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Review

Sustainable management of electric vehicle battery remanufacturing: A systematic literature review and future directions

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ABSTRACT

The increasing adoption of electric vehicles (EVs) and the corresponding surge in lithium-ion battery (LIB) production have intensified the focus on sustainable end-of-life (EOL) management strategies (i.e., reuse, repurpose, remanufacture, and recycle). This paper presents a systematic literature review of the entire remanufacturing process of LIBs, aiming to offer a cohesive perspective on the approach that reduces the environmental impact of LIB waste by prolonging their lifecycle for reuse in their original EV applications. It reveals major issues from EOL collection to renewed batteries, clustering results into six research streams, and proposes a research agenda to develop integrative, data-driven models that incorporate technical, economic, and environmental considerations. Key findings highlight the need for standardised, non-damaging joining techniques, enhanced safety protocols for disassembly, and scalable cathode re-functionalisation methods. Recommendations include leveraging advanced technologies such as AI, machine learning, IoT, and blockchain to optimise remanufacturing processes and enhance supply chain transparency and efficiency. This comprehensive review aims to foster the development of sustainable remanufacturing practices, contributing to the circular economy and supporting the growth of the EV industry.

1. Introduction

The rise in social awareness regarding environmental issues, the introduction of legislation aimed at reducing CO_2 emissions, and significant technological advancements in the automotive sector towards electric propulsion have led to a substantial increase in the sales of electric vehicles (EVs) [1]. Electrification is seen as key to decarbonising transport, with increasing investments in EVs and incentives for zero-emission and low-emission vehicles [2]. This trend is likely to continue, reaching 17 million EVs sold worldwide, indicating that the future of mobility will increasingly rely on the electrification of transport [3]. The growth in global EV sales (see Fig. 1) has resulted in an increase in the production and sale of batteries, which are crucial for energy storage. Policymakers are advancing storage incentives and fossil fuel phase-out to meet net-zero policy targets. In 2023, nearly 45 million EVs on the road contributed to alleviate the need for 8 million barrels of oil per day [3].

The most commonly used type is the lithium-ion battery (LIB), which currently represents the most expensive component of an EV [4]. Due to their advantageous electrochemical properties over other chemistries [5], LIBs are often regarded as the top choice for commercial applications, since the development of rechargeable LIBs in the early 1990s [6]. Respect to Lead-Acid and Nickel Metal Hydride batteries, the other two technologies dominating the EV sector, the LIBs provide the highest energy and power densities and longer lifecycle, relatively less pollution and lighter cell designs; in addition, they can incorporate smart management systems for safety applications [7,8]. Despite the present high cost of the LIBs, research trends indicate a potential considerable reduction to a range of $ 100–200 per kWh, making LIBs the preferred option for EV applications [9]. LIBs generally contain a graphitic carbon anode and a cathode composed of materials like lithium cobalt oxide, separated by a liquid organic electrolyte, polymer separator, and current collectors [10]. Graphite has been the leading anode material for the past two decades due to its availability, affordability, and moderate energy density. In contrast, lithium titanium oxide (LTO) anodes, although more expensive, offer higher volumetric capacity and longer lifespans. The choice of cathode material varies based on specific application requirements, including energy density, power density, cost, and durability. The electrolyte, facilitating the movement of Li-ions between the cathode and anode during charging and discharging, is typically made from organic compounds such as propylene carbonate, ethylene carbonate, and di-methyl

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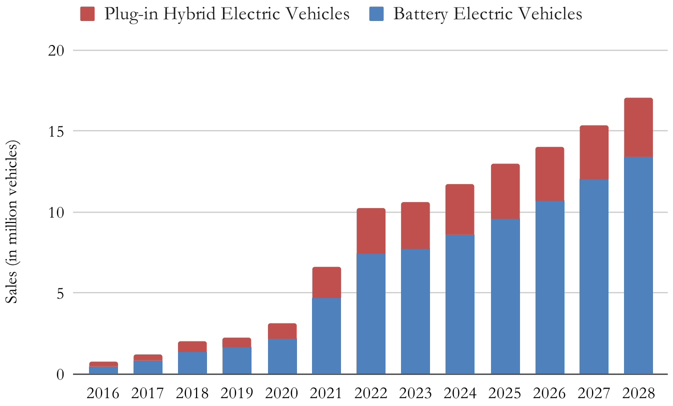

Fig. 1. EV global sale, by type.
Source: Statista Market Insights.

carbonate in EVs, though these substances come with safety risks. Solid-state electrolytes, in contrast, enable the creation of smaller, more compact batteries without compromising power or storage capacity, unlike liquid electrolytes, which lose efficiency when reduced in size and pose safety issues [11]. The separator, which holds the electrolyte, ensures ionic conductivity while preventing direct contact between the anode and cathode, thus avoiding short circuits and potential battery failures, including fire hazards. These separators are designed with pores specifically sized for Li-ions (20–25 μm), promoting efficient ion movement necessary for battery charging and discharging [12].

With the increased use of LIBs, there is rising concern about their management once they have reached the end-of-life (EOL) in EVs [13]. The management of LIBs at their EOL poses significant environmental challenges due to their hazardous components, including heavy metals and toxic and flammable chemicals [14]. An ignition hazard exists for LIBs disposed at landfills, recommending proper disposal routing [15] and safe handling and transportation [16]. If disposed at waste-to-energy facilities for incineration, the non-volatile metals (e.g. cobalt) may concentrate at the bottom of the ash and, during combustion process, the separator and electrolyte generate a large amount of harmful gases [17]. Given the significant rise in EV sales, a large quantity of batteries could soon be discarded, potentially generating between 250,000 and 350,000 tons of waste by 2025 [18,19]. On the other hand, a total capacity of returning battery systems of about 200 GWh is expected in Europe by 2030, representing significant market growth and enabling companies in the battery circular economy to have a higher market presence [20]. In this context, proper policies and regulatory frameworks are essential to support and incentivise efficient reverse supply chains [21], while facilitating the information exchange along the whole value chain [22], taking into account the potential hazard of managing the LIBs [23], and assigning responsibility for recycling [24].

The surge in LIB demand is driving up the extraction of raw materials such as nickel, cobalt, and lithium [25]. In 2019, most cobalt available worldwide was extracted in Congo [26]. Therefore, the LIB supply chain is also at high risk of disruption, primarily due to dependency on dominant suppliers, which could result in future supply shortages [27]. Like any other vehicle component, LIBs deteriorate over time and with use. Automobile manufacturers recommend replacing them when they reach 80% of their state of health (SOH), as they are no longer deemed adequate for their intended function despite retaining much of their residual capacity. Therefore, batteries cannot endure the average lifespan of conventional vehicles (i.e., 15 years) [28]. Recovering EV batteries presents a sustainable solution to mitigate long lead times caused by unreliable and complex supply chains. Implementing circular strategies is crucial to reducing manufacturing impacts, focusing on resource efficiency, prolonging product use, and facilitating recycling [29,30]. Remanufacturing is one of the three major strategies, along with reuse and recycling. Reuse can be direct or indirect, depending on the final sector where the battery will be exploited: primary, secondary, or tertiary (also called repurpose) applications. Remanufacturing is particularly interesting because it enables primary application even if the battery's SOH does not allow it, by replacing damaged cells [31]. Remanufacturing spent LIBs can lessen environmental impacts and guard against price spikes in critical materials like cobalt and nickel [32]. Fig. 2 illustrates the lifecycle of an LIB in an EV, detailing the progression from raw material extraction to EOL management, including reuse, remanufacturing, and recycling. Initially, raw materials are processed into battery components, cells, modules, and finally battery packs, which are then integrated into vehicles. Upon reaching the end of their first life, batteries can be reused, remanufactured, or recycled. Reuse involves disassembly, cleaning, inspection, replacement of damaged parts, reassembly, and quality testing for second-life applications. Remanufacturing follows a similar process but aims to restore batteries for further vehicle integration and use. Recycling involves disassembly and material recovery to reintegrate valuable components into the production cycle, thereby promoting sustainability and resource efficiency.

Several previous reviews focused on LIB recovery through the circular approach. Specifically, these reviews target process and technology comparisons among recycling, remanufacturing, and repurposing approaches, Life Cycle Assessment (LCA) analysis for EOL strategies, and current innovations in particular stages of the remanufacturing process (e.g., robotic disassembly). For instance, Hua et al. [17] emphasise the importance of a systematic approach to managing EOL LIBs by proposing the 5R principle (reduce, redesign, remanufacture, repurpose, and recycle). This review highlights the need for advanced technologies and improved regulation to create a sustainable circular value chain. Similarly, Lai et al. [33] evaluate the environmental impacts of battery production, usage, secondary utilisation, and recycling by presenting an LCA study.

Furthermore, several studies focus on the technical aspects of disassembling EV batteries, particularly the integration of robotic systems. For example, Kaarlela et al. [34] and Rettenmeier et al. [35] review the current state of robotic disassembly technologies. They explore the role of artificial intelligence and human–robot collaboration in improving efficiency and safety and recognise standardised design and safety issues in handling processes as significant challenges for industry and policymakers. Additionally, Xie et al. [36] provide a comprehensive analysis of battery SOH estimation strategies, focusing on data-driven methods. This review discusses various dimensions of SOH estimation, including dataset integration, health feature parameter extraction, and SOH estimation model construction. It highlights future directions for SOH assessment, including the development of segmented management approaches and the integration of cloud computing technologies.

Moreover, Tarrar et al. [37] discuss the importance of efficient recovery processes for EOL vehicles and their components, identifying batteries as a critical area. This study emphasises the need for investments in disassembly infrastructure and workforce development to improve the overall efficiency of vehicle end-of-life management. In addition, Xia and Li [38] compare the environmental impacts of EVs and internal combustion engine vehicles, highlighting the significant environmental benefits of repurposing and remanufacturing retired batteries. The study underscores the need for optimising power structures, upgrading battery technologies, and improving recycling efficiency to support the large-scale promotion of EVs.

Existing research on LIB remanufacturing often focuses on specific aspects like circular economy approaches, lifecycle impacts, and technical stages such as disassembly and SOH estimation. However, there is a lack of comprehensive reviews that cover the entire remanufacturing process from start to finish. Many studies provide valuable insights into individual steps but fail to integrate these into a complete remanufacturing pipeline from initial collection to final testing. This fragmented

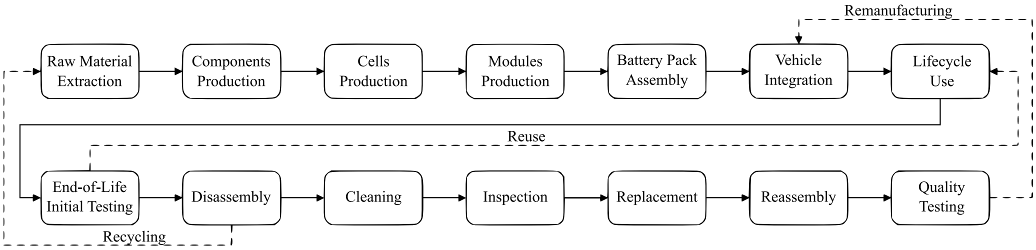

Fig. 2. Simplified remanufacturing strategy.

Table 1
Table of acronyms.

Acronym	Description
AR	Augmented Reality
BMS	Battery Management System
DM	Degradation Mechanism
EOL	End-of-Life
EV	Electric Vehicle
IoT	Internet of Things
LCA	Life Cycle Assessment
LIB	Lithium-Ion Battery
OCV	Open Circuit Voltage
OEM	Original Equipment Manufacturer
RUL	Remaining Useful Life
SEI	Solid Electrolyte Interface
SOC	State of Charge
SOH	State of Health

approach misses opportunities to optimise the overall process for maximum environmental and economic benefits. A comprehensive review is needed to synthesise existing knowledge, identify gaps, and provide a roadmap for future research and practical implementations, ensuring the sustainable growth of the EV industry. Thus, the main contributions of this research are: (1) to perform a systematic literature review encompassing articles from 2012 to 2024, (2) to uncover major issues during the remanufacturing process from EOL collection to renewed battery, and (3) to cluster results into different research fields considering topics and stages.

According to this gap, this article presents a systematic literature review structured as follows. Section 2 explores the remanufacturing process and its associated challenges, including technical, economic, and environmental issues. Section 3 details the materials and methods used in the literature review. Section 4 presents the review results, highlighting major research fields and key findings from the reviewed literature. Section 5 discusses the retrieved literature focuses, providing a research agenda. Finally, Section 6 provides conclusions and recommendations, summarising insights and suggesting future research directions. Table 1 contains a summary of acronyms.

2. Overview of remanufacturing process

Currently, Europe has negligible LIB production, mainly relying on Asia. To reduce dependence on concentrated production and foreign imports, there is a surge in battery factories, particularly in Europe, where manufacturing capacity is projected to reach 960 GWh by 2030, accounting for 33% of global capacity. In 2023, the global LIB capacity exceeded 2.8 TWh, with China contributing about 70% of the world's annual LIB capacity. In Europe, Germany was the largest market, with 150.8 GWh of LIB capacity, accounting for roughly 5.4% of the total capacity, as presented in Fig. 3.

Despite this increase, Europe will still rely on primary materials from Asia [39]. Therefore, among different EOL practices for EV batteries (i.e., reuse, remanufacturing, and recycling), remanufacturing can become an interesting alternative to capitalise on the great number of EVs sold [40]. Remanufacturing focuses on restoring the entire battery to its original condition, as opposed to refurbishment or retrofitting, which target individual components for upgrade or repair. This process involves restoring LIBs to a condition where they can be reused in their original applications. Studies indicate that remanufacturing can be cost-effective, offering savings of about 40% compared to new battery production [38,41]. The flowchart in Fig. 4 illustrates the lifecycle and potential EOL pathways for LIBs. Initially, the process begins with the extraction of raw materials required for battery production. These raw materials are processed into various components of the battery, which are then assembled into individual cells. These cells are further assembled into modules, and the modules are assembled into complete battery packs. These battery packs are integrated into electric vehicles, where they are used until they reach the end of their useful life.

LIBs are packs of modules, which are combinations of cells [43]. Cells have different geometries and sizes, such as cylindrical, prismatic, or pouch cells, significantly influencing the space arrangement and overall pack design. Electrical connections within the pack enable the flow of current and the monitoring of temperature and voltage through integrated sensors. Structural connections secure the cells and modules in place, maintain proper internal pressure, and isolate the pack from external environments. Thermal management is achieved through various cooling and heating systems, which can be passive or active, and air or liquid-based, ensuring the battery operates within safe temperature ranges. The external case of the pack provides protection against mechanical stresses, pollution, and vibrations, contributing to the pack's stability and longevity [44].

LIB displacement can be associated with multiple scenarios: ancillary failure (i.e., internal system failure), battery pack/module performance degradation, and crash-driven damages [45]. The battery remanufacturing process starts at the collection facility, where it is checked and sorted. The handling process must minimise the chances of damage [28]. LIBs are classified as Category 9 hazardous materials due to their unstable thermal and electrical properties, as well as the risks of thermal runaway [46]. At the end of their lifecycle in vehicles,

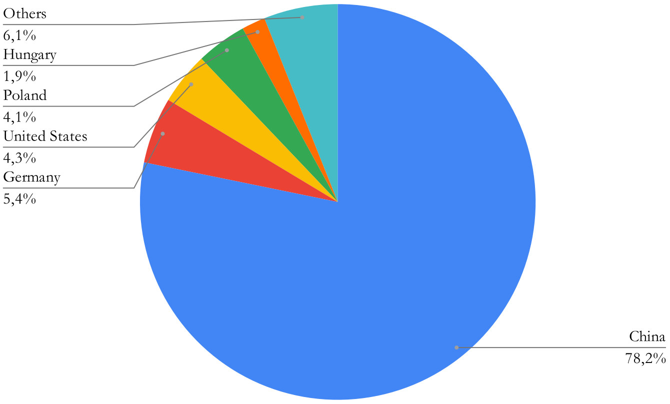

Fig. 3. LIB capacity [GWh], by country.
Source: S&P Global Market Intelligence (July 27, 2023).

batteries are collected for further processing. They undergo a physical inspection to determine their condition. The logistics for the collection of used LIBs towards refurbishment centres require safe handling and storage.

Initially, the LIB must undergo a visual assessment for surface defects [45]. If the batteries are found to be intact (not damaged), they proceed to initial testing. Damaged batteries are directed towards disassembly for recycling. To be suitable for remanufacturing, batteries must exhibit good health (State of Health, SOH) and meet all Original Equipment Manufacturer (OEM) specifications for power, energy, and cycle life. There is no universally accepted definition of SOH, and researchers usually define it based on either the reduction in capacity or the increase in internal resistance, as presented in Eqs. (1)–(2). C_i and C_0 represent the current maximum usable capacity and the initial rated capacity of the battery, respectively, while R_i, R_e, and R_0 denote the current cycle test internal resistance, the internal resistance at retirement, and the initial internal resistance, respectively.

$$SOH = \frac{C_i}{C_0} \times 100\% \tag{1}$$

$$SOH = \frac{R_e - R_i}{R_e - R_0} \times 100\% \tag{2}$$

The collected batteries undergo initial testing to assess their SOH. Batteries with an SOH greater than 90% are suitable for direct reuse, while those with an SOH greater than 80% are suitable for direct repurposing. Batteries with an SOH below 80% proceed to further disassembly and testing. Disassembly planning for EV batteries encompasses several critical issues: creating an accurate representation of the product, devising effective disassembly sequences, and identifying the best disassembly sequence and level [28]. For recycling or remanufacturing purposes, battery packs are disassembled into modules, which are then tested individually. Modules with an SOH greater than 85% are sorted and reassembled into battery packs. Modules with an SOH below 85% are further disassembled into individual cells. The cells undergo testing, and those with an SOH greater than 50% are sorted and reassembled into modules. Cells with an SOH below 50% are considered for final recycling.

Disassembling LIBs poses both safety and economic challenges. This process includes several stages, such as opening the battery pack's casing in a controlled environment to minimise oxidation, disconnecting mechanical and electrical links between cells, and removing auxiliary electronic components. This disassembly process is inherently risky and requires specialised skills and equipment. Currently, the disassembly process is performed manually. Detachable connectors, modular housing for easy cell replacement, and pluggable peripheral components enhance worker safety by simplifying disassembly, unlike challenging joining technologies such as gluing or welding [43].

After removing the defective cells, replacement cells are sourced and installed. This step requires precision to ensure that the new cells are compatible with the existing ones and meet the OEM specifications. Once the cells are replaced, the battery pack is reassembled. Reassembly involves reconnecting the cells and securing the battery pack's structural integrity. Reassembled modules that pass testing are then reassembled into battery packs. These reassembled battery packs undergo final testing to ensure quality before being put back into use. The reassembled battery pack then undergoes rigorous quality testing to ensure it meets all safety, performance, and durability standards. Testing includes checks for electrical performance, thermal stability, and overall reliability. Once the battery pack passes these quality tests, it is packaged appropriately to protect it during storage and transportation. Finally, the remanufactured battery is stored in inventory, ready for distribution and reuse in its original or similar applications. This comprehensive remanufacturing process not only extends the life of LIBs but also contributes to resource efficiency and sustainability. One key challenge is the diverse shapes and features of LIBs, which complicate the standardisation of remanufacturing processes. Addressing this issue requires designs that prioritise modularity and ease of disassembly. Optimised design for second-life applications can enhance suitability [43].

Reassembly is another critical phase, necessitating the involvement of original manufacturers to ensure compliance with OEM standards. The remanufacturing process encompasses diagnostic testing, partial disassembly of battery packs, replacement of damaged cells or modules, and reassembly into new battery packs. Given the complexity and time-consuming nature of the diagnostic step, employing machine learning techniques to analyse sensor data is beneficial. These methods lower costs and enhance the remanufacturing process by providing accurate SOH and lifespan predictions.

3. Methodology

The article retrieval is accomplished by querying two scientific search engines: Scopus and Web of Science, due to their comprehensive coverage of peer-reviewed journals and high-quality conference proceedings. The analysis selected the most important works published between 2012 and 2024. In the initial phase, search strings

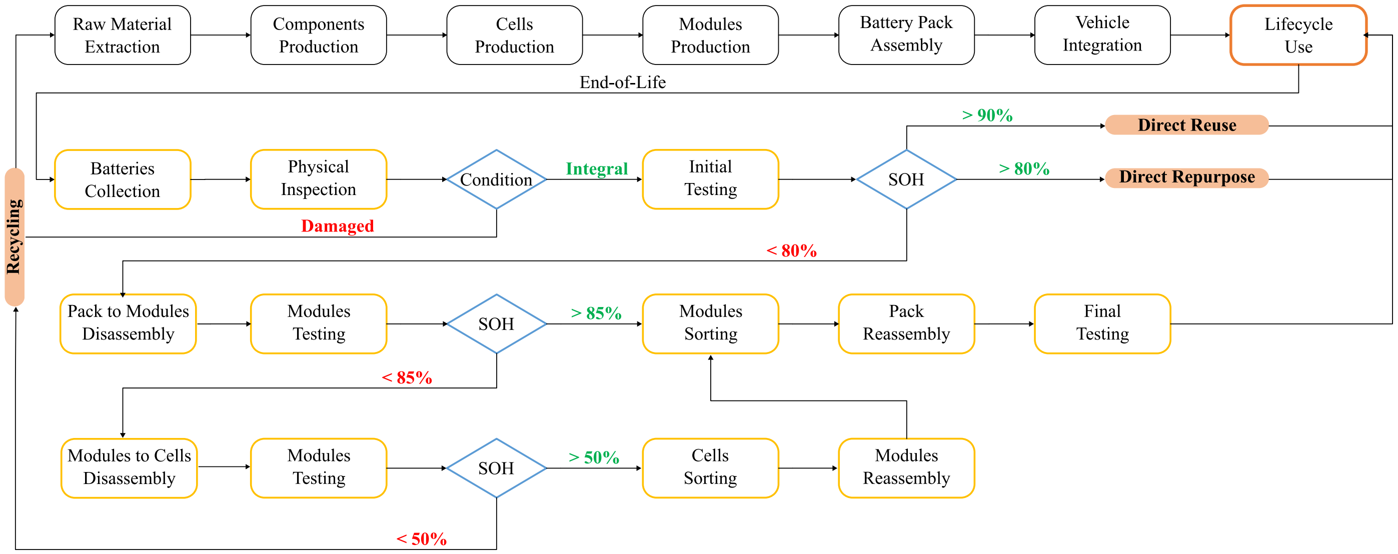

Fig. 4. Remanufacturing process [42].

Table 2
Keywords used for searches in databases.

N°	Keyword	Boolean operator
1	Electric vehicle batter*	OR
2	EV batter*	OR
3	LIB*	OR
4	Lithium ion batter*	AND
5	Remanufacturing	

included a set of keywords (Table 2) composed by Boolean juxtaposition to target vehicle battery articles associated with recovery by remanufacturing. Only one synonym has been used for remanufacturing since it prioritises the finished product, as opposed to refurbishment or retrofit, which focus on exchanging, modernising, or repairing individual components.

The inclusion criteria targeted studies published within the last 12 years, written in English, and providing empirical data on remanufacturing processes, technological advancements, economic assessments, environmental impacts, or regulatory implications. Eligible publications included peer-reviewed journal articles, conference papers, and review articles that specifically focused on LIB remanufacturing and were relevant to key industry segments such as EV. Exclusion criteria were applied to exclude studies that did not address LIB remanufacturing, lacked empirical evidence, were outdated, written in languages other than English, were duplicates, or contained insufficient data or unclear conclusions. The article selection and screening process, detailing each step, is presented in Fig. 5.

The final article set includes 62 journal papers and 20 conference papers. For each article, data were extracted and organised in a spreadsheet to make graphs for visualising bibliometric insights. Fig. 6 presents the temporal distribution of papers, while Fig. 7 shows publishing sources and academic journals. There is a clear upward trend in publication numbers over the years, with significant peaks in 2020 and 2023, each exceeding 18 papers. Notable increases are also seen since 2020, reflecting growing academic interest and research activity in the field.

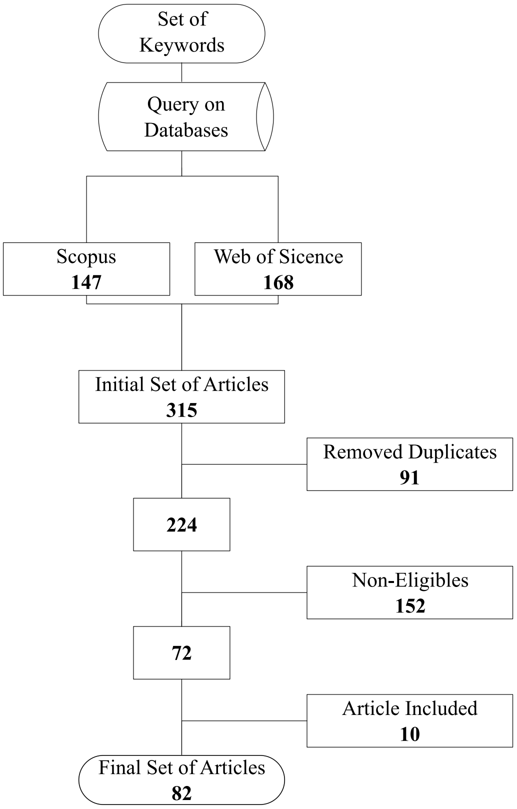

Fig. 5. Selection of articles.

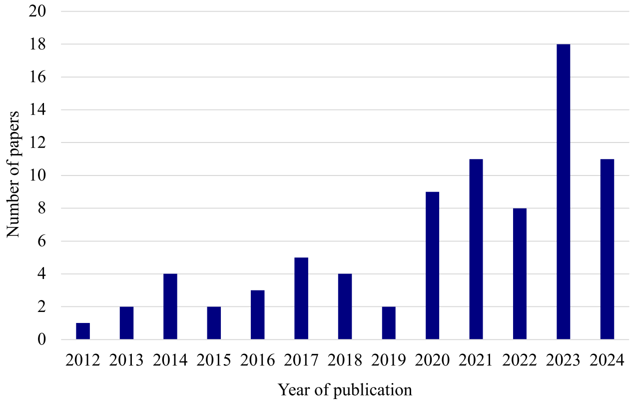

Fig. 6. Paper classification per year of publication.

Elsevier is the most prolific, with around 30 papers, followed by *Springer* with approximately 12 papers, and *MDPI* with 9 papers. *IEEE*, *Cell Press*, *SAE International*, and *OmniaScience* each have a smaller but notable number of publications. Other publishers, including *Wiley*, *Trans Tech Publications*, and *Taylor & Francis*, contribute fewer papers, ranging from one to five.

The *Journal of Cleaner Production* leads with five papers, followed by *Resources, Conservation and Recycling* and *Journal of Remanufacturing* with four papers each. Other notable journals include *Joule*, *Energies*, and *Waste Management*, each with three papers. The remaining journals, such as *Applied Energy*, *Sustainability*, and *Advanced Materials Research*, among others, have one or two papers each. A concentration of papers is noticed among journals focusing on sustainability, manufacturing, and energy.

4. Results

Following the research aim, the categorisation of the articles included in the review is defined according to their target topics. The articles are not confined to a single research stream; instead, each can belong to multiple streams due to their broader aim and scope. This categorisation was developed based on a broad review of the existing literature, focusing on those key areas where significant advances, combined with challenges, have become obvious. These categories

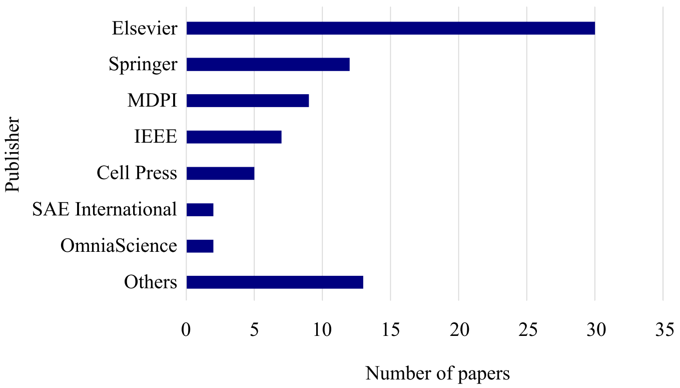

Fig. 7. Journal article classification per publisher.

represent the multifaceted nature of remanufacturing, ranging from purely technical issues to more general concerns.

Six research streams capture the focuses of current research on the remanufacturing of EV batteries:

- S1 — Battery design: Focuses on the development and standardisation of battery components to facilitate easier disassembly and remanufacturing.
- S2 — Disassembly processes and technologies: Examines the methods and technologies used in the disassembly of EV batteries, including automation and safety considerations.
- S3 — Cathode restoration and re-functionalisation: Investigates techniques for restoring and re-functionalising cathodes from end-of-life batteries to extend their usability.
- S4 — Diagnostic and screening methods: Explores methods for assessing the SOH and remaining useful life (RUL) of batteries to determine their suitability for remanufacturing.
- S5 — Data sharing and transparency: Addresses the need for effective data sharing frameworks and transparency throughout the battery lifecycle to improve decision-making in remanufacturing.
- S6 — Supply chain design and government policies: Discusses the design of supply chains for battery remanufacturing and the impact of government policies and subsidies on promoting sustainable practices.

Table 3 details the match between papers and streams, where a tick indicates that the paper addresses the stream in the corresponding column. Multiple matches are possible, indicating a multi-perspective focus and partial overlaps among the research streams. Furthermore, Table 3 lists articles by year, from past to present, allowing tracking the emergence and evolution of each topic in the literature. Some trends in the research streams come to light: specific battery-related technical subjects, namely battery design issues (S1) and cathode degradation mechanisms and recovery (S2), were mainly investigated at the beginning of the selected time frame, likely due to the developmental stage of the LIBs technologies. The diagnostic and screening procedures stream (S4) developed subsequent to S1 and S2. The disassembly procedures are determined by the battery design and develop as technology and digitalisation advance, keeping this issue relevant. Data sharing and an effective supply chain have long been acknowledged as critical components of a circular strategy, but data sharing raises security concerns and technological limits that have yet to be resolved, and value chain stakeholders have not been fully integrated. As a result, the disassembly process stream (S3), data sharing concerns (S5), and supply chain design issues (S6) continue to be explored throughout the term.

4.1. Battery design

In automotive applications, three cell shapes dominate the market: pouch, cylindrical, and prismatic hard-case cells. Among these, pouch cells are emerging as the preferred design due to their efficient use of space and 90%–95% packaging efficiency [28]. The main factors driving the variety of lithium-ion battery modules are installation space specifications, and power and energy requirements [61]. Standardising battery components reduces costs and improves quality in the separation and sorting of used LIBs, increasing their recovery potential [52]. This also enables cells from various sources to be tested and repacked into compatible groups [64]. Design-for-disassembly would enable the remanufacturing of LIBs, enhancing recovery [64]. A well-designed battery pack should be modular to facilitate the easy and safe disassembly and replacement of defective cells. Easily replaceable components can be designed with planned obsolescence to reduce costs and requirements. Peripheral components such as sensors, management systems, and cooling mechanisms should ideally be easily pluggable and connectable. However, automated disassembly is challenged by

Table 3
Literature review: research trend and stream classification.

Authors	Year	S1	S2	S3	S4	S5	S6	Ref.
Ramoni and Zhang	2012			x				[47]
Nong and Pang	2013						x	[48]
Ramoni and Zhang	2013	x		x				[28]
Ganter et al.	2014			x				[49]
Zhang et al.	2014				x			[50]
Wegener et al.	2015		x					[51]
Bauer et al.	2016	x						[52]
Groenewald et al.	2016					x		[45]
Hartwell and Marco	2016					x		[53]
Kampker et al.	2016	x						[43]
Liu et al.	2016			x				[54]
Kampker et al.	2017		x					[55]
Ramoni et al.	2017			x				[56]
Zhang et al.	2017			x				[57]
Groenewald et al.	2018				x			[58]
Li et al.	2018						x	[59]
Gu et al.	2018						x	[60]
Kampker et al.	2018	x						[61]
Okorie et al.	2018					x		[62]
Okorie et al.	2019					x		[63]
Alamerew and Brissaud	2020	x	x			x	x	[64]
Alfaro-Algaba and Ramirez	2020		x					[65]
Diani and Colledani	2020		x					[66]
Garrido-Hidalgo et al.	2020					x		[67]
Gentilini et al.	2020		x					[68]
Ke et al.	2020		x					[69]
Mossali et al.	2020	x						[44]
O’Hern et al.	2020		x					[70]
Rallo et al.	2020		x					[71]
Schäfer et al.	2020		x					[72]
Shi et al.	2020				x			[73]
Alipanah et al.	2021						x	[74]
Baazouzi et al.	2021		x					[75]
Casper and Sundin	2021	x			x			[76]
Deveci et al.	2021						x	[77]
Edge et al.	2021			x				[78]
Fleischer et al.	2021		x					[79]
Glöser-Chahoud et al.	2021		x					[80]
Gu et al.	2021						x	[81]
Gu et al.	2021						x	[82]
Kampker et al.	2021	x						[83]
Mowri et al.	2021				x			[84]
Wewer et al.	2021					x		[85]
Xiao et al.	2021		x			x		[86]
Zhu et al.	2021		x		x	x		[16]
Börner et al.	2022				x			[87]
Fan et al.	2022			x				[88]
Gastol et al.	2022			x				[89]
Huster et al.	2022						x	[90]
Luong et al.	2022		x					[91]
Pannala et al.	2022				x			[92]
Rajaeifar et al.	2022						x	[93]
Wenzhu Liao and Luo	2022						x	[94]
Wu et al.	2022		x					[95]
Zang and Wang	2022		x					[96]
Zhao and Behdad	2022				x			[97]
Chirumalla et al.	2023					x		[98]
Chu and Chen	2023		x					[99]
Garrido-Hidalgo et al.	2023					x		[100]
Graner et al.	2023	x						[101]
Kamath et al.	2023						x	[102]
Klohs et al.	2023		x					[103]
Lander et al.	2023	x						[104]
Phophongviwat et al.	2023		x					[105]
Schimanek et al.	2023	x	x					[106]
Shafique et al.	2023							[25]
Villagrossi and Dinon	2023		x					[107]
Xiao et al.	2023		x					[108]
Yang et al.	2023					x	x	[109]
Zhan et al.	2023		x					[110]
Chai et al.	2024						x	[111]
Gahlaut and Dwivedi	2024					x		[112]

(*continued on next page*)

Table 3 (*continued*).

Garrido-Hidalgo et al.	2024						[113]
Jiao et al.	2024	x					[114]
Kaarlela et al.	2024	x					[34]
Neri et al.	2024				x		[115]
Ogihara et al.	2024		x				[116]
Packianather et al.	2024	x					[42]
Qu et al.	2024	x					[117]
Tavana et al.	2024					x	[118]
Wu et al.	2024	x					[119]
Zhao and Pham	2024	x					[120]

the wide variety of module designs influenced by installation space specifications, power and energy requirements, production processes, and fixed connections or adhesives [43].

During remanufacturing, cells and auxiliaries must be separated and reconnected. However, current joining methods (e.g., resistance welding, laser welding, ultrasonic welding, and mechanical joining) do not facilitate this process [43]. Research should focus on developing localised, non-damaging joining and disjointing techniques to enhance the efficiency and durability of battery reassembly after remanufacturing and repairs [28]. Essential features include detachable connectors and wiring, with the housing serving as a modular interface for cell insertion. Accessible and removable joining systems facilitate testing and reconfiguration of sub-components, supporting end-of-life strategies. Proper pack case design ensures accessibility for testing and reversible opening with standard tools, minimising risks and promoting efficient recovery and reuse [44]. Moreover, modular design would allow grouping functions with similar failure rates or maintenance needs, facilitating the replacement of failed components by replacing entire modules instead of disassembling the entire product [83].

Kampker et al. [83] argue that to fully recover the value of EV battery cells, disassembly must reach the cell level due to the complex architecture of these batteries. By outlining the requirements for the three common cell types, the paper also presents three solutions, focusing on product design advancements and key technologies like laser cutting and welding, essential for optimising disassembly and reassembly processes. Mossali et al. [44] employ the House of Quality methodology to prioritise engineering specifications crucial for the recovery of LIBs. The evaluation matrix reveals that assembly specifications, particularly junction types, greatly influence the ease of disassembly and overall recovery efficiency. Key recommendations include enhancing module-pack holding, cell–cell holding, module–module joining, cell geometry, cell-busbar joining, and pack case closure to improve the remanufacturing and recycling processes.

Schimanek et al. [106] emphasise that current LIB designs hinder automated disassembly. To address this issue, they propose a novel LIB pack design that enhances the efficiency of automated remanufacturing. This design facilitates the separation of ultrasonic wire bonds, thereby enabling the efficient replacement and reconnection of defective cells. Key design recommendations include ensuring that all bond points and contact points required for cell or stack replacement are clearly visible and easily accessible. Additionally, the incorporation of standardised geometries, such as hooks or engagement points, is suggested to simplify the removal of defective cells. The design should also support the straightforward bonding of new wire connections from the cell to the designated rebond points. Lander et al. [104] recommend a collaborative effort involving researchers, industry, and policymakers. They encourage OEMs to reduce the number of modules in battery packs and transition from current fasteners to clip fasteners. Additionally, they advocate for the standardisation of screws to facilitate easier disassembly. Table 4 bsummarises the design principles collected during the analysis.

4.2. Disassembly processes and technologies

The correct strategy to disassemble obsolete batteries to a certain level (pack, module, or cell) is relevant for all second-life application pathways, from repurposing or remanufacturing to recycling. Electric vehicle batteries differ in size and structure, making standardised disassembly processes impractical. Therefore, a flexible integration of various processes is required for efficient disassembly [121]. Non-destructive disassembly is essential for remanufacturing purposes [80]. Since some joints (joining of cells or electrical connections) can be non-reversible, Schäfer et al. [72] investigate alternative designs and joining technologies suitable for non-destructive disassembly and remanufacturing.

Together with the absence of a design-for-disassembly approach [64], the main challenge of the disassembly process is the huge range of battery pack designs that can vary in size, electrode chemistry, and shape factors [16]. However, some disassembly steps and safety concerns can be generalised. The disassembly sequence includes the removal of the covers, the service plug, the coolant, the junction block, the Battery Management System (BMS), and the battery modules. The task sequence required to perform the previous steps is not unique [68].

Ke et al. [69] propose a disassembly sequence planning method based on frame-subgroup structure to maximise disassembly income. Alfaro-Algaba and Ramirez [65] propose a model for the techno-economic and environmental disassembly sequence planning for remanufacturing, focusing on the optimal level of the disassembly process to achieve both the maximum profit and the minimum environmental impact. Considering the main hazards related to battery disassembly (electrical risk, chemical hazards, and thermal runaway), Alamerew and Brissaud [64] highlight the need for the correct storage and handling of EOL batteries and for a well-ventilated area for disassembly to avoid toxic gas concentration [70]. Gentilini et al. [68] propose a mathematical model to establish the disassembly sequence that minimises the exposure of operators to hazardous voltages. In fact, LIBs can trigger thermal runaway events, especially under overcharge, short-circuit, mechanical abuse, and heat exposure. Combustible mixtures from battery failures can cause explosions, particularly when common carbonates in LIBs are exposed to high temperatures and pressures [91].

Since the current disassembling processes are mainly manual, they allow managing relatively low volume of EOL batteries at high costs; it is estimated that the disassembly phase alone costs more than half the price of a new pack, to which hardware costs, such as BMS, must be added [16]. Rallo et al. [71] evaluate a cost of 76 €/kWh to manually disassemble the battery pack from a Smart ForFour to the cell level. So, among the studies regarding remanufacturing, the need to automate the disassembly process emerges to reduce costs, minimise injury risk for workers, and allow a constant quality of disassembled components Fleischer et al. [79]. The analysis performed by Kampker et al. [55] shows that a full manual line or a hybrid line, including human–robot-collaborative systems, can manage low to medium demand cost-effectively. Wegener et al. [51] identify six main disassembly steps, including cover removal, disconnecting electrical connections, removing mechanical connections, extracting the BMS, removing the battery modules, and extracting the battery cells. Considering a specific battery system (AUDI Q5 Hybrid battery), these steps can be further divided into 19 basic operations that require the use of various techniques depending on the battery design and whose automation is therefore expensive. However, half of these operations involve disassembly by unscrewing. So, the authors propose a human–robot system in a common workstation where the robot performs unscrewing tasks, possibly supported by a camera-based detection of screws to speed up the process. Fleischer et al. [79] present a conceptual design of a two robot-based flexible disassembly system for LIB modules based on product analysis. The disassembly system's flexibility aims to manage various battery designs. One robot manages the handling tasks, while the other handles the separation steps. To ensure flexibility

Table 4
Design principles to enhance remanufacturing efficiency.

Principle	Description	Reference
Standardisation	Reduces costs and improves quality in separation and sorting of used LIBs, increasing recovery potential. Enables cells from various sources to be tested and repacked into compatible groups.	[64]
Modular design	Facilitates easy and safe disassembly and replacement of defective cells. Includes detachable connectors and wiring, and a housing that serves as a modular interface for cell insertion.	[44,64]
Design-for-Disassembly	Proper pack case design ensures accessibility for testing and reversible opening with standard tools.	[64,83]
Easily replaceable parts	Peripheral components such as sensors, management systems, and cooling mechanisms should ideally be easily pluggable and connectable.	[43]
Non-damaging joining techniques	Focus on developing techniques to enhance the efficiency and durability of battery reassembly after remanufacturing and repairs.	[28]
Accessibility of bond points	Ensure all bond points and contact points required for cell or stack replacement are clearly visible and easily accessible.	[106]
Standardised geometries	Simplify the removal of defective cells by incorporating standardised geometries, such as hooks or engagement points.	[106]
Enhanced module-pack holding	Improve remanufacturing and recycling processes by enhancing module-pack holding, cell–cell holding, module–module joining, cell geometry, cell-busbar joining, and pack case closure.	[44]

while reducing equipment downtime to change tools, the handling and cutting tools must cover a large range of operations. A thermal camera can provide continuous monitoring of the battery temperature, and the disassembly system can be designed to be hermetically lockable in case of emergency. In addition, the system can be equipped with a 3D scanner that captures the battery's shape. The economics of the system is not discussed. Glöser-Chahoud et al. [80] demonstrate the need for a systematic industrial disassembling system with the development of robot-assisted highly automated disassembly lines for LIBs, supported by proper EV and LIB design and reverse logistics strategies.

Numerous studies present human–machine interaction as an enabler of efficacy and security for battery disassembly operations [96]. Collaboration between humans and robots leverages each other's complementary abilities. Humans provide knowledge and subjective experience, while robots provide strength, consistency, precision, and the ability to function in risky environments. Wu et al. [95] proposes a human–machine collaborative cell-level disassembly model for waste modules, demonstrating the model's reliability and validity through a case study on Tesla Model S batteries. The study highlights the effectiveness of assigning hazardous component disassembly to robots while complex tasks are handled by humans, optimising workstations, idle times, and costs using the NSGA-II algorithm. Similarly, Jiao et al. [114] and Wu et al. [119] explore human–robot collaborative disassembly lines, developing mathematical models and algorithms to balance workloads and improve efficiency. Jiao et al. [114] focuses on minimising cycle times and costs, incorporating human factors such as safety and cognitive behaviour, while Wu et al. [119] utilises a mixed-integer programming model and hybrid local search genetic algorithm to achieve optimal workstation configurations and smoothness in operations. Zhan et al. [110] introduces a dual-objective disassembly sequence planning model aimed at minimising hazard index and energy cost. The study employs an efficient metaheuristic algorithm based on the northern goshawk optimisation algorithm, demonstrating its effectiveness through a Tesla Model 1 case study. Chu and Chen [99] proposes a human–robot collaboration model to minimise disassembly completion time by integrating three key optimisation problems: scheduling, disassembly procedures, and human–robot task assignment. They use a hybrid particle swarm optimisation combined with the Q-learning algorithm.

Packianather et al. [42] develops a discrete event simulation model to identify bottlenecks and improve the performance of the remanufacturing process. The model, implemented using WITNESS, significantly increases throughput and reduces blockage times.

The integration of advanced technologies such as augmented reality (AR), digital twin technology, and teleoperation presents new opportunities for improving battery disassembly. Zhao and Pham [120] proposes a teleoperated disassembly system that integrates AR and digital twin technology, enhancing operator safety and efficiency by providing real-time feedback and control during complex disassembly tasks. Garrido-Hidalgo et al. [113] proposes a conceptual digital twin model comprising a physical twin, a virtual twin, and information exchange dimensions, identified as three essential components.

The complexity and variability of EV battery designs present significant challenges for automation. Klohs et al. [103] identifies product-side hurdles, such as the variety of battery designs, and process-side challenges, like opening housing covers and removing cables. The study underscores the importance of data availability for product and component data, which is crucial for enhancing the degree of automation in battery disassembly.

Schimanek et al. [106] discusses the potential of automated remanufacturing for LIBs, proposing a process that includes the separation of ultrasonic wire bonds for cell replacement. The study emphasises the necessity of handling a variety of battery designs in a non-destructive manner to enable multiple life cycles for remanufactured batteries.

Villagrossi and Dinon [107] and Qu et al. [117] also explore robotic solutions for battery disassembly. Villagrossi and Dinon [107] highlight the benefits of human–robot collaborative disassembly for flexibility and productivity, proposing guidelines for designing robotic cells that comply with ATEX standards. Qu et al. [117] demonstrates a robotic disassembly platform for plug-in hybrid electric vehicle batteries, showcasing the advantages of autonomous disassembly and addressing limitations such as positional uncertainties and tool handling. Xiao et al. [108] combine human–robot collaboration with a dynamic disassembly sequential task optimisation algorithm using Multi-Agent Reinforcement Learning (MARL). The aim is to determine optimal disassembly paths addressing resource waste and environmental impacts. Finally, Cyber–Physical Systems (CPS), investigated by Diani and Colledani [66], are systems composed of integrated hardware and software components that continuously exchange information and actions. The proposed architecture can optimise processes, supporting a robust circular economy. Baazouzi et al. [75] introduce an adaptive disassembly planner with an integrated strategy optimiser designed to determine optimal strategies, optimising three key decisions: disassembly sequence, depth, and circular economy strategy at the component level.

4.3. Cathode restoration and re-functionalisation

Various degradation mechanisms influence LIBs' SOH and performance during their working lifetimes due to external stress factors such as temperature, State-of-Charge (SOC), and load profile. Among these mechanisms, the formation of a passivation layer on cathodes, known as the Solid Electrolyte Interface (SEI) and also called cathode electrolyte interface, is one of the most investigated degradation mechanisms as it limits cell capacity and consumes electrolyte solvents, resulting in an increase in cell impedance. The combination of SEI formation and the other degradation mechanisms trigger the loss of active material and delithiation [78]. The SEI formation at the cathode starts during the first charging, and continues during subsequent cycles, due to the oxidation of electrolyte and the decomposition of cathode materials [122]. The chemical composition of SEI strongly depends on the electrolyte and typically consists of lithium alkyl carbonates, lithium alkoxides (ROLi), lithium carbonate, and others [123]. As the number of battery cycles rises, the SEI layer thickens leading to an increase in interface resistance and a greater degree of cathode polarisation, impacting the reversible capacity and rate capacity of the battery [122]. Gastol et al. [89] investigate a cathode remanufacturing route involving cell disassembly, exhaustive cathode shredding, and metal recovery, demonstrating that the economics of the process is highly dependent on the cathode purification step. Alternatively, cathode re-functionalisation through SEI removal is considered an effective and sustainable remanufacturing technique for restoring cell performance. The two main restoration techniques discussed in the retrieved papers are laser cleaning and chemical lithiation. Laser cleaning is a physical process, independent of the chemical composition of the SEI layer, that allows precise removal of the layer without damaging the surface of the cathode, introducing or driving contaminants within the cathode. This is due to the fact that the laser energy can be tuned to concentrate in the SEI layer and break molecular bonds providing the ablation of SEI or break the inter-atomic bonds to desorb SEI from cathode (photochemical ablation) [28]. Chemical lithiation technique is a refunctionalization treatment aiming at insert lithium in degraded cathodes, to recover Li-ions availability [49].

Ramoni and Zhang [28,47] propose a physical removal of the insoluble SEI from the $LiFePO_4$ cathodes (the most used in electric vehicles and grid) using a laser surface cleaning process to avoid issues regarding the chemical solubility of SEI and chemical contamination in the cell. Liu et al. [54] use a pulsed Nd-YAG laser to remove the SEI film from the $LiFePO_4$, with laser energy intensity ranging from 0.035 to 0.169 J/mm^2. After the morphological and structural analysis of the cleaned cathode surface, a theoretical recovered capacity ratio of about 95% has been estimated. Ramoni et al. [56] use filters to tune the pulsed Nd-YAG laser energy density on the $LiFePO_4$ cathode surface and break the inter-atomic bonds, allowing SEI desorption from the electrode surface. They do not observe cathode surface damage nor crystallisation of cathode particles, and, using the treated cathode in a cell, they measure a cell performance comparable to a new one. Zhang et al. [57] apply the laser ablation technique to a graphite electrode, obtaining a cleaned electrode surface.

Ganter et al. [49] demonstrate the effectiveness of re-lithiation techniques applied to end-of-life $LiFePO_4$ cathodes as re-functionalisation treatments. The chemical lithiation process shows promising scalability and a 50% reduction in cathode embodied energy compared to the synthesis of virgin materials. Fan et al. [88] propose an in situ electrochemical cathode regeneration strategy including the substitution of the commercial electrode separator with a functionalised pre-lithiation separator, which stores releasable active Li^+ ions, allowing restored cell capacity and long-term stability. This method reduces the costs of remanufacturing and shows good compatibility with the existing battery assembly processes. Ogihara et al. [116] investigate a process to restore cell capacity by injecting Li^+ ions into the cathode using alkali metal arenide reduction reagents for radical anions that donate electrons and Li^+ ions. The method consists of generating a negatively charged state by supplying electrons to the cathode through a chemical reduction reaction while simultaneously supplying carrier Li^+ through spontaneous charge compensation. The authors find that the process allowed cathode and battery regeneration with low energy consumption. Gu et al. [124] remanufacture EV battery cathodes by extracting essential metals from EOL LIBs from cell phones and laptops using a high-efficiency leaching technique. The metals are then used to create the NCM622 cathode material.

4.4. Diagnostic and screening methods

Experts in remanufacturing methods agree that expertise and testing equipment are critical in remanufacturing EV parts, notably LIBs [76]. Indeed, identifying the technological viability of second-life uses for retired LIBs includes evaluating battery performance. In their thorough analysis, Zhu et al. [16] describe the state-of-the-art and future perspectives for diagnostic and screening methodologies, taking into account the continuous evolution of battery technology and the types of second-life applications. After the mechanical integrity evaluation, performed visually by operators or by advanced non-contact experimental techniques (digital image-based approaches, X-ray-based techniques, and acoustic tools), the electrochemical performance assessment includes the measurement of Open Circuit Voltage (OCV), internal resistance, capacity, and temperature. To estimate the RUL and SOH of the retired batteries, the degradation mechanisms (DMs) have to be understood. Charge–discharge curve-based prognostic methods, such as differential voltage and incremental capacity, are frequently used to evaluate battery degradation. Mowri et al. [84] suggest a modified DM detection procedure that identifies a threshold point, allowing cell grading and ensuring that the cells and modules in the remanufactured battery pack are in the same performance state.

On the other hand, as pointed out by Zhang et al. [50], from a remanufacturing perspective, it is necessary to find out what is the most appropriate time to establish the EOL of the battery. An optimal remanufacture time can avoid the battery's severe deterioration and ensure that the majority of active materials wrapped in electrodes are reused in the remanufacturing process at a low energy cost. When they examine the relationship between cycle number, discharge capacity, and impedance, they discover that the plots show two turning points, dividing the curves into three working stages: after the second turning point, the discharge capacity decreases significantly and the impedance increases sharply, indicating that the batteries are nearing the end of their life. This second turning point has been established as the ideal battery remanufacturing point. Shi et al. [73] introduce a method to optimally predict the EOL time for product remanufacturing by assessing energy and cost consumption throughout the product's life cycle. A multi-objective optimisation approach is applied to these functions to determine the optimal EOL time.

Groenewald et al. [58] show that monitoring the variation of internal resistance when investigating pre-conditioning strategies is critical for predicting the expected lifetime of a remanufactured battery system, determining the best SOC balance, and ensuring that all cells in the series string meet the updated lifetime requirement. Phophongviwat et al. [105] employ performance tests to determine the appropriate second-life use (remanufacturing or repurposing) based on the SOH of retired batteries. A new BMS that controls battery performance in the second-use application must be developed.

A wide consensus is found in the literature on the importance of automated diagnostics and fast-screening methods for battery health estimation and remanufacturing purposes. The use of data gathered by sensors already placed in the battery system is the most cost-effective method of selecting the batteries for second-life applications, especially when machine learning techniques are used [87]. Data-driven approaches are widely studied to allow RUL prediction by investigating the proper input features [16].

Moreover, simulation and prediction models can support the ageing analysis of LIBs and the decision-making process for remanufacturing purposes [92,97].

4.5. Data sharing and transparency

Each stakeholder throughout the lifecycle of batteries should be able to assess the SOH of each battery. Unfortunately, different information barriers and technical constraints hinder the diffusion of information. The vehicle owner is able to express concerns about range and capacity based on the BMS. Nevertheless, at the EOL stage, OCV, current, and temperature alone are not enough to make proper decisions, as the BMS is constrained by hardware and software specifics, leading to historical data losses and deficiencies [45]. Historical information (manufacturer, model, production date, battery type, operation history, retirement reasons) must be taken into account. This data helps determine the salvage value and decide if the battery should be remanufactured or not [16]. Collaboration among different stakeholders is crucial to leverage know-how throughout the entire battery lifecycle [98]. Utilising information technology to achieve comprehensive visibility throughout the supply chain and enhance coordination among stakeholders is essential for reducing uncertainty and improving planning and responsiveness [24]. Key requirements for data sharing include timeliness, cost, flexibility, and accuracy, which correspond to low latency, low cost, flexibility, and reliability in the Internet of Things (IoT) domain [67]. In this regard, Hartwell and Marco [53] address two key barriers to adopting remanufacturing strategies: ambiguity in the definition of remanufacturing and uncertainty in managing intellectual property. They propose a new framework for managing IP uncertainty, which can be used by both OEMs to protect their innovations and by independent organisations.

Okorie et al. [62] introduce a data-driven decision-making tool encapsulating data employed in remanufacturing. This framework highlights the interdependencies among stakeholders and the need for manufacturing data from IoT-enabled vehicles. This study identifies crucial manufacturing data captured by sensors, including battery temperature, voltage, current during run, air flow, vibration data within the battery cage, battery inlet pressure, and distances from the OEM to the remanufacturer and from the remanufacturer to the spares supplier. These data points are essential for enhancing the remanufacturing process of LIBs used in EVs. The use of sensor data not only improves decision-making by providing precise remanufacturing parameters but also enhances the quality and rate of remanufacturing compared to traditional methods. Garrido-Hidalgo et al. [100] propose a multi-agent network management system that enhances EOL condition monitoring through an IoT data-driven approach, leveraging LoRa's spreading factor orthogonality and time-slotted scheduling. Blockchain technology coupled with IoT enables the collection of comprehensive life cycle data from various owners and different stages in a supply chain, securely and efficiently [109]. Additionally, the study highlights the potential of sensor data to track carbon emissions throughout the remanufacturing supply chain, contributing to sustainability assessments. This greater visibility across the entire reverse logistics supply chain further improves the overall quality and efficiency of remanufacturing operations [63]. Yet, standardised battery labelling would reduce battery sorting, testing times, and costs related to the dismantling of the battery packs and modules. It also helps to identify the battery chemistry along with disclosing dedicated information about the disassembly process and usage history [64]. However, data storage for second-life applications is challenging due to the numerous stakeholders involved and potential conflicts of interest, which limit free data access. Technologies like blockchain offer potential solutions for secure data storage and access [85]. A digital battery passport, detailing manufacturing and disassembly information, can facilitate automation and allow systems to pre-identify materials and joining technologies [101,115]. Dimensions such as materials chemistry, origin, and SOH could be effectively tracked [112].

Due to the complexity and diversity of battery categories, there is no unified definition for disassembly information, necessitating regulation by a standard committee. There is also a lack of data modelling approaches for product analysis, disassembly planning, and sequencing. Representing uncertainty conditions like environmental factors (corrosion, damage) is challenging. Xiao et al. [86] propose a STEP-compliant approach to disassembly information, detailing tasks and plan activities to decompose batteries into modules and cells. Key elements include defining specific tasks, sequencing, identifying necessary tools, and outlining detailed working steps and strategies. Recognising features like strong and weak connections helps tailor the approach to different modules and components. Manual and robot operations should be specified, and understanding the final components' status after disassembly is crucial.

4.6. Supply chain design and government policies

The supply chain is crucial for understanding and improving the complex network of activities involved in the production, remanufacturing, and recycling of LIBs. Collection and transportation are identified as significant obstacles, contributing 1% to 3.5% of total life cycle GHG emissions during recovery [93]. Effective supply chain models can help identify cost-saving opportunities, reduce environmental impacts, and ensure the economic viability of remanufacturing processes [64,74]. Fig. 8 shows a general structure of the LIB supply chain, identifying the closed-loop entities.

To begin with, Li et al. [59] underscore the economic and environmental benefits of integrating remanufacturing into LIB supply chains. By designing a closed-loop supply chain, this work supports the feasibility and financial viability of remanufacturing. They develop an optimisation model to maximise profit and conduct a sensitivity analysis to identify important parameters. Results show how processing costs, transportation costs, and spent battery returns dictate the profitability of the network. Notably, the most valuable parameter to consider is the cost at the collection centre and remanufacturing activities. Furthermore, Deveci et al. [77] present a decision-making framework for selecting locations for LIB remanufacturing facilities. This study introduces a hybrid multi-criteria decision-making tool designed to identify key evaluation criteria and reduce uncertainties in the site selection process. They find that the most influential macro-criteria for choosing a location, in order of importance, are economic, technical, environmental, and social factors. Among these, the most critical criterion is the investment cost, followed by operational costs, subsidies, and resource accessibility, particularly the availability of EOL batteries.

Additionally, Wenzhu Liao and Luo [94] explore the design of reverse logistics networks by developing a fuzzy optimisation model to determine the number and location of facilities, considering both recycling and remanufacturing processes. This model accounts for uncertainties in product quality and carbon emissions. Through a case study in China, the model's effectiveness is tested and validated. Sensitivity analysis reveals that carbon emission prices have little to no effect on network design, as environmental costs constitute a small proportion of total costs. In contrast, higher product quality leads to increased revenue and greater demand for remanufacturing centres, whereas lower quality necessitates more recycling centres.

Moreover, Tavana et al. [118] integrate IoT and big data into a bi-objective optimisation model that aims to reduce costs and carbon emissions. This work influences remanufacturing by presenting the benefits of enhanced traceability, efficiency, and sustainability in the remanufacturing process. Similarly, Yang et al. [109] focus on optimising product acquisition for remanufacturing decisions, addressing quality assessment. This study highlights the benefits of using multi-dimensional data from various sources, such as collectors, to obtain valuable information on core quality before disassembly. Leveraging historical data on core quality from multiple third-party brokers allows remanufacturers to improve decision-making processes, resulting in more efficient remanufacturing decisions and reduced operational costs.

In terms of collaboration, Chai et al. [111] indicate that cooperation between suppliers and downstream partners improves profitability and supply chain performance. A cooperative mechanism is particularly beneficial for overall supply chain profitability and environmental outcomes [48]. Similarly, Gu et al. [60] analyse the economic dynamics of manufacturers and remanufacturers through a three-period model

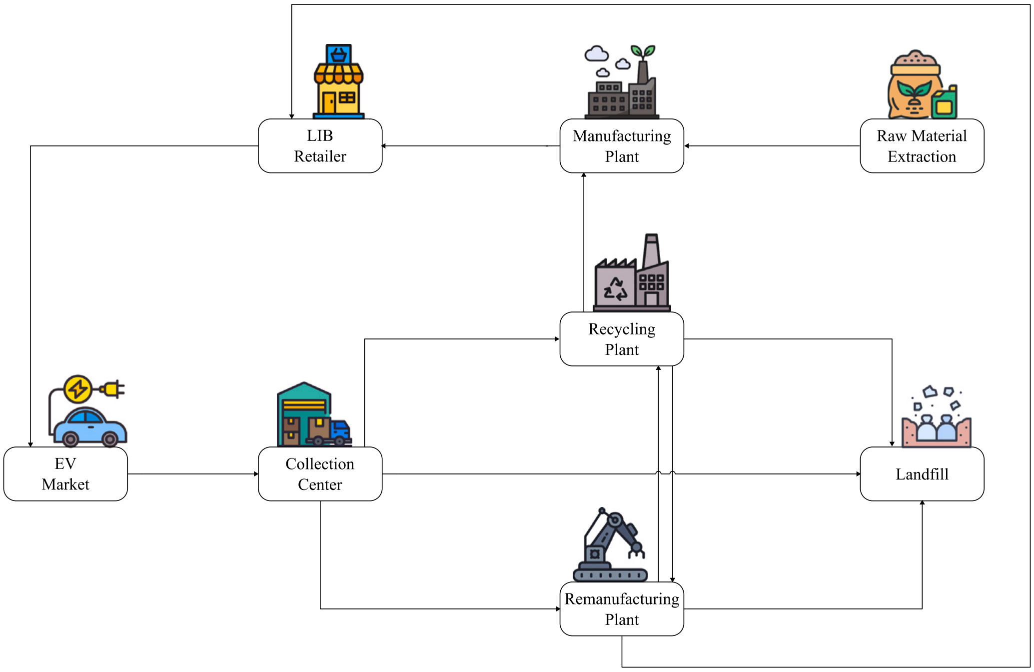

Fig. 8. LIB recovery supply chain structure [59].

and Nash equilibrium. The study underlines that the purchase price for returned batteries significantly impacts remanufacturer decisions, suggesting better-designed incentives to support the growing sector.

Moreover, Gu et al. [82] more deeply examine the role of government subsidies in promoting the secondary use of EV batteries. They find that if the quality of reusable batteries is lower than the remanufacturing rate, no subsidy is needed; otherwise, a subsidy is necessary. Lower quality demarcation of secondary usable batteries leads to higher subsidies, increasing battery prices and decreasing demand. Furthermore, government subsidies can reduce profits if the quality of reusable batteries is high. Gu et al. [81] further examines the impacts of battery recycling rates, quality, raw material costs, and government environmental spending. Therefore, government subsidies are crucial in promoting cooperation between manufacturers and suppliers. Additionally, government incentives can drive R&D in remanufacturing, leading to better economic and environmental outcomes, as supported by Chai et al. [111]. Kamath et al. [102] develop a system dynamics model to evaluate the impact of incorporating a remanufacturing stage before recycling EOL batteries. As new battery prices decrease, the economic value of remanufacturing diminishes, potentially reducing the overall economic value of recycling EOL batteries with the added remanufacturing step. However, this reduction in economic value can be mitigated by subsidies and incentives for recovered batteries, thereby enhancing profitability. Huster et al. [90] analyse German-specific scenarios, comparing a linear model where remanufacturing is not considered with one that incorporates remanufactured batteries as spare parts for older vehicles. The results demonstrate that remanufacturing can decrease new battery demand by 6%–7% when battery lifetimes are shorter than vehicle lifetimes, and by up to 2% when battery lifetimes exceed vehicle lifetimes.

5. Discussion and research agenda

The increasing adoption of EVs and the corresponding rise in LIB production has intensified the focus on sustainable EOL management strategies for these batteries. While significant progress has been made in understanding various aspects of LIB recovery, there remain several gaps and opportunities for further research. This research agenda (summarised in Fig. 9) aims to outline key areas for future investigation to advance the remanufacturing of EV batteries, fostering circular economy.

Developing non-destructive joining and disassembly techniques. Several gaps in the literature on module designs warrant further investigation. One primary gap is the development and standardisation of non-damaging joining and disassembly techniques. Current methods, such as resistance welding, laser welding, and ultrasonic welding, often fail to facilitate efficient separation and reconnection of cells during remanufacturing. Future research should prioritise innovative joining techniques that enable localised, non-destructive disassembly, thereby enhancing the durability and efficiency of battery reassembly. Exploring advanced methods like laser cutting and specialised mechanical fasteners can provide more effective and sustainable solutions. Additionally, comprehensive studies on implementing modular design principles that facilitate the easy and safe disassembly and replacement of defective cells are needed. Investigations should focus on designing detachable connectors, modular interfaces for cell insertion, and standardised geometries that simplify the removal and replacement of components. Collaboration between researchers, industry stakeholders, and policymakers is essential to develop and adopt standardised design protocols that ensure the accessibility and visibility of bond points, and the incorporation of clip fasteners and simplified engagement points. Lastly, research should explore the implications of standardising components and geometries on the cost-effectiveness and quality of LIB remanufacturing.

Standardising modular designs for efficient disassembly. Current methods for disassembling EV batteries face significant challenges due to the variability in battery pack designs, sizes, and structures. This complexity makes standardised disassembly processes impractical, highlighting the need for flexible approaches that can adapt to different configurations effectively. To address this, future research should focus on developing standardised and modular battery designs that simplify disassembly. This includes creating uniform assembly protocols that consider the EOL phase. Additionally, enhancing robotic systems with advanced AI and machine learning can improve precision and adaptability in disassembly tasks.

Implementing robust protocols and advanced technologies. Safety is another critical area, necessitating robust protocols and real-time monitoring systems to mitigate risks like thermal runaway and hazardous material exposure. Teleoperation and AR technologies present promising solutions for managing complex disassembly tasks, offering real-time feedback and remote operation capabilities to enhance safety and efficiency.

Scalable methods for cathode restoration and re-functionalisation. Despite advancements in LIB degradation, practical and scalable methods for cathode re-functionalisation, particularly through SEI removal, remain underexplored. Future research should focus on comparative studies of laser cleaning and chemical lithiation across different battery chemistries, optimising laser cleaning parameters, and developing hybrid techniques combining physical and chemical methods. Additionally, comprehensive lifecycle assessments, economic analyses, and long-term performance and safety studies are needed to evaluate the environmental impacts, cost-effectiveness, and reliability of these re-functionalisation methods. Addressing these areas will help extend LIB lifespan and enhance performance, meeting the demand for efficient energy storage solutions.

Integrating diagnostic and screening methods. Notably, there is a need for more comprehensive and integrative approaches that consider both technical and economic factors to determine the EOL of batteries more accurately. One promising area for future research is the development of predictive models that integrate technical performance metrics with economic and environmental considerations. Such models could leverage advanced machine learning techniques to analyse large datasets collected from BMS. Future research should explore the development and testing of new BMS technologies tailored for second-life applications, ensuring that these systems can efficiently manage batteries with varying SOH. Additionally, there is a need for standardised methodologies to evaluate the accuracy and reliability of these models across different battery chemistry and use cases. Researchers could focus on creating benchmark datasets and performance metrics to facilitate comparative studies and improve the robustness of RUL predictions.

Improving data sharing and transparency. Current BMS face limitations in data retention, affecting EOL decision-making. Future research should focus on developing secure data-sharing frameworks using blockchain and IoT to integrate comprehensive historical data from multiple stakeholders. Standardising battery labelling and data modelling approaches is crucial to streamline disassembly and improve remanufacturing efficiency. A battery passport system detailing manufacturing and disassembly information could facilitate automation and accurate component identification, enhancing SOH tracking. Advanced decision-making tools leveraging sensor data from IoT-enabled vehicles should be developed to improve remanufacturing quality and speed. Additionally, integrating sensor data to monitor carbon emissions in the reverse logistics supply chain could significantly enhance sustainability assessments.

Holistic supply chain design and policy impact assessment. The current literature often focuses on isolated components of the supply chain rather than adopting a holistic approach. Future research should aim to develop comprehensive models that integrate collection, transportation, remanufacturing, and recycling processes, thereby providing a more accurate representation of the entire LIB lifecycle. Additionally, there is a need for more detailed studies on the impact of regional variations in economic, technical, and environmental factors on the viability of remanufacturing operations. Such studies could utilise advanced data analytics and machine learning techniques to predict and optimise location-specific supply chain configurations. Moreover, the role of government policies and subsidies in promoting remanufacturing is well-documented; however, there is limited understanding of the long-term effects of these interventions. Research should focus on longitudinal studies to assess the sustainability and economic impacts of government incentives over extended periods. Furthermore, while existing studies emphasise the importance of quality assessment, there is a lack of standardised methodologies for evaluating the quality of returned batteries. Developing uniform standards and protocols for core quality assessment can enhance the consistency and reliability of remanufacturing processes. Additionally, the potential for blockchain technology to enhance transparency and trust in the LIB supply chain warrants further investigation. By addressing these gaps, future research can contribute to more resilient, efficient, and sustainable LIB supply chains.

6. Conclusion

This paper addresses the increasing adoption of EVs and the corresponding rise in LIB production, emphasising the need for sustainable EOL management strategies for these batteries. It highlights the growing interest and research activity in remanufacturing EV batteries to

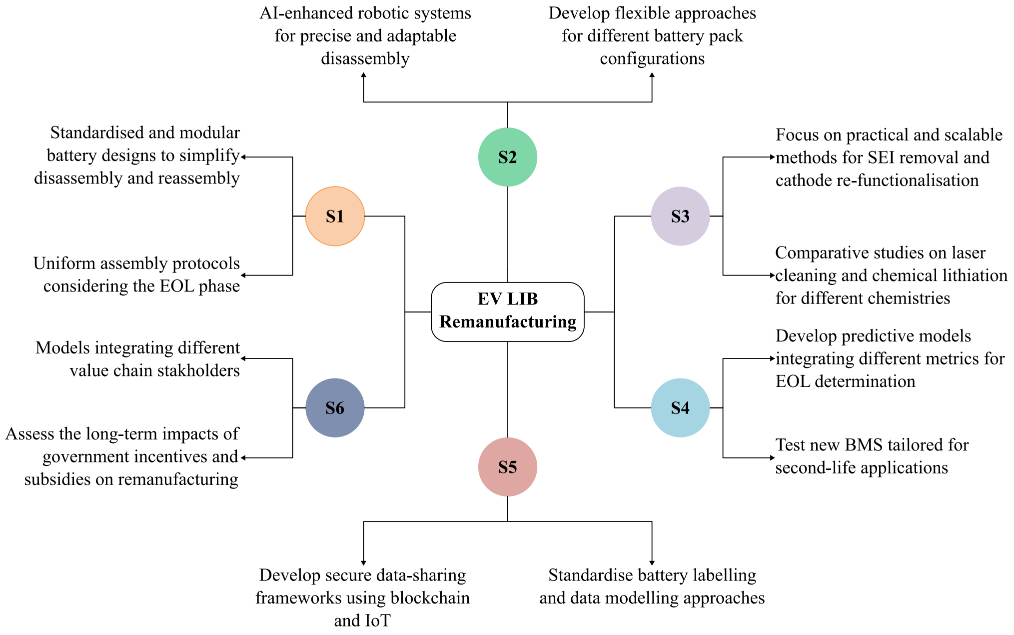

Fig. 9. Schematic of research agenda.

foster a circular economy by extending the lifespan of LIBs. The literature review covers various aspects of the remanufacturing process, including module design, automatic and safe disassembly, cathode restoration, diagnostic and screening methods, data sharing, and value chain design. It systematically reviews articles published between 2012 and 2024, identifying major issues during the remanufacturing process from EOL collection to renewed batteries and clustering results into different research fields.

The review identifies significant advancements in LIB remanufacturing but also highlights key areas for further research. Standardisation and modular design are essential for improving disassembly and reassembly efficiency. Human–robot collaboration and advanced technologies like AR can enhance safety and efficiency. Cathode re-functionalisation shows promise for restoring cell performance. Automated diagnostics using machine learning are critical for assessing battery health. Secure data-sharing frameworks and standardised battery labelling can streamline processes. Comprehensive supply chain models integrating collection, transportation, remanufacturing, and recycling are needed, with government policies and subsidies playing a crucial role.

Modular battery design and non-destructive disassembly by industrial stakeholders could be taken further; this would be supported with AI-enhanced robotic systems and AR for complex tasks, increasing efficiency and safety in remanufacturing. Given a digital battery passport system, the data of manufacturing, usage, and disassembly can effectively be tracked; therefore, many processes will be simplified and more transparent. Policy framers have to come up with modular design standards, provide incentives, and introduce secure blockchain and IoT-enabled data-sharing formats that enhance EOL management.

Future research should focus on developing integrative models that consider both technical and economic factors, creating standardised and modular battery designs, enhancing robotic and AI technologies for disassembly, and exploring hybrid cathode restoration methods. Secure data-sharing frameworks and comprehensive supply chain models should be developed, with an emphasis on assessing the long-term impacts of government policies and subsidies. Based on these future prospects, Table 5 presents potential research paths in the form of questions, highlighting specific and crucial open areas for future development.

Addressing these areas will support the sustainable growth of the EV industry and efficient LIB management, promoting a circular economy.

CRediT authorship contribution statement

Alessandro Neri: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Conceptualization. **Maria Angela Butturi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Conceptualization. **Rita Gamberini:** Writing – review & editing, Validation, Project administration, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to improve the language and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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

Table 5
Open research questions.

Stream	Questions
S1	1. How can localised, non-destructive disassembly of battery cells during remanufacturing be enabled by developing innovative joining techniques? 2. What standardised modular design principles can be implemented to streamline the disassembly of diverse EV battery configurations?
S2	3. How can the safety and efficiency of complex disassembly tasks be improved by integrating teleoperation and AR technologies?
S3	4. What scalable and cost-effective methods can be developed for cathode re-functionalisation, such as hybrid techniques combining laser cleaning and chemical lithiation, to extend the lifespan and performance?
S4	5. What new BMS technologies can be designed to manage batteries with varying SOH effectively in second-life applications?
S5	6. How can secure data-sharing frameworks be created by utilising blockchain and IoT to integrate comprehensive historical data from multiple stakeholders in battery remanufacturing? 7. How can detailed manufacturing and disassembly information be provided to improve SOH tracking and automation in remanufacturing through a battery passport system?
S6	8. How do the viability of remanufacturing operations get influenced by regional variations in economic, technical, and environmental factors, and how can location-specific supply chain configurations be optimised? 9. What long-term effects do government policies and subsidies have on the sustainability and economic viability of operations?

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