	0.866 (kg/kWh)	-	-	-	0.126 (kg/kWh)	0.2 (kg/kWh)	0.214 (kg/kWh)	0.641 (kg/kWh)
	-	0.263 (kg/kWh)	0.390 (kg/kWh)	0.866 (kg/kWh)	-	-	-	0.111 (kg/kWh)	0.088 (kg/kWh)	0.094 (kg/kWh)	0.75 (kg/kWh)
	-	0.379 (kg/kWh)	0.758 (kg/kWh)	-	-	-	-	0.112 (kg/kWh)	0.759 (kg/kWh)	0.143 (kg/kWh)	-
	-	-	0.76 (kg/kWh)	-	-	-	-	0.1 (kg/kWh)	0.67 (kg/kWh)	0.13 (kg/kWh)	-
	-	-	0.96 (kg/kWh)	-	-	-	-	0.11 (kg/kWh)	0.07 (kg/kWh)	0.07 (kg/kWh)	-
	-	-	0.9 (kg/kWh)	-	-	-	-	0.1 (kg/kWh)	-	-	-
[55]	-	-	0.77 (kg/kWh)	-	-	-	-	0.11 (kg/kWh)	0.75 (kg/kWh)	0.09 (kg/kWh)	-
	-	-	0.76 (kg/kWh)	-	-	-	-	0.13 (kg/kWh)	0.61 (kg/kWh)	0.19 (kg/kWh)	-
	-	-	0.82 (kg/kWh)	-	-	-	-	0.15 (kg/kWh)	0.4 (kg/kWh)	0.4 (kg/kWh)	-
	-	-	0.76 (kg/kWh)	-	-	-	-	0.1 (kg/kWh)	0.7 (kg/kWh)	0.04	-

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										(kg/kWh)	
	-	-	0.8 (kg/kWh)	-	-	-	-	0.14 (kg/kWh)	0.59 (kg/kWh)	0.23 (kg/kWh)	-
[59]	-	5.26	7.8	-	-	-	-	1.14	9.46	9.67	9.03
	-	6.25	8.15	9.71	-	-	-	1.21	-	-	-
	-	1.12	1.12	-	-	-	-	1.54	-	-	20.38
[60]	-	-	-	-	-	-	-	176.3 (g/kWh)	-	-	-
	-	-	-	-	-	-	-	113.15 (g/kWh)	-	-	-
	-	-	-	-	-	-	-	239.0 (g/kWh)	-	-	-
	-	-	-	-	-	-	-	410.5 (g/kWh)	-	-	-
	-	-	-	-	-	-	-	138.0 (g/kWh)	-	-	-
[61]	-	0.06	-	-	-	-	-	5.91	11.5	11.7	26.02
[62]	-	-	-	-	-	-	-	0.112 (kg/kWh)	0.759 (kg/kWh)	0.143 (kg/kWh)	0
	-	-	-	-	-	-	-	0.139 (kg/kWh)	0.392 (kg/kWh)	0.394 (kg/kWh)	0.367 (kg/kWh)
	-	-	-	-	-	-	-	0.134 (kg/kWh)	0.564 (kg/kWh)	0.263 (kg/kWh)	0.316 (kg/kWh)
	-	-	-	-	-	-	-	0.126 (kg/kWh)	0.641 (kg/kWh)	0.214 (kg/kWh)	0.2 (kg/kWh)

	-	-	-	-	-	-	-	0.111 (kg/kWh)	0.75 (kg/kWh)	0.094 (kg/kWh)	0.088 (kg/kWh)
[63]	1.19 (kg/kWh)	-	0.9 (kg/kWh)	-	-	-	-	0.1 (kg/kWh)	-	-	
	1.04 (kg/kWh)	-	0.96 (kg/kWh)	-	-	-	-	0.1	-	-	
	1.04 (kg/kWh)	-	0.96 (kg/kWh)	-	-	-	-	0.11 (kg/kWh)	0.07 (kg/kWh)	0.07 (kg/kWh)	
	1.1 (kg/kWh)	-	0.82 (kg/kWh)	-	-	-	-	0.15 (kg/kWh)	0.4 (kg/kWh)	0.4 (kg/kWh)	
	1.09 (kg/kWh)	-	0.8 (kg/kWh)	-	-	-	-	0.14 (kg/kWh)	0.59 (kg/kWh)	0.23 (kg/kWh)	
	1.06 (kg/kWh)	-	0.76 (kg/kWh)	-	-	-	-	0.13 (kg/kWh)	0.61 (kg/kWh)	0.19 (kg/kWh)	
	1.06 (kg/kWh)	-	0.77 (kg/kWh)	-	-	-	-	0.11 (kg/kWh)	0.75 (kg/kWh)	0.09 (kg/kWh)	
	1.08 (kg/kWh)	-	0.76 (kg/kWh)	-	-	-	-	0.1 (kg/kWh)	0.67 (kg/kWh)	0.13 (kg/kWh)	
	-	-	0.6 (kg/kWh)	-	-	-	-	0.22 (kg/kWh)	-	-	

Table 5. Disaggregated cost of electric vehicle battery structure elements.

Ref	Al	Cu	Fe	Li	Ni	Co	Mn
[49]	-	-	-	-	208,000 (IDR/kg)	832,000 (IDR/kg)	48,000 (IDR/kg)
[50]	2.6 ($/kg)	9.1 ($/kg)	0.435 ($/kg)	70.29 ($/kg)	13 ($/kg)	49 ($/kg)	0.0052($/kg)

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[58]	2,658 ($/Ton)	9,688 ($/Ton)	90.5 ($/Ton)	30,930 ($/Ton)	20,171($/Ton)	61,550($/Ton)	5.4 ($/Ton)

4. Discussions

The comparative evaluation of different EV/HEV battery chemistries provides essential insights into their technical performance, recyclability, and sustainability, especially in the context of increasing global efforts towards a circular economy. Based on the collected data, Lithium Nickel Manganese Cobalt Oxide (NMC) and Lithium Iron Phosphate (LFP) batteries emerge as prominent contenders, each offering distinct characteristics in terms of energy density, environmental impact, and economic viability during recycling.

4.1. Energy Density and Technical Performance

One of the primary considerations in battery technology is the energy density, which directly influences the vehicle's driving range and overall efficiency [68]. Among the studied chemistries, NMC batteries show the highest energy density values, making them particularly suitable for long-range electric vehicles. Their high specific energy (ranging between 150-220 Wh/kg) enables automotive manufacturers to design vehicles that require fewer battery modules for a given range, thus optimizing space and weight.

Conversely, LFP batteries offer lower energy density values, generally in the range of 90-160 Wh/kg. Although this is a limitation for high-performance electric vehicles, LFP batteries compensate with superior thermal and chemical stability, longer cycle life, and greater resistance to thermal runaway. These attributes make LFP batteries particularly attractive for applications such as buses, commercial fleets, and lower-range passenger vehicles where safety, longevity, and cost take precedence over high range.

4.2. Recycling Efficiency and Metal Recovery

The recyclability of batteries is increasingly critical given the finite nature of raw materials like cobalt, nickel, and lithium. The study indicates that NMC batteries exhibit higher recovery rates for critical metals, with cobalt and nickel recovery efficiencies often exceeding 90% in optimized recycling processes such as hydrometallurgical treatment [69,70]. However, lithium recovery remains notably lower, typically ranging between 70-85%, due to its dispersion in the electrode materials and the technical challenges associated with its selective extraction.

In contrast, LFP batteries pose a different scenario. The absence of high-value metals such as cobalt and nickel simplifies the chemical processes involved in recycling but simultaneously reduces the economic incentive for recycling operations. While iron and phosphate recovery is technically achievable, the lower market value of these elements compared to cobalt and nickel results in a weaker economic case. Therefore, LFP battery recycling strategies often focus more on the recovery of lithium and the reuse of cathode materials rather than elemental extraction.

4.3. Environmental Impact and Process Conditions

The environmental burden associated with battery recycling is heavily influenced by the process conditions required for material recovery. NMC batteries, with their complex material compositions, often require high-temperature treatments (pyrometallurgy) or chemical-intensive methods (hydrometallurgy) for effective material recovery. These processes, although efficient in terms of metal yield, are energy-intensive and may generate hazardous waste streams if not carefully managed [71,72].

LFP batteries, owing to their simpler material composition and absence of heavy metals, can be recycled through less intensive processes, leading to potentially lower environmental impacts. For instance, direct recycling methods, which aim to recover entire cathode structures rather than elemental metals, are more feasible with LFP batteries and offer significant energy savings.

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Nonetheless, the widespread adoption of such methods requires advancements in sorting, pre-treatment, and process optimization to ensure high material purity and performance.

4.4. Cost Considerations and Economic Viability

The economic viability of recycling is a complex function of material value, processing costs, and market demand. NMC batteries, due to their high cobalt and nickel content, generally offer greater revenue potential per ton of recycled material [73]. However, the high complexity of the recycling process - involving multiple stages of disassembly, chemical leaching, and material purification - increases operational costs significantly.

On the other hand, LFP batteries, with their lower intrinsic material value, often result in a net negative economic outcome when processed through traditional recycling methods. The low market price of recovered iron and phosphate compared to cobalt and nickel diminishes profitability. Consequently, innovative business models, such as battery second-life applications before recycling, or government subsidies for recycling non-valuable materials, may be necessary to make LFP recycling economically sustainable.

4.5. Safety Considerations: State of Charge (SOC) and Thermal Stability

The State of Charge (SOC) parameters are crucial for both the operational safety of batteries and their handling during end-of-life processing. Batteries that operate within narrower SOC windows tend to exhibit greater stability but at the expense of reduced effective energy usage. The data indicates that LFP batteries maintain excellent thermal and electrochemical stability even at high states of charge, significantly reducing the risk of fire or explosion during transportation, storage, and recycling [74,75].

In comparison, NMC batteries, while offering higher energy densities, are more sensitive to overcharging and high temperatures. This necessitates stringent safety protocols during collection, transportation, and dismantling stages of recycling operations, including pre-discharge procedures, thermal monitoring, and specialized packaging.

4.6. Strategic Implications for Future Battery Design and Recycling

Given the EU’s Green Deal targets, the "Fit for 55" package, and other global regulatory frameworks, the future of EV battery design must be tightly linked to end-of-life management strategies. Eco-design principles - designing batteries for easier disassembly, standardized component labeling, and modular construction - will be key enablers of more efficient recycling [76,77].

Furthermore, developing "closed-loop" recycling systems, where recovered materials are directly reintroduced into the battery production supply chain, will be essential for reducing dependence on virgin raw materials. This is particularly important for critical materials such as cobalt and lithium, whose geopolitical supply chains are subject to significant volatility.

For NMC batteries, efforts should focus on improving lithium recovery rates and developing more environmentally benign recycling methods. For LFP batteries, innovations in direct recycling technologies and second-life applications (e.g., stationary energy storage) can enhance their economic and environmental profile.

4.7. Policy and Market Dynamics

Public policies and market mechanisms will play a decisive role in shaping the recycling landscape. Extended Producer Responsibility (EPR) regulations, mandatory recycling targets, and recycling content requirements for new batteries are likely to become more stringent. Financial incentives, subsidies for recycling infrastructure, and penalties for non-compliance will further influence manufacturers' choices regarding battery chemistry and design [79,79].

In particular, mandating minimum recovery rates for lithium and other critical materials can drive technological innovation in recycling processes. Similarly, establishing certification schemes for recycled materials can build trust among battery manufacturers and stimulate demand for secondary raw materials.

4.8. Processing

The new dataset offers a comprehensive examination of the concentrations and specific energy values (expressed in kg/kWh or g/kWh) of various elements (C, Al, Cu, Fe, Ag, Au, Pd, Li, Ni, Co, and Mn) across different samples (N = 1 to 19). This rich dataset enables a more detailed analysis of material compositions, particularly important for applications like battery recycling, metallurgical recovery, and energy storage systems.

4.8.1. General Overview

The dataset reveals that elements such as aluminum (Al), copper (Cu), lithium (Li), nickel (Ni), cobalt (Co), and manganese (Mn) are frequently present and show relatively significant concentrations across various samples. Elements like silver (Ag), gold (Au), and palladium (Pd), although present in smaller amounts, are nonetheless important due to their high economic value and critical role in electronic and catalytic applications.

In the first part of the dataset (N = 1-6), elemental concentrations are presented without energy normalization. These raw concentration values provide the initial mass content in different materials or components. Starting from sample N=7, the values are normalized based on energy output (kg/kWh or g/kWh), providing insights into the specific material intensity per unit of generated or stored energy. This transition is crucial for assessing the environmental impact and sustainability of energy systems.

4.8.2. Elemental Trends and Highlights

- **Carbon (C):**

  Carbon values are reported only sporadically. For instance, in sample 4, C is measured at 1.6%, while sample 5 shows a high value of 22.44%. Carbon concentration appears strongly associated with organic or polymeric materials rather than metallic systems.

- **Aluminum (Al):**

  Aluminum shows consistent presence across the samples, notably with 36.6% in sample 4. In energy-normalized data (N=7 onwards), Al concentrations vary between 0.075 kg/kWh and 0.457 kg/kWh. These results emphasize aluminum's crucial role, likely due to its application in casings, connectors, and structural supports within battery modules.

- **Copper (Cu):**

  Copper concentrations are notably high, peaking at 21.6% in sample 1 (second row). In energy-normalized terms, copper shows considerable variance from 0.075 kg/kWh to 0.758 kg/kWh across different energy scenarios, reflecting its extensive use in conductors, wiring, and battery current collectors.

- **Iron (Fe):**

  Iron is notably present in raw form (e.g., 18.2% in sample 1), but fewer energy-normalized values are reported for Fe. Its lower representation in energy-specific terms suggests that Fe, although important, is less critical when viewed from a performance-to-weight ratio perspective compared to elements like Li or Ni.

- **Silver (Ag) and Gold (Au):**

  Ag and Au show very small mass percentages, often around 0.001% to 0.06%. Despite low concentrations, their strategic value in electronics and catalysis makes them noteworthy. Au reaches up to 0.393% in some entries, highlighting selective opportunities for targeted recovery.

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- **Palladium (Pd):**

  Pd is significant particularly in sample 1 (24.3% and 71.9% in different entries). These figures suggest a specific type of sample, possibly related to catalytic components, where Pd is heavily used.
- **Lithium (Li):**

  Lithium appears from sample 4 onwards with energy-normalized values starting at 0.084 kg/kWh and going as high as 1.21 kg/kWh. Sample 16 highlights lithium contents in grams per kWh (e.g., 176.3 g/kWh to 410.5 g/kWh), revealing lithium's central role in battery energy densities.
- **Nickel (Ni) and Cobalt (Co):**

  Nickel and cobalt concentrations track each other closely. For example, in N=7 and N=18 samples, values like 0.759 kg/kWh (Ni) and 0.394 kg/kWh (Co) appear together, matching the stoichiometric ratios found in common battery chemistries like NMC (Nickel-Manganese-Cobalt) batteries.
- **Manganese (Mn):**

  Mn content, particularly in sample 17, reaches 26.02%, emphasizing manganese's contribution to stabilizing the structure of battery cathode materials and improving cycling stability.

4.8.3. Observations on Energy-Normalized Values

Energy-normalized datasets provide critical insight into resource intensity per energy unit, important for life cycle assessments (LCA). Key observations include:

- The highest normalized mass concentration across the samples is associated with lithium (Li) and manganese (Mn).
- For instance, sample 16 shows 410.5 g/kWh lithium content, suggesting a lithium-rich energy storage solution, likely associated with high-energy-density battery chemistries (e.g., LCO or NMC batteries).
- Nickel and cobalt display typical co-dependence, reflecting modern trends in battery technology where high-nickel cathodes (like NMC811) are increasingly preferred for their higher energy density despite their higher cost and environmental impact.

4.8.4. Trends Across Samples

Analyzing the variation from samples 7 to 19 reveals gradual shifts:

- In earlier samples (N=7 to N=11), moderate values of Al, Cu, and Fe dominate, suggesting a mix of structural and conductive material focus.
- Samples 15–18 show more emphasis on active materials, particularly lithium, nickel, and cobalt, implying a shift from supporting structures to the active battery core materials.
- Sample 19 reveals relatively consistent normalized values for C, Cu, and Li, hinting at a stable design focused on performance consistency, possibly from a standardized battery cell production line.

4.8.5. Implications for Recycling and Sustainability

The heavy presence of aluminum, copper, lithium, nickel, cobalt, and manganese suggests that recycling efforts should prioritize these elements to maximize resource recovery and economic feasibility. The small quantities of precious metals (Au, Ag, Pd) remain attractive due to their high market value despite their low concentration.

Additionally, the normalized data allows evaluation of material criticality in future battery designs. High cobalt and nickel content may face supply chain risks and environmental concerns. Therefore, alternative chemistries like LFP (Lithium-Iron-Phosphate) that eliminate cobalt entirely may become more desirable, despite the trade-offs in energy density.

Conclusion

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This systematic review provides a comprehensive analysis of recent developments in the field of electric vehicle battery (EVB) recycling, focusing on technological progress, persisting challenges, and future opportunities. Covering studies published between 2020 and April 15, 2025, this work captures a critical period of growth, innovation, and policy-driven urgency aligned with global sustainability goals, particularly within the context of decarbonization, circular economy adoption, and the Fit for 55 and EU 2030 objectives.

The results reveal that while significant strides have been made in the development of battery energy storage systems (BESS) and material recovery technologies, several gaps and inefficiencies still hinder large-scale, economically viable, and environmentally sustainable recycling efforts. Lithium, cobalt, nickel, and manganese remain the primary focus in most studies due to their high commercial value and critical role in cathode chemistry. Technologies such as hydrometallurgy and pyrometallurgy continue to dominate, but newer methods-including direct recycling and bioleaching-are gaining traction for their potential to reduce energy consumption and environmental harm.

From the data reviewed, a consistent theme emerges around the inefficiency of current material recovery processes when scaled beyond laboratory settings. Energy consumption per kilogram of material recovered often exceeds sustainability thresholds when not optimized through integrated BESS or renewable-powered processing systems. Additionally, many studies emphasize that the carbon footprint of recycling operations must be critically examined to ensure that the process genuinely contributes to decarbonization goals.

One of the clearest challenges identified in this review is the lack of standardization in battery design, which directly complicates the disassembly, sorting, and material recovery stages. Variability in chemistry (e.g., LFP vs. NMC), packaging, and manufacturing methods results in technical difficulties and cost inefficiencies. Furthermore, the absence of harmonized regulatory frameworks across regions creates barriers to cross-border collaboration and investment in recycling infrastructure.

At the same time, significant opportunities are evident. The use of artificial intelligence and machine learning to optimize disassembly, predict battery health, and automate sorting is a rapidly evolving area with strong promise. Moreover, second-life applications for EV batteries-particularly in stationary storage systems-present an underutilized yet practical approach to extending battery lifespan and reducing waste. This dual benefit supports both grid stabilization and energy access, especially in remote or developing areas.

From a policy and economic standpoint, this review highlights the importance of extended producer responsibility (EPR) schemes, subsidies for recycling innovation, and stricter end-of-life regulations to incentivize investment and compliance. The European Union’s Battery Regulation, although still evolving, is a step in the right direction and may serve as a global benchmark for battery lifecycle governance.

In summary, while EV battery recycling technologies are progressing, the field is still in a transitional stage where large-scale, sustainable implementation remains limited. Overcoming the identified challenges-technical, economic, regulatory, and environmental-will require a multi-stakeholder approach involving governments, industry, academia, and consumers. The opportunity to establish a closed-loop battery economy is within reach but will depend on integrated innovation, policy coherence, and strategic investment. This review underscores the urgency and complexity of the task, while also pointing to a future where battery recycling becomes not only feasible but foundational to the sustainable energy transition.

CRediT authorship contribution statement. Hamid Safarzadeh: Writing, Investigation, Methodology, Investigation, Formal Analysis, Writing, Validation. Francesco Di Maria: Original draft, Validation, Formal analysis, Conceptualization.

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Nomenclature

BEV	Battery Electric Vehicle
BMS	Battery Management System
BESS	Battery Energy Storage System
Co	Cobalt
EV	Electric Vehicle
EOL	End of Life
LIB	Lithium-Ion Battery
Li	Lithium
LFP	Lithium Iron Phosphate
LCO	Lithium Cobalt Oxide
LMO	Lithium Manganese Oxide
Li-NMC	Lithium Nickel Manganese Cobalt Oxide
Li-NCA	Lithium Nickel Cobalt Aluminum Oxide
Ni	Nickel
NMC	Lithium Nickel Manganese Cobalt Oxides
MHEV	Mild hybrid electric vehicle
Mn	Manganese
Pyrometallurgy	High-temperature process for metal recovery
Hydrometallurgy	Aqueous solution-based metal extraction
Direct Recycling	Recovery of battery components with minimal reprocessing
SOH	State of Health (battery degradation metric)
SOC	State of Charge
WEEE	Waste Electrical and Electronic Equipment Directive (EU legislation)
VOC	Volatile Organic Compounds
Circular Economy	Economic system aimed at eliminating waste and continual resource use

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